Climate change impacts on crop–weed interaction and herbicide efficacy

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Weeds are likely to show more resilience and adaptation to rising carbon dioxide (CO_2) concentration and temperature than crops because of their diverse gene pool and greater physiological plasticity. In agroecosystems, C_3 and C_4 plants exhibit varied responses to elevated CO_2 (eCO_2) and temperature (eTem), which can impact the crop–weed competition and efficacy of herbicides. Most C_3 plants respond positively to eCO_2 by increasing their photosynthetic rate and biomass production. Weeds compete with crops for nutrients, water and light, and considerably reduce yield and quality of the produce. Hence more attention is needed on crop–weed interaction and management under changing climate to ensure sustainable agricultural production. This study emphasizes on the impacts of climate change on crop–weed interaction, herbicide efficacy and weed flora shift, and also highlights the research gaps for further studies.

Keywords: Carbon dioxide concentration, climate change, crop–weed interaction, elevated temperature, herbicide efficacy, weed flora shift.

WEEDS are one of the most significant biotic constraints in agriculture. They not only reduce crop productivity by competing with crop plants with major inputs (nutrients, moisture and solar radiation), but act as alternative hosts for insect-pests and disease-causing pathogens. Climate change along with greenhouse gas (GHG) emission in the atmosphere has become a major constraint on agriculture and pest dynamics. Among different pests, weeds are likely to react directly to elevated carbon dioxide (eCO_2) levels in the Earth's atmosphere[1]. Concentration of CO_2 in the atmosphere has risen to 419.05 ppm in 2021 (ref. 2). It may exceed 600–700 ppm by the end of the 21st century[3,4]. Temperatures are estimated to have risen by 0.1–0.3°C per decade worldwide since pre-industrial times[5] and projected to increase by 1.1–6.4°C by the end of the 21st century[4].

Temperature and CO_2 shifts are likely to have major direct (CO_2-induced growth) and indirect (climatic variability) effects on weeds, influencing the balance of crops–weeds or contributing to weed invasion. In order to assess the vulnerability of agricultural production in different parts of the world, a better understanding of the potential interactions between crops and weeds in the context of climate change is necessary[6].

Weeds appear to be more genetically diverse and physiologically flexible than crops, and adapt rapidly under diverse environmental conditions. The effects of climate change are projected to enhance weed competitiveness, resulting in larger output losses if the weeds are not properly controlled[6,7]. Climate change, particularly eCO_2, is likely to favour yield and quality of C_3 crops. By 2050, higher CO_2 levels are anticipated to improve food production up to 13% (ref. 8). However, the beneficial effects of eCO_2 on crop performance are negated by the adverse impacts of concomitant temperature rise for most food crops[9]. On the contrary, eCO_2 causes partial stomatal closure, resulting in increased plant tissue temperature which has a detrimental impact on plant growth and production. Other directly related issues with climate change, such as irregular rainfall patterns and high temperature may impair agricultural output and quality[10,11].

Climate change may cause global range expansion (migration or introduction into new regions), changes in the life cycle of species, and population dynamics in weedy vegetation. Weed migration will lead to differences in the structure and composition of weed populations in natural and managed ecosystems. Under the changing climate scenario, there are three distinct shifts in weedy vegetation (range, niche and trait shifts), occurring at different scales (landscape, community and population scales)[12].

Herbicides are the best tools to manage agricultural weeds and increase agricultural productivity. eCO_2 and elevated temperature (eTem) can alter herbicide efficacy by affecting the time of weed seedling emergence, stomatal conductance, absorption, translocation and metabolism[13–15].

Climate change will bring about changes in the weed population and their phenology. This may allow certain non-potent weeds to dominate weed abundance[16]. Apart from geographic distribution, climate change may influence the weed population biology, enabling them to relocate to new places at greater altitudes and latitudes[1,17–19]. Many species of weeds can expand their range and spread into new areas. Witchweed (*Striga* spp.), has been proposed to expand its geographic range and will have several adverse consequences[20]. Information about the impact of climate change on weeds and weed management is sparse. In this study,

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we analyse the effects of climate change on crop–weed interaction, weed flora shift and efficacy of herbicides.

Impact of climate change on weed growth and biomass

Impact of elevated CO_2

The eCO_2 generally enhances the performance of C_3 plants, whereas C_4 plants show less response[21]. Many studies have suggested that eCO_2 positively impacts the vegetative growth of C_3 in comparison to C_4 plants[1]. Under eCO_2, several important C_3-weeds like wild oats (*Avena ludoviciana*), blistering ammannia (*Ammania baccifera* Linn.), baconweed (*Chenopodium album* L.), littleseed canarygrass (*Phalaris minor* Retz.), etc. show decreased stomatal aperture and improved water-use efficiency[1,22], thereby making them more hostile and difficult to track. Ziska and Goins[19] suggest that broadleaf C_3 weeds are better selected at eCO_2 levels.

Several studies reported that C_3 weeds like wild oats, wild poinsettia (*Euphorbia geniculata* Ortega.)[23], weedy rice (*Oryza* spp.)[24], smooth chaff flower (*Alternanthera paronychioides* A. St.-Hil.)[25], *P. minor*, bur clover (*Medicago denticulata* Willd.) and grass pea (*Lathyrus sativa* L.)[24,26], *C. album*[26], spreading dayflower (*Commelina diffusa* Burm. f.)[27], *Parthenium hysterophorus*[28], thistle (*Cirsium arvensis* L.), velvetleaf (*Abutilon theophrasti* Medic), Italian ryegrass (*Lolium multiflorum* Lam.), wild buckwheat (*Polygonum convolvulus* L.), bindweed (*Convolvulus arvensis* L.), cocklebur (*Xanthium strumarium* L.), couch grass (*Elymus repens* L.) and cheatgrass (*Bromus tectorum* L.) showed enhanced growth and photosynthesis under eCO_2 (refs 7, 8, 29–32).

However, in C_4 weeds, namely kochia (*Kochia scoparia* L.), Johnson grass (*Sorghum halepense* L. Pers.), goosegrass (*Eleusine indica* (L) Gaertn)[11,33], barnyardgrass (*Echinochloa crus-galli* L.), large crabgrass (*Digitaria sanguinalis* L.), redroot pigweed (*Amaranthus retroflexus* L.) and bermudagrass (*Cynodon dactylon* (L) Pers.), the rate of photosynthesis and growth significantly reduced at eCO_2 (refs 34–38).

Impact of elevated temperature

At eTem, weeds with a C_4 pathway have a competitive advantage over C_3 crops[39]. The C_4 plant species are more adapted to heat stress and may induce stimulation of meristematic region, quick growth of canopy and root proliferation at eTem (ref. 12). Photosynthesis and growth are enhanced in various C_4 weeds like *K. scoparia*, *S. halepense*, *E. indica*[11,33], *E. crusgalli*, *D. sanguinalis*, *A. retroflexus* and *C. dactylon* at eTem (refs 34–37).

Similarly, photosynthesis and growth of several C_3 weeds like *A. fatua*, *C. album*, *C. arvensis*, *A. theophrasti*, *L. multiflorum*, *P. convolvulus*, *C. arvensis*, *X. strumarium*, *E. repens* and *B. tectorum* are reduced at eTem (refs 4, 6, 29, 31, 32).

Interactive effects of elevated CO_2 and temperature

Plant response to CO_2 and temperature interaction effects is complicated[40]. Some studies indicated that low or high temperature reduces CO_2-induced growth[41], while others revealed that eCO_2 can enhance crop tolerance to severe temperatures[42]. eCO_2 levels have been suggested to ameliorate the impact of sub-optimal temperature on plant growth[43] and other sources of stress[40]. eTem effects on quack grass (*Elytrigia repens* L.) were strengthened by eCO_2 (ref. 44). The productivity in rice (C_3 crop) may be improved relative to barnyard grass (*Echinochloa glabrescens* Munro ex Hook. F.) (C_4 weed) with eCO_2 alone, but eCO_2 + eTem favour C_4 species[45]. At 480 ppm CO_2, *A. ludoviciana* plants produced 44% more seeds than at 357 ppm.

The growth of Chinese sprangletop (*Leptochloa chinensis* (L.) Nees; C_4) was enhanced under eCO_2 and eTem (Figure 1). Similarly, leaf area of *A. paronychioides* was enhanced at eCO_2 and eTem (ref. 25). The C_3 weed species, namely *E. geniculata*, *C. album*, *P. minor*, *E. colona* and wrinklegrass (*Ischaemum rugosum* Salisb.) were the most responsive to eCO_2 and eTem (refs 28, 46, 47).

Impact of drought

The rate of photosynthesis, transpiration and stomatal conductance were significantly reduced under low soil moisture content[48]. Aridity may increase in many agriculturally significant places in the near future because of the increase in temperature (1–5°C) with each doubling of atmospheric CO_2 levels. eTem causes greater evaporation and rainfall variability predicts that monsoon regions will get drier[49], resulting in an increase of drought-prone areas by 5–8% (ref. 37). Under this condition, the spread of weeds and their pervasiveness will be a major issue in agricultural ecosystems, and dry spells in the summer season will affect weed control in crops sown during spring[50]. C_4 and parasitic weeds like witchweed will survive better under extreme drought spells[51]. Scarce information is available on the effect of drought on crop–weed interaction, and this must be explored in the near future.

Crop–weed interaction

Effect of enhanced atmospheric CO_2 concentration

CO_2 enrichment has been linked to considerable stimulation in the growth and development of numerous plant species[21]. The type of photosynthetic pathway (C_3/C_4) in plants is responsible for variation in their response under eCO_2.

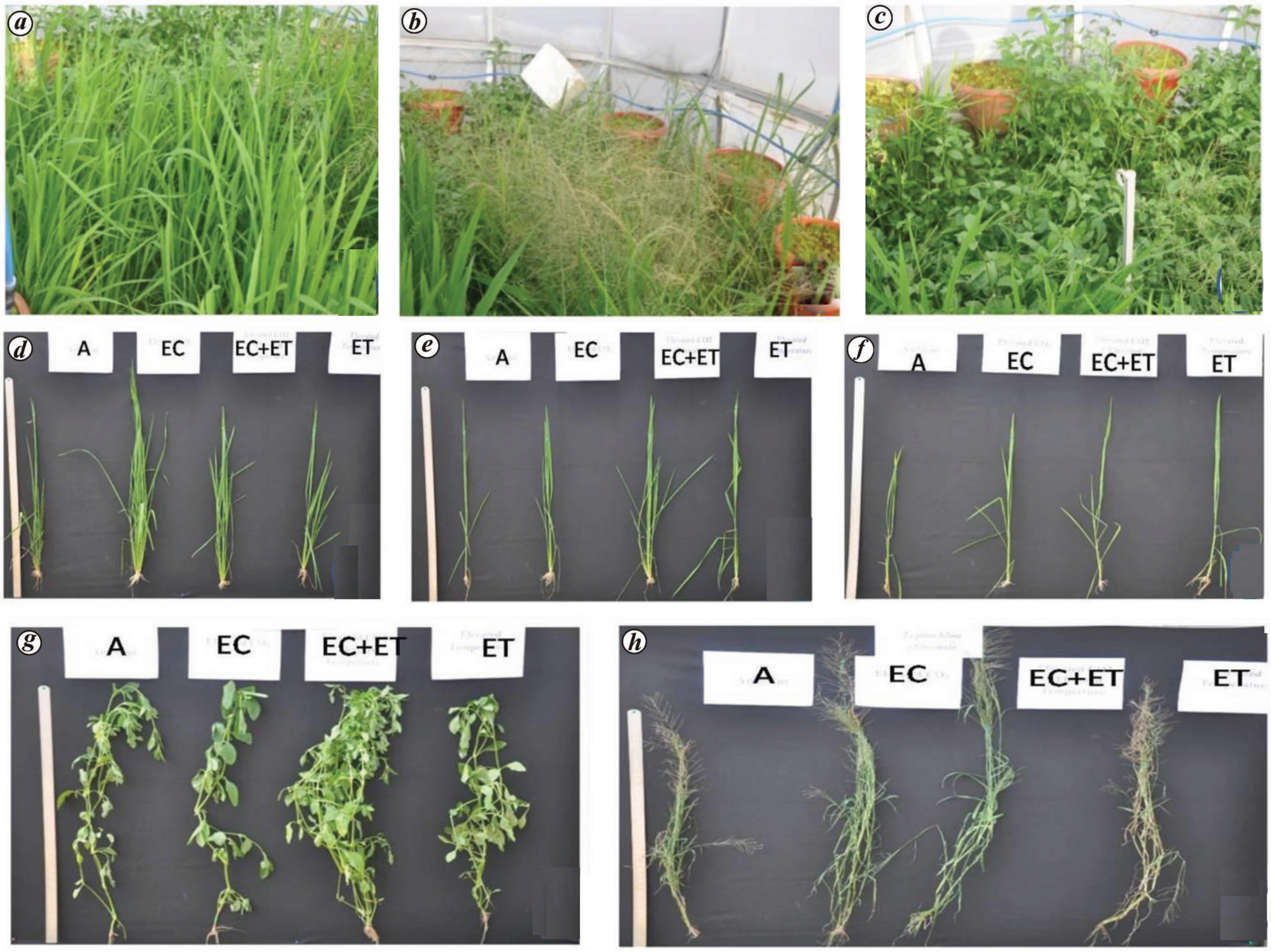

Figure 1. Crop–weed interaction under different growth conditions. ***a***, ***d***, Rice plants in weed-free conditions. ***b***, ***e***, Rice plants in competition with *Leptochloa chinensis*. ***c***, ***f***, Rice plants in competition with *Alternanthera paronychioides*. ***g***, *A. paronychioides* plants under different growth conditions. ***h***, *L. chinensis* plants under different growth conditions. A, Ambient conditions; EC, Elevated CO_2 conditions; EC + ET, Elevated CO_2 + elevated temperature conditions; ET, Elevated temperature conditions.

Better photosynthetic efficiency in C_3 crops (rice, wheat, soybean, etc.) indicates that they will respond more favourably to eCO_2 than the C_4 weeds (*Amaranthus palmeri* L., *Amaranthus rudis*, *K. scoparia*, etc.)[52]. In rice and wheat, high CO_2 concentration along with C_4 weeds have a beneficial impact on crop competitiveness[39]. However, *P. minor* was more competitive with eCO_2 over wheat under drought[53].

Under eCO_2, the yield of C_3 plants (soybean and *C. album*) was considerably higher than C_4 plants (millets and pigweeds)[7]. Increase in biomass and yield of weedy rice in contrast to rice grown at eCO_2 advocates a larger decline in the yield of cultivated rice in the future because of greater physiological flexibility and higher genetic variations among cultivated lines and wild species[54,55]. C_3 weeds like *C. album*, *A. theophrasti*, *Ambrosia artemisiifolia* and *Ambrosia trifida* will respond more favourably to eCO_2 and offer higher competition to C_4 crops (maize, sorghum, sugarcane, etc.). However, there was no improvement in the biomass of *A. retroflexus*, a C_4 weed, at eCO_2 and soybean yield loss fell from 45% to 30% (ref. 56).

eCO_2 positively impacted the overall growth of chickpea and its major weeds (*Lathyrus sativa* and *M. denticulata*)[24]. It also profoundly impacted leaf area, number of tillers/plant, net photosynthesis and transpiration in cultivated rice and weedy rice[24]. The growth of maize was affected by *E. geniculata* under eCO_2 than ambient CO_2 (ref. 23). At eCO_2, the highest rate of photosynthesis was recorded in *C. diffusa* followed by *E. geniculata*, while it was the lowest in green gram[27]. Higher relative growth rate (RGR) was observed in *L. sativa* compared to chickpea and other weed species like *P. minor*, *M. denticulata* and *C. album* under eCO_2 (ref. 26). Increase in dry biomass build-up at eCO_2 was 19.5%, 90.8% and 75.6% in mungbean (*Vigna radiata* L.), baans gha (*Brachiaria reptans* L.) and *Eragrostis diarrhena* (Schult.) Steud. respectively[57].

Impact of elevated temperature

At eTem, plants with the C_4 pathway (mostly weeds) have a competitive advantage over crop plants with the C_3 pathway[39]. A rise in temperature by 3°C led to significant enhancement in the growth of itch grass (*Rottboellia cochinchinensis* (Lour.) W. D. Clayton), a major C_4 weed in crops like sugarcane, corn, cotton, soybean, grain sorghum and rice[17].

C_4 weed species like *S. halepense* and *A. retroflexus* are projected to fix CO_2 at a greater rate than C_3 crops like soybean and cotton at higher temperatures and light intensity. Since high temperatures increase evaporative demand, C_4 photosynthesis is adapted much better to high evaporative demand because of its higher CO_2 compensation point and water-use efficiency[58]. With doubling of CO_2 concentration, it has been observed that C_4 weeds have a greater stimulation in photosynthesis and biomass than C_4 crops[59]. Until the Kranz anatomy of C_4 plants is fully differentiated, they utilize the C_3 pathway[60]. During this early growth stage, a major part of the leaf area of these plants performs under the C_3 pathway and, therefore are benefited under eCO_2. Under warmer conditions, green foxtail (*Setaria viridis* (L.) P. Beauv.) germinated late[61]. This may become a serious threat in maize because of its synchronicity with germination[50].

Interactive effect of elevated CO_2 and temperature

P. minor has a competitive advantage over wheat at eTem alone or in combination with eCO_2. eCO_2 + eTem delayed panicle maturity in cultivated rice, weedy rice and wild rice[38,62]. At eCO_2, eTem and a combination of the two, there was competitive advantage of *E. geniculata* (C_3) over green gram and C_4 weeds like *A. viridis*[28]. eTem alone or in combination with eCO_2 had a negative impact on wheat, but no such effect was noticed in *P. minor*[62]. Studies revealed that under changing climate, *E. geniculata* and *A. viridis* may dominate green gram[28].

eCO_2 alone and in combination with eTem positively impacted overall improvement of maize, *C. album* and *P. minor*[46]. Similarly, eCO_2 and eTem had positive consequences on soybean and its major weeds *E. colona* and *I. rugosum*[47]. Plant height and leaf area were enhanced in *A. paronychioides* (C_3) and *L. chinensis* (C_4) under eCO_2 and eTem compared to ambient[25].

Impact of drought

Drought and arid conditions favour the growth of C_4 weeds because of their strong internal physiological mechanisms. Competition of cotton with *A. theophrasti* and spurred anoda (*Anoda cristata* Schlecht.) was more under drought[63]. A decline in yield due to *X. strumarium* was prominent in well-watered soybean compared with water-stressed soybean[64]. More rainfall resulted in greater competition to wheat growth and yield against *C. arvense*[65]. Weed competition had little effect on crops under water-deficit conditions, as the potential crop yield was already reduced by water stress[1,66]. In contrast, spiny amaranth (*Amaranthus spinosus* L.) and *L. chinensis* survived under water stress and produced a significant number of tillers/branch and leaves even at the lowest soil water content[66]. There is an urgent need to explore this aspect to cope with the future climate change challenges.

Herbicide efficacy

The efficacy of herbicides was affected by climatic factors such as temperature, precipitation, wind and relative humidity[67]. The efficiency and selectivity of herbicides can be exaggerated by prolonged high temperature after application, indicating that selective herbicides may become non-selective at eTem. Many studies have reported that efficacy of herbicides declined under eCO_2 (ref. 68). Some studies have suggested that as CO_2 enhances the growth and development of some weeds (C_3), which promote plant immunity and detoxify mechanisms (high volume of tissues).

Effect of elevated CO_2

eCO_2 decreased the effectiveness of glyphosate[69] and sulphosulphuron (against *P. minor*)[38,62]. It also caused morpho-physiological and anatomical modifications in plants, which impact the rate of herbicide absorption and translocation[68,70]. The number and conductance of stomata decreased in C_3 plants but leaf thickness increased interfering with herbicide foliar absorption[71], as well as significant rise in starch build-up on the leaf surface[1]. Furthermore, if vegetative growth is accelerated due to enhanced photosynthesis in response to eCO_2, perennial weeds may become more problematic. Due to the dilution effect, these alterations are likely to impair the efficacy of the applied herbicides. Furthermore, increase in the root–shoot ratio may be important for herbicide effectiveness[30].

Effect of elevated temperature

The efficacy of foliage-applied herbicides is regulated by the local climate/microclimate[72]. The volatility of trifluralin increased at eTem, making it less effective[73]. Temperature had less impact on acifluorfen phytotoxicity in *X. strumarium* and *A. artemisiifolia* than relative humidity[74]. However, the degradation of herbicides like flumetsulam and thifensulphuron was significantly affected by eTem in the soil[75]. The glyphosate assimilation relies on temperature as evident from *Desmodium tortuosum* a C_3 weed[76]. An increase in relative humidity or temperature resulted in a threefold increase in the efficacy of mesotrione on *X. strumarium* and *A. theophrastii*[14]. Temperature beyond the range 20–34°C lowered the efficiency of the pyrithiobac on *A. palmeri*[77]. Glufosinate was more efficient in controlling wild radish (*Raphanus raphanistrum* L.) at eTem (ref. 78).

The efficacy of sulphosulphuron against *P. minor* was reduced under eTem and eCO_2 + eTem (ref. 38). Bispyribac sodium showed 2, 5 and 8 days delayed effect on *E. colona* under eTem, eCO_2 and eCO_2 + eTem respectively. However, 2 and 1 day early response of this herbicide was noticed on sunberry (*Physalis minima*) at eTem and eCO_2 + eTem. Similarly, *Dinebra retroflexa* showed 1, 4, 7 and 1 days delayed response to topramezone + atrazine and tembotrion + atrazine under eTem, eCO_2 and eCO_2 + eTem respectively. Sulphosulphuron + metsulphuron showed 3 days early response against *P. minor* and 2 days delayed response on *A. ludoviciana* under eTem (ref. 79).

Impact of drought

Weeds under moisture stress can react by thickening their leaf cuticles, slowing down vegetative growth and flower quickly. Drought-stressed weeds are hard to manage with post-emergent herbicides. Pre-emergent herbicides require soil moisture to enter their target sites. Drought can lessen the efficacy of pre-emergent herbicides[80].

Herbicide penetration will be reduced by increased cuticle thickness and leaf pubescence in response to drought[1]. These characteristics can also affect crop and weed growth, and restoration following herbicide administration. Drought and aridity will increase herbicide volatilization, while regular rainfall may reduce the rain safe times available for herbicide treatment in a particular agricultural system, resulting in multidimensional weed control issues. High rainfall (either in a single event or over time) may encourage the leaching of herbicides sprayed to the soil, resulting in groundwater pollution[81].

Weed flora shift

Climate change will have an impact on plant distribution, as well as ecosystem functioning and output. In the forests worldwide, expanding abundance of woody vines due to rising CO_2 levels has been linked to higher tree mortality and impaired tree regeneration[82]. Many weeds were more tolerant to cold temperature under eCO_2 (ref. 83), indicating that weed species may expand towards the geographic poles[19,33]. The spread of invasive weed *P. hysterophorus* has been attributed to its response to climate change, particularly eCO_2 (ref. 84).

Similarly, in rainfed agriculture, a rise in parasitic weed populations would pose a significant risk to rice and sorghum crop yield[37]. Due to the colder temperatures at higher latitudes, majority of the harmful C_3 and C_4 weeds in the arable land are restricted to tropical and subtropical regions[85].

Climate change has induced altered weed distribution, such as the emergence of *Marsilea* spp. in India under the wet conditions of rice. Severe drought forces the transition to direct-seeded rice, encouraging recalcitrant grass weeds such as crowfootgrass (*Dactyloctenium aegyptium* L.), *E. indica*, *L. chinensis* and aerobic rice[86]. Temperature change also triggered shifts in weed flora in the face of climate change. For instance, *I. rugosum* was mostly seen in the tropical parts of India, but it is now ubiquitous in North India[11]. Under projected climate change, these weeds are expected to expand their geographic range, impacting the productivity of rainfed corn, sorghum and rice crops.

Due to a deficiency of rainfall and protracted drought, arable crops and pastures will develop slowly, leaving barren land and allowing more robust, drought-tolerant weeds to invade. In addition, attention is also required regarding the effect of eCO_2 on the geographical spreading of weeds in managed ecosystems[33].

Conclusion

Weeds are among the agricultural pests that can and will be strongly affected by climate change. Under such a scenario, handling weeds would be more complex and expensive. They will be directly affected by the expected rise in CO_2 levels and temperature. Previous studies indicated that efficacy of herbicides declined under climate change. Therefore, right time application of herbicide is an important step in the weed control. Proactive measures are needed to prevent the expansion of invasive weeds to new places under the future climate change scenarios. The timing of herbicide application and other weed control measures will be heavily influenced by seasonal precipitation and temperature fluctuation. Higher amounts of certain herbicides may be required at usual intervals, that will have severe environmental consequences. Additionally, in such circumstances, a higher number of weeds may develop herbicide resistance more rapidly. Hence comprehensive research efforts encompassing ecological, physiological and molecular studies are needed to examine the interacting impacts of diverse climatic factors on plant growth and herbicide efficacy.

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