

Weeds and their response to changing climate – A Review

ABSTRACT

Climate change is one of the most important parameters to cause alteration in weed composition, population growth, life processes, physiological development, and infestation pressure. A few of the weed species may become inactive, while the rest may become aggressive invaders. Weeds possess unique biological characteristics and ecological range that enable them to tolerate and successfully intrude in any ecosystem with varied environmental conditions. Rising carbon dioxide, will benefit C₃ crops to expand their photosynthetic capacity, thus leading to increased biomass production and productivity, on the other hand increased temperatures will benefit the C₄ crops. These differences in response of C₃ and C₄ crops to changing climate will influence crop-weed interaction, most likely at the expense of crop. Moisture is another important environmental factor which plays a major role in weed seed germination, thus the survival. Temperature and relative humidity influence the course of absorption, translocation, and metabolism of herbicides in plants, any change in their range leads to decreased herbicide efficacy and thus the weed control. Studies should be focussed on the performance of weeds under elevated environmental factors so that strategic decisions should be taken on their management before having their impact on change in weed biological aspects, and we can foresee the future with elevated temperature and carbon dioxide conditions.

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Key words: Climate change, C₃-C₄ weeds, Carbon dioxide, Glyphosate efficacy, Herbicide efficacy, Photosynthetic pathways, Rainfall, Temperature

1. INTRODUCTION

Climate is the sum of weather conditions of a given area, quantified as long-term statistics of meteorological variables. Climatic variables include temperature, wind, precipitation and sunshine hours. Among these variables, temperature, moisture and light are very important as they determine the distribution and adaptation of weeds in a particular

ecosystem. Climate has a pronounced role in deciding the agricultural production directly and indirectly. Besides soil fertility; temperature, rainfall, humidity should be optimum for good crop growth and productivity. These parameters affect crops directly as the various critical stages of the crop are sensitive to these factors. Climate change will affect both crops and its competitive counterpart weeds. Efficiency of these two groups of plants in responding and adapting to this change in climate determines the ultimate winners in a climatically altered future.

Doug Larson, defined weed as a plant that has mastered every survival skill except for learning how to grow in rows. There are some adaptive mechanisms to make their chance of survival under various agro-climatic conditions viz., prolific seed production, seed dormancy, different mechanisms for seed dissemination, various modes of propagation (Rhizomes, tubers, suckers, bulbs etc.) inherent hardiness, self-regeneration, selective invasion and weed succession – reasons for their ubiquitous nature. They are of our concern since they share the same trophic level with crops and competes for limited resources such as nutrients, soil moisture, solar radiation and space thereby affecting the crop productivity and quality. Weeds are the major pests causing largest yield reduction in crops among different biotic factors. The yield loss in direct seeded rice under unweeded conditions as measured by the weed index was 75.60 per cent with a benefit cost ratio (BCR) of 0.87 and in second year the yield loss reached its peak with a BCR of 0.70, indicating the detrimental impact of the seed bank accumulated during the previous year in unweeded areas [1]. In wet seeded rice, uncontrolled growth of *Schoenoplectus juncooides* resulted in an 81% decrease in net income compared to the most cost-effective weed management approach [49]. Co-occurrence of weedy rice plants at a density of 7.3 plants per m² or 175 g per m² in low land rice lead to 40.23 percent loss in yield of cultivated rice [7].

2. IMPACT OF CLIMATE CHANGE ON WEEDS

Climate change can affect the variations in vegetative growth, vigour and competitiveness. Weeds undergo geographic range expansion by introduction and migration when its eco-physiological requirements get altered. The spreading of *Schoenoplectus juncooides* has been documented in wet seeded paddy fields through seeds, vegetative buds, and rhizomes[48]. Weed species make alterations in the life cycle so as to complete its growth and development before the approaching adversity, leaving weed seeds to replenish the seed bank.[7] examined variations among weedy rice types in rice ecosystems of Kerala and observed that similarities between weedy and cultivated rice types have been increasing,

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indicating that the weedy type may be acquiring characteristics similar to those of cultivated rice.

2.1. Response of weeds to variation in photosynthetic pathways

Photosynthesis – a basic survival mechanism for both crop and weeds, efficacy of this process determines the futuristic flora in a climate changing scenario. This process reflects the role of climatic parameters in supporting life in the planet. Any change in the climate can drastically affect plants i.e., both crops and weeds. In C3 plants with (Calvin) pathway, CO₂ in the atmosphere enter the plants through stomata. Ribulose 1, 5- bis phosphate (RuBP) in the mesophyll cells fixes this CO₂ by carboxylation. Phospho Glyceric Acid (PGA, 3- Carbon compound) is the first stable compound produced in the presence of the enzyme RuBisCO (RuBP Carboxylase Oxygenase). PGA undergo reduction to form Glyceraldehyde tri- phosphate (G3-P, 3 C). A part of G3-P produces glucose (6 C) and the remaining G3-P regenerates to form RuBP again and completes the C3 cycle or Calvin cycle. Patterson (1995) observed that under hot and humid conditions, RuBisCO has a higher affinity for O₂. The closure of stomata restricts the entry of CO₂ into the mesophyll cells and escape of O₂ to the atmosphere, resulting in high O₂: CO₂ concentration around RuBisCO. Since RuBisCO catalyses carboxylation and oxygenation, a higher O₂: CO₂ ratio leads to oxygenation in C3 plants by a process known as photorespiration.

Majority of the cultivated crops have C3 pathway. Cereals such as rice, wheat, oats, vegetables like tomato, chilli, brinjal, okra and fruit crops like banana, jack, mango, etc. are C3 crops. C3 weeds include grasses little seed canary grass (*Phalaris minor*), wild oats (*Avena fatua*) - major weeds in wheat, weedy rice (*Oryza sativa f sp. spontanea*) - major weed in rice, aquatic weeds such as water hyacinth (*Eichhornia crassipes*), parasitic weed (*Striga asiatica*) and other weeds like day flower (*Commelina benghalensis*), goat weed (*Ageratum conyzoides*), *Chenopodium album*, *Abutilon theophrastii*, sickle pod (*Cassia obtusifolia*), field bind weed (*Convolvulus arvensis*) and canada thistle (*Cirsium arvense*). *Cyperus difformis* with C3 and *Cyperus iria*, *Cyperus compressus* and *Fimbristylis miliacea* with C4 photosynthetic pathway were the major cyperaceous weeds found at all the growth stages of semi dry seeded rice.[11] The abundant growth of C3 weed *Schoenoplectus juncooides* in the water channels, lowlands, undisturbed fields and field bunds as an annual/perennial was reported by [50].

In C4 plants with (Hatch and Slack) pathway, the first stable compound formed in the mesophyll cell is Oxaloacetic acid (OAA, 4C) in the presence of the enzyme, Phospho Enol

Pyruvate (PEP) Carboxylase. OAA produces malate or aspartate, which undergo decarboxylation inside the bundle sheath cells thereby enhancing the CO₂ concentration in the area surrounding RuBisCO thus avoiding the photorespiration process. [15] reported that under high temperatures, C₄ pathway is more efficient due to the absence of photorespiration.

Maize, sugarcane, sorghum (crop camel), minor millets and members of brassicaceae family such as cabbage and cauliflower are C₄ crops. Three groups of weeds grasses, sedges and broad-leaf weeds (BLW) have species with C₄ photosynthesis. Grasses like bermuda grass (*Cynodon dactylon*), crow-foot grass (*Dactyloctenium aegypticum*), barnyard grass (*Echinochloa sp.*), goose grass (*Eleusine indica*), sedges such as *Cyperus rotundus*, and *C. iria* and BLW like *Monochoria vaginalis* and *Amaranthus sp.* are the common C₄ weeds. The most common C₄ weed *C. rotundus* displayed the highest percentages of regrowth and viability of indicating that the newly formed tubers readily sprouted without showing any seasonal dormancy [4,5].

2.2. Response of weeds to elevated carbon dioxide

a. Response of crops and weeds with C₃ pathway

[38] observed that potentially fast-growing wild species and plants with nitrogen fixing roots gained more biomass than slow-growing species (54% vs. 23%) with increase in CO₂ from 300 to 720 ppm. Elevation in CO₂ concentration enhances the efficiency of C₃ pathway by increasing the CO₂: O₂ ratio around RuBisCO, thus favouring carboxylation and reducing photorespiration. C₄ plants are unaffected or the least affected by the elevation in atmospheric CO₂ concentration since they have an internal CO₂ concentrating mechanism.

[62] studied the response of rice (C₃ crop) and red rice (*Oryza sativa* fsp. *spontanea*, C₃ weed) in ambient (300 ppm) and elevated concentrations (400 and 500 ppm) of CO₂. He observed that the tiller number, panicle number, tiller weight, leaf weight, panicle weight and 50 seed weight of cultivated rice increased at 400 ppm but reduced at 500 ppm. Beyond 500 ppm rice showed no response. While, its C₃ weed counterpart- red rice had a linear increase in both biomass and seed yield with elevation in CO₂ from 300 ppm to 500 ppm. All the yield attributes were double for red rice at 300 ppm and four to five-fold more at 400 and 500 ppm when compared with cultivated rice. The difference in response is due to physiological plasticity and genetic diversity of red rice compared to cultivated rice. [10] reported a strong response of weedy rice to elevated CO₂ as evident from a higher tiller production and plant

height of weedy rice compared to two popular rice varieties in Kerala: Uma and Jyothi when grown in open top chamber. Weedy rice grown in an atmosphere with enriched CO₂ produced taller plants with high anthocyanin pigmentation compared those grown under open conditions with ambient concentration of CO₂.

b. Response of crops and weeds with C₄ pathway

[58] conducted a study in four C₄ crops viz. grain amaranth (*Amaranthus hypochondriacus*), sugarcane (*Saccharum officinarum*), sorghum (*Sorghum bicolor*) and maize (*Zea mays*) and six weed species namely *Amaranthus retroflexus*, *Echinochloa crus-galli*, *Panicum dichotomiflorum*, *Setaria faberi*, *Setaria viridis* and *Sorghum halapense*. Both crops and weeds were grown at ambient (385 ppm) and elevated (680 ppm) concentrations of CO₂ up to 60 days after sowing (DAS). Photosynthesis of weeds increased by 19 percent, which was nearly double that of crops (10 %). Among the selected plants redroot pig weed (*Amaranthus retroflexus*) showed the maximum increase in photosynthesis (+30 percent) and the least photosynthetic stimulation was observed in maize (*Zea mays*) i.e., +5 percent with elevation in CO₂ concentration. *Fimbristylis miliacea* with C₃-C₄ intermediate photosynthetic mechanism dominated in the double-cropped wetlands as reported by [43]. Barnyard grass (*Echinochloa crus-galli*) a troublesome graminaceous weed infesting rice fields having C₄ photosynthetic pathway reduced rice grain yields by 58 per cent when it was planted at a density of 8 plants per square metre. Results revealed that barnyard grass reduced the Rubisco activity, leaf photosynthetic capacity, and energy conversion efficiency in rice [52].

c. Response of C₃ crop with C₄ weeds and C₄ crop with C₃ weeds

Generally, plants respond to elevated CO₂ by partial closure of stomata which reduces the transpiration loss. Hence, water requirement decreases and water use efficiency (WUE) increases with increase in the level of CO₂. [26] opined that, if the WUE of C₃ and C₄ plants triggered to 70- 100 percent, there will be a threat of C₃ weed invasion into drier habitats.

Sorghum (*Sorghum bicolor*) and common cocklebur (*Xanthium strumarium*) were provided with a higher concentration of CO₂. On taking observation 41 DAS, a higher leaf area and biomass production was obtained for cockle bur with C₃ pathway than the C₄ crop

sorghum. Thus,[55] opined that in the presence of C₃weeds the vegetative growth, competitiveness and yield of economically important C₄ crops gets reduced.

d. Response of C₃/ C₄ crop in a C₃-C₄ weed association

Under field conditions, crop experiences competition from both C₃ and C₄ weeds. [54] conducted an experiment to study the response of a C₃ crop, soybean (*Glycine max*) to elevated CO₂, when grown in combination with a C₃ weed, *Chenopodium album* and a C₄ weed, *Amaranthus retroflexus*. Sole cropping of soybean increased the biomass and yield by 32 and 23 percent. Soybean, when grown along with *Chenopodium album*, the biomass reduction increased from 23 to 34 percent and consequently seed yield reduction increased from 28 to 39 percent. Soybean, grown in combination with C₄ weed *Amaranthus retroflexus* showed a decrease in yield reduction from 45 to 30 percent. C₃ crop get the benefit of elevated CO₂ when grown in isolation and C₃ weed have a greater competitive advantage over the crop, while C₄ weed competition decreased but not nil.

A study conducted by [56] revealed that sorghum when grown in a weed free environment with increased CO₂ had significant difference leaf weight and leaf area but there is no significant difference in terms of yield related to ambient CO₂condition. In the presence of C₃ weed - at ambient CO₂condition, there is no significant loss in biomass or yield in sorghum but at elevatedCO₂, sorghum yield was reduced by 16 percent and biomass by 14 percent. But in the presence of C₄ weed – at ambient and elevated CO₂concentrations, there is significant biomass and yield loss in sorghum. At elevated CO₂condition, sorghum yield and biomass were reduced by 23 percent and 20 percent relative to elevated CO₂ weed-free condition.

e. Changes in weed biology

All the aspects of weed biology can be influenced by increased carbon dioxide concentration, temperature and precipitation [36].Canada thistle (*Cirsium arvense*), a C₃ weed showed 70 percent increase in growth when exposed to elevated atmospheric CO₂ [57]. [29] observed higher growth and biomass accumulation by a C₄ weed, *Amaranthus viridis* with increase in CO₂. This observation can be explained by the result of [31], in which they found out that developing leaves of C₄ plants use C₃ pathway until the complete differentiation of Kranz anatomy. Hence, all C₄ plants are C₃ during their early development and access all the benefits of elevated CO₂ as C₃ plants.

Alterations in weed biology give rise to tall and large sized plants. [39] opined that increase in plant height and size help the wind dispersed invasive species such as *Cirsium arvense*, *Sonchus arvensis* and *Carduus nutans*. [59] analyzed the pollen production of common rag weed (*Ambrosia artemisiifolia*) in three concentrations (280, 370 and 600 ppm) of atmospheric CO₂. Pollen production shot up from 131 percent at 280 ppm to 320 percent at 600 ppm due to increase in the number and size of floral spikes. Floral weight decreased from 21 to 13 percent but the weight of total pollen increased from 3.6 to 6 percent between 280 and 600 ppm.

[30] conducted an experiment in the Directorate of Weed Science Research at Jabalpur, to study the response wild oats (*Avena fatua*) to change in the CO₂ concentration. Ambient CO₂ concentration was 370 ± 20 ppm and the elevated CO₂ concentration was 550 ± 30 ppm. Wild oats showed early maturation (13 days prior to that under ambient CO₂ concentration) and seed shattering thus enriching the weed seed bank. Drought conditions prolong the viability of weed seed bank in the soil.

A study conducted by [23] in three weed species namely *Bromus tectorum*, *Hordeum murinum*, and *Lactuca serriola* indicated that leaf area consistently responded to higher CO₂ concentration than a combination of high CO₂ concentration and elevated temperature. Bhajwa *et al.* (2019) observed the growth and productivity of *Parthenium hysteroporous* under elevated CO₂ conditions. Results revealed that at under ambient CO₂ concentration parthenium grew taller with a greater number of leaves, flowers, and dry biomass compared to the ambient CO₂ concentration.

2.3 RESPONSE OF WEEDS TO RISING TEMPERATURE

Soil and above ground temperature are important, in governing the reproduction and establishment of weeds. Weed species distribution in a geographical area was indicated by atmospheric temperature [35]. As most of the physiological processes such as photosynthesis, respiration and transpiration are highly temperature dependent, any changes in temperature might affect plant growth. [27] opined that phenological development of plant was more influenced by increased temperature than elevated CO₂. Increased temperature alters the weed proliferation and competitive advantage in crop stands.

Under normal warm conditions, [18] explained the presence of a temporal non-synchrony between the C₄ weed – green foxtail (*Setaria viridis*) and C₄ crop - maize (*Zea*

mays) during seedling emergence, such that *Setaria* emerges only after the establishment of maize crop. [36] observed that higher temperature result in synchronous emergence of *Setaria viridis* and maize, leading to competition at the emergence stage. High temperature triggers the germination and subsequent emergence of *Setaria* seeds. Hence, at higher atmospheric temperature minor weeds may pose threat to the crop. Ramesh *et al.* (2017) observed that a 4°C rise in temperature, caused early emergence of *Chenopodium album* and *Setaria viridis* by 26 and 35 days and flowering advanced by 50 and 31.5 days, respectively.

[47] analyzed the variations in the root: shoot ratio of soybean, prickly sida (*Sida spinosa*) and sickle pod (*Cassia obustifolia*) with rise in temperature. A higher photosynthate translocation to the plant roots was observed in *Cassia obustifolia* at 36°C (day temperature) and 31°C (night temperature). Root:shoot ratio of *Sida spinosa* and *C. obustifolia* was 1.3 and 1.6 respectively, and that of soybean was 0.8. Thus, it is evident that under high atmospheric temperature, weed has advantage over the crop, since the underground propagules remain viable and helps in the regeneration of the plant after the high temperature stress, while the crop has very low re-growth potential. The resilience of *C. rotundus* under various pressures originates from its strong underground tuber system, where each tuber produces multiple active buds, enabling continuous growth in conjunction with its allelopathic impact [6].

2.4. RESPONSE OF WEEDS TO CHANGES IN RAINFALL

For a species to have its optimum growth and development, specific moisture regime is required. In arable and non-arable lands, moisture stress is likely to happen as a result of climate change with prolonged drought and floods. When compared to crops, weeds have greater physiological plasticity and genetic variations and are believed to sustain better under adverse climatic fluctuations.

[53] analyzed the floristic diversity of the basin and observed two alien weed species in the rice fields, which eradicated the native *Echinochloa* sp. It was inferred that the amphibious adaptation (survival both under flood and residual moisture) of the two alien species: *Marsilia quadrifolia* and *Leptochloa chinensis* resulted in the weed shift. [42] opined that under excess rainfall, *Rhamphicarpa fistulosa* - a parasitic weed in cereals would pose a serious threat to the crop.

[34] reported that *Anoda cristata* and *Abutilon theophrasti* are two common C₃ weeds in cotton. Prevalence of drought leads to severe competition of these two weeds with cotton, causing a yield reduction in cotton. [42] predicted the infestation of the parasitic weed, *Striga hermonthica* under conditions of prolonged drought. Past research gave thrust in the manipulation of species response to CO₂ enrichment and not on associated increase in temperature or drought [19]. [22] forecasted the changes in temperature and moisture, and explained that changes will have implications on germination, spatial and temporal emergence of weed seeds and seedlings. In reality, crops and weeds get exposed to a multitude of climatic changes. Hence, considering a combination of climate change consequences is of significance.

2.5. RESPONSE OF WEED TO CHANGE IN CARBON DIOXIDE AND TEMPERATURE

[21] opined that at low and high temperatures, growth enhancement due to elevated CO₂ decreases. On the contrary, [14] observed that CO₂ enriched atmosphere provided extreme temperature tolerance to plants. [46] reported the amelioration of high temperature-induced stress in quack grass (*Agropyron repens*) in an atmosphere with elevated CO₂ concentration.

[33] observed that at high temperature of 23°C day temperature and 19°C of night temperature, wild oats (*Avena fatua*) completed its development faster. Since maturation is faster, more seeds get deposited in soil seed bank thereby increasing the plant number. At 480 ppm CO₂, 44 percent more seeds were produced, compared to 397 ppm. At high temperature and light intensity during midday C₄ weeds like redroot pigweed (*Amaranthus retroflexus*) and Johnson grass (*Sorghum halapense*) efficiently fix CO₂ than C₃ crops like soybean and cotton. [16] reported that high temperature increases the evaporative demand. Since C₄ plants have high water use efficiency and CO₂ compensation point they are best adapted to an atmosphere with high CO₂, temperature and light intensity.

[30] reported that infestation of *Phalaris minor* in wheat, aggravate with increase in CO₂ due to climate change and the condition may worsen with water scarcity. With CO₂ enrichment, wheat gain biomass against *P. minor*. Under water stress conditions, *P. minor* survived better and had an advantage over wheat. [51] assessed the response of tomato (*Solanum lycopersicum*) and *Amaranthus retroflexus* at three different levels of CO₂ viz. 400, 600 and 800 ppm, with and without water stress. Without water stress, leaf photosynthetic rates, plant height, leaf area and biomass increased with elevation in CO₂ concentration for

tomato. The plant height and biomass of *Amaranthus retroflexus* increased even under water stress.

[28] conducted a study to know the response of *Cynodon dactylon* growth under elevated temperature and moisture conditions with three temperature levels ambient (0°C), +2°C and +4°C increase over the ambient and with two moisture levels viz., supply of moisture at 100 percent of evaporation and 60 percent of evaporation occurred previous day. The results inferred that, because of its high acclimatization capacity *C. dactylon* produced more growth under elevated temperature of +4°C with sufficient moisture. C₄ photosynthetic pathway might have helped the weed to utilize moisture and temperature more efficiently even under stress conditions.

3. WEED MANAGEMENT IN CHANGING CLIMATE

The growth of underground parts such as roots and rhizomes are highly stimulated than that of shoots under elevated CO₂, which makes mechanical tillage less efficient since, it helps in the dispersal of weed propagules [60]. observed significant differences in morphometric characteristics of weedy and cultivated rice during early growth stages. Variations were noted in culm thickness and ligule length and the most notable distinction was found in tiller count, with 87% of weedy rice variants exhibiting a higher number of tillers per plant (ranging from 11 to 20) compared to cultivated rice varieties ('Jyothi (Ptb-39)' and 'Uma-MO-16' had 10 and 9 tillers, respectively). Weedy rice plants were observed to be taller and lankier (ranging from 105 to 115.67 cm) with predominantly round culms, sometimes displaying anthocyanin pigmentation at the nodal regions. They also tended to have shorter ligules, early flowering times compared to cultivated rice, a greater number of tillers per plant, and predominantly awned grains. The study concluded that morphological adaptations displayed by these morphotypes in response to the changing climatic conditions strongly suggested the potential for weedy rice to pose a persistent threat to rice cultivation.

3.1 Herbicide efficacy in changing climate

Herbicides are the chemicals used for killing undesired plants in the cultivated field. The toxic component (active ingredient) binds with the target site of the plant and affects the normal functioning of metabolic pathways, thereby suppressing the plant to death. Environmental factors are known to interact significantly with the performance of herbicide

on plants causing marked variation in the site of action of plants, both in time and space. [49] found that applying ethoxysulfuron at a rate of 15g per hectare at 15 days after sowing followed by hand weeding at 35-40 DAS, proved to be an effective strategy for controlling *Schoenoplectus juncooides* (Roxb.) Palla in wet seeded rice. Herbicide-environment interaction may be caused by the elements of edaphic and atmosphere in two ways: Firstly, by modifying morphology, physiology and course of biochemical reaction in plants. Secondly, by influencing herbicide availability at the site of its uptake by plants at intended rate and in desired quantity.

There are many factors affecting the efficacy of herbicide viz., temperature, relative humidity, wind and light. [9] reported the significance of relative humidity (RH) on the phytotoxication of glufosinate-ammonium as it changes the cuticle hydration leading to droplet drying. Employing a combination of stale seedbed followed by glyphosate plus oxyfluorfen application, then cyhalofopbutyl plus carfentrazone ethyl, effectively suppressed the germination and establishment of *C. iria* and *M. vaginalis* during the initial stages of wet-seeded rice cultivation [44].

3.2 Mechanisms of herbicide resistance

Gene mutations in the target site leads to a modified target site such that the herbicide molecule would not recognize the actual site of action. This leads to target site resistance. Any hindrance in the herbicide's translocation path leads to non-target site resistance. Non-target site resistance occurs due to several reasons: (a) Fast metabolism of toxic herbicide molecules into safe, non-toxic forms (b) decreased translocation of the applied herbicide due to drought or high temperature (c) reduced leaf uptake due to certain modifications in the leaf structure and (d) sequestration of the herbicide molecule in the vacuole.

[20] observed a new mechanism of herbicide resistance called 'gene amplification' in *Amaranthus palmeri* where, 5-enol pyruvyl shikimate 3-phosphate synthase (epsps), the target site of glyphosate undergo amplification by increasing the copy number of epsps, to 160-fold. The combined post-emergent herbicide penoxsulam + cyhalofopbutyl exhibited significantly higher efficacy in terms of weed dry weights, effectively controlling grasses, sedges, and broadleaf weeds in wet-seeded rice [40].

3.3 Changes in leaf under elevated carbon dioxide and herbicide resistance

[13] observed depolarisation of guard cells, stomatal closure and reduced stomatal conductance under elevated CO₂. [8] observed the changes in outer cuticle as increased cuticle thickness and leaf pubescence. In wet-seeded rice, bensulfuron-methyl + pretilachlor demonstrated the highest weed control efficiency and was comparable to pyrazosulfuron-ethyl, effectively controlling grasses, sedges, and broadleaf weeds [41].

3.4 Causes for reduction in glyphosate efficiency

Glyphosate, popularly known by its trade name- Roundup is a non-selective, post-emergent, systemic herbicide used worldwide for general weed control. Advent of roundup ready crops has enabled the use of glyphosate in cropped fields also, since the crops are modified genetically for showing resistance to roundup. Glyphosate, either alone or in combination with 2,4-D, has exhibited potential in managing *C. rotundus* growth due to its rapid translocation to the tubers [2]. Glyphosate has lost its efficiency as a total weed killer due to various adaptations in the weeds to cope up with climate change. Seedling stage is the herbicide sensitive stage of weeds, hence shortening of this stage results in reduced efficacy of herbicides. Eg. *Chenopodium album* spent 5 days less on seedling stage [61]. Closure of stomata, reduced stomatal number and stomatal conductance during dry conditions affect the entry and translocation of glyphosate, thereby reducing its efficacy, as it is post emergent (foliage applied). Increased cuticular thickness and starch deposition affects the penetration and entry of herbicide. [12] found that regardless of whether herbicides were applied before or after plant emergence, they persisted in the active surface soil, causing fluctuations in soil enzyme activities across different post-treatment days in semi-dry rice. Profuse underground growth help weeds to re-grow and produce new flushes after the destruction of above ground portion by the herbicide. This leads to herbicide dilution, since the recommended dose of the herbicide is not sufficient to control the weeds. [3] documented a decrease in tuber viability (20-23.3%) and regeneration (6-8 sprouts per m²) when using a stale seedbed in combination with pre-plant application, followed by directed post-emergence glyphosate application for *C. rotundus* management. Heavy rains after herbicide spray would wash off the herbicide from foliage. Unpredictable rains reduce rain safe period that is required after herbicide application. Roundup Ready crops facilitate the use of glyphosate in cropped fields for selective killing of weeds. But, [37] inferred that Roundup Ready Soybean translocated more C₁₄-glyphosate to meristematic tissues at 35°C than at 15°C, indicating a potentially higher glyphosate injury at higher temperatures.

4. FUTURE WEED THREATS

4.1 *Sphagneticola trilobata*

Sphagneticola trilobata has attained the status of an invasive plant in the open areas of Kerala due to its profuse growth and insensitivity to herbicides. High heat stress tolerance of this plant is due to its highly thermostable photosynthetic apparatus. [45] reported that under high temperature the potential damage was minimized by effective partitioning of energy to photosystem II complex thus helping the weed to retain greater capacity for carbon assimilation.

4.2 *Datura stramonium*

High temperature triggers profuse growth of *Datura stramonium* (thorn apple). Hence [17] opined that, this plant is a potential candidate under climate change scenario.

4.3 *Lantana camara*

Lantana camara, also known as Spanish Flag or West Indian Lantana, is a species of flowering plant belonging to Verbenaceae family is a native of American tropics. It has the ability to occupy over wide range of environments as birds help in effective dispersal of berries thus, expanding its range. Once established it will survive under drought for long periods. [25] opined that biological control of *Lantana* would not be effective because of the effect of altered climate on the distribution of biocontrol agents.

4.4 *Parthenium hysterophorus*

Parthenium hysterophorus is an invasive weed species introduced to India. It possesses a C₃-C₄ intermediary pathway of photosynthesis. [32] observed an increased growth and seed output in *P. hysterophorus* at an elevated concentration of CO₂ (550 ppm) and at cooler (30°C day temperature and 15°C night temperature) and wetter conditions. During warm temperature, taller plants with greater biomass, shorter life span, high seed production, seed filling and seed longevity were produced.

4.5 *Eichhornia crassipes*

Eichhornia crassipes, commonly known as water hyacinth, is a perennial fast growing broadleaved aquatic plant, native to tropical and sub-tropical South America. It is a highly problematic invasive species introduced to India. Mode of propagation is by offsets, increased rainfall intensity with frequent floods helps in the easy dispersal of offsets and thus its entry to new areas.

4.6 *Prosopis juliflora*

Prosopis juliflorais an invasive species introduced in 1877 from Central America to India. It has invaded nearly 6.0 M ha of land contributing to 1.8% of the total geographical area of the country [24]. Greater assimilate partitioning towards roots lead to enlargement of roots, rapid regeneration of the plant after mechanical lopping. It has the ability to tolerate extreme climatic situations *viz.*, summers with high temperatures and a monsoon with water inundation and flooding thus, making the management of this weed nearly impossible.

5. CONCLUSION

Ability of weeds to adapt to the changing climate makes them more efficient in competing with the crops. Due to the presence of profuse underground growth, C₄ pathway and C₃-C₄ intermediate pathways, perennial weeds are expected to pose more threat in a changed climate, since they cannot be effectively controlled by herbicides due to dilution effect and several weed adaptations. Modifications in the morphology of leaves and the development of resistance within the weeds result in reduced efficacy of herbicides. Being more efficient in adverse environmental conditions, C₄ pathway plants are benefitted. Rice, being our staple food crop needs to be improved in production. Since it is a C₃ crop, the performance of the crop gets affected with climate change. Hence, development of rice with C₄ mechanism needs a higher thrust. Weeds evolve effectively during stress and climate change is inevitable so weed utilization by bioprospecting helps in managing the weeds in a useful manner. A weed dominated future gives us the opportunity to identify potential crops from weeds.

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Comment [A3]: Replace more up-to-date sources if possible.

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