Weeds and their Management under Changing Climate: A Review

Jeena Mary

ABSTRACT

World is now facing a greater menace of climate change and this has a long term impact on agriculture system. Weeds are one of the major factors that hold back the crops from attaining potential yield. The changing climate can have an effect on weed diversity, establishment and management. The response of weeds to altering climate mainly leans on the physiological characteristics of the weed and how productively it can respond to the immediate climatic condition. Due to high plasticity of weeds, management of these unwanted plants become difficult. This has significant repercussions on weed control practices, especially herbicide performance and effectiveness. Therefore, an integrated approach of weed management is adopted to reduce the impact of climate change on crop- weed interaction.

Key words: Climate change, Management, Plasticity, Weed shift.

Climate is a major strength in our environmental system. In recent decades, changes in climate have caused significant impacts on natural and human ecosystems. Both extreme weather events and rapid climatic changes interrupt the stability of cultivated ecosystems and increase the level of disturbance (Dukes and Mooney, 1999). In the present situation, climate change is the important point of discussion among the nations around the world and so many treaties have been adapted to mitigate its ill effects. Because of the importance of rising climate change, oxford declared the word of the year 2019 as ‘climate emergency’.

Climatic variations have increased both spatially and temporally over the past 50 years in India (Davis et al., 2019). Basic effect of radiation emitted from the greenhouse gases and water vapour are important for determining the variations of the climate change across the regions of India (Dash and Hunt, 2007). The mean temperature in India is projected to increase by 0.1 – 0.3°C in kharif and 0.3 – 0.7°C during rabi by 2010 and by 0.4–2.0°C during kharif and 1.1– 4.5°C in rabi by 2070. This pattern of rising temperature is important for explaining migration or expansion of some plants to higher altitudes. Similarly, mean rainfall is projected to increase by up to 10% during kharif and rabi by 2070 and there is an increased possibility of climate extremes, such as the timing of onset of monsoon, intensities and frequencies of drought and floods (Khan et al., 2009). Temperature and rainfall are the climate variables most critical to measure with regards to food systems (Okesie et al., 2011). Unpredictable climatic conditions are one of the factors that holding back our country from attaining top position in the Food Security Index (FSI) list. Kumar and Upadhyay (2019) reported that the FSI has negatively affected by maximum temperature and has a serious impact on the crop productivity of major states as both are directly linked.

Weeds are the major competitors for the crop plants as they take up the resources available for them. Any plants that survive in this world belong to either C₃ or C₄ or CAM pathways. Because of more response and endurance of weeds towards altered climate, majority of the weeds belong to C₄ pathway. Major C₄ weeds are Cirsium arvense, Avena fatua, Xanthium strumarium etc and Cyperus rotundus, Sorghum halepense, Echinochloa crus-galli etc are major C₃ weeds.

Crop – weed interactions under altering climate

Weeds are the plants which coevolved along with crops, continuously competing with domesticated plants for common resources and making the cultivation difficult. The crop yield was reduced due to weed competition by 31.5% in India and yield loss will differ because of varying competitive ability of weeds and crops (Bhan et al., 1999). In another study, Gharde et al. (2018) reported that potential yield loss was very high in case of soybean (50–76%) followed by groundnut where 45–71% yield loss was recorded due to weeds. High variation in the yield losses were observed among the different states of India, in the case of direct-seeded rice (15–66%) and maize (18–65%). As weeds have greater genetic diversity, plasticity and also climate resilience power, associated weeds in a cropping system respond well to changing climate compared to crops.
These interactions may change in future also due to climatic alterations, as weeds can undergo several modifications to equip with changing environment (Naidu et al., 2015). Not only native weed species but also, invasion of alien species becomes a major menace to cropped as well as non-cropped fields under climate change. The minor or sleeper weeds also become problematic under these circumstances. These are subset of plants that have naturalised in a region, but have not yet increased their range and abundance exponentially. Example - Cuscuta suaveolens, Aeschynomone paniculata, Hieracium aurantiacum and Asystasia gangetica (Beaumont et al., 2009; Ren et al., 2020; Skinner, 2015; Yoho et al., 2009). Evidence indicates, however, that they may become invasive or have impact in the future. Therefore, species hierarchies in ecosystems will change, leading to new dominants that may have invasive tendencies. One of the key factors for successful invasion is the climate similarity between native and invasive ranges (Williamson, 2006). The climate change since last 60 years have been an important factor in the selection and shifting of weeds and also a contributing factor to invasion of these species. Unstable events create conditions favourable for weeds to expand their range and invade new areas or out-compete native species in their existing range. The degree of competition between native crops and introduced ones will be depending on several driving factors like adaptability, plasticity and how well it responds to new environmental conditions (Barua et al., 2015), finally filling up the gaps left by susceptible species and changing the ecosystem composition (Naidu and Murthy, 2014).

Effect on weed flora shift and weed seed bank dynamics
Climate change leads to shift in weed flora as weeds can survive in diverse conditions and adapt to those circumstances by modifying its germination rate or morphological features. Weed shift is the change in the relative frequencies of weeds in a weed population or community in response to natural or human-made environmental changes in an agricultural system (Rana et al., 2016). This change in the composition can be related with weed seed bank in the soil system. The weed seed bank is the reserve of viable weed seeds present on the soil surface and scattered in the soil profile. It is composed of many species, with a few dominant species comprising 70 to 90% of the total seedbank, a second group comprising 10 to 20% of the seedbank and the final group includes a small percentage of the total seed and includes recalcitrant seeds from previous seedbanks, newly introduced species and seeds of the previous crop (Wilson et al., 1985). This final group undergoes considerable changes in terms of geographical range expansion or migration and becomes dominant during climate change. Any alteration in climate, specifically temperature and moisture content will definitely controls the seed germination as well as plant regeneration by change in dormancy or by germination elicitation (Hardegree, 2006). The new environmental conditions may not be optimal to undergo any adjustments in dormancy or change in germination timing and rate for both crops as well as weeds. Thus, competitive ability is not fixed, it reflects the conditions under which competition occurs and can evolve as plant density or other elements guiding competitive advantage shift (Grace, 1990). The major threat to seed bank persistence may be resulting from more sporadic rainfall or frequent droughts in combination with increased temperatures, leading to a greater chance of failed germination and seedling mortality. As weeds are more diverse and can acclimatize to new situations, these can be recruited and can germinate faster from soil seed bank (Walck et al., 2011; Ooi, 2012), leads to shift in natural selection and adaptive evolution occurs (Sakai et al., 2001). Banerjee et al. (2019) studied about the spatio-temporal patterns of climatic niche dynamics of invasive weed, Mikania micrantha and its distribution under the projected climate change. According to their study, in South Asia, the Western Ghats of south India, parts of northeast India, eastern parts of Vietnam and Laos, southern China and Taiwan were predicted to be climatically suitable for M. micrantha. Among Southeast Asian countries and parts of Indonesia had low to high climatic suitability. Like non parasitic weeds, changing climate will play major roles in determining geographic distributions of parasitic weeds directly by affecting germination, growth and development, or indirectly through its associated hosts. Example – Striga (Mohamed et al., 2007).

Response to increased temperature, CO₂ and altered precipitation
The multi-faceted interactions among the humans, microbes and the rest of the biosphere, have started reflecting an increase in the concentration of greenhouse gases (GHGs) causing warming across the globe along with other harmful consequences in the form of shift in rainfall pattern, melting of ice, rise in sea level etc (Khan et al., 2009). Atmospheric temperature is regarded as an important indicator of weed species distribution in a geographical area. Its rise could alter weed proliferation and competitive behaviour in weedy vegetation as well as in crop stands. Enhanced greenhouse effects are predicted to increase global surface temperatures and the frequency of extreme temperature events (IPCC, 2014). Increase in temperature favours C₃ weeds than C₄ weeds (Singh et al., 2011). Change in the temperature will definitely affect both crop and weeds. As weeds are more adaptive in nature than crops, it can resilient the temperature change. Bir et al. (2018) studied the growth response of weed species in a paddy field under elevated temperature. The estimated maximum dry weight of rice at the ambient +3.4°C was 30.4% higher while dry weight of annual weeds, Echinochloa oryzicola, Monochoria vaginalis and Ludwigia prostrata were 78.2%, 171.4% and 211.8% higher, respectively, at the ambient+3.4°C than that of the ambient and dry weights of perennial weeds, Scirpus planiculmis,
and showed that leaf had high acclimatization capacity and produced similar "emerged as most responsive to elevated CO-1" (Vollmer, 2006). The problematic weed Cynodon dactylon had high acclimatization capacity and produced more growth under elevated temperature up to +4°C, with sufficient moisture. The C3 pathway of this weed helps to utilise the temperature more efficiently even during stress and produce more growth (Mandal et al., 2017). Similar studies were conducted by Mandal et al., 2017 in Tradhema portucastrum and reported that this problematic weed problem had high acclimatization capacity and produced more growth under elevated temperature up to +4°C, under sufficient moisture. Likewise, Zhang et al. (2014) reported that global warming would facilitate or accelerate the invasiveness and competitiveness of Lantana camara and showed that leaf area (double) and stem length (four times) were higher at elevated temperature (30°C) than at (22°C).

Migration of weeds will result in a differential structure and composition of weed communities within natural and managed ecosystems due to temperature change. Thermophile weeds are the major groups most favoured by temperature. Spread of tropical and subtropical weeds into temperate areas and to increase the numbers of many temperate weeds currently limited by the low temperature at high latitudes. Example - Parthenium hysterophorus. For parthenium, the no. of branches (8/plant) and capitula (288/plant) produced per plant were more in summer when compared to winter (5/plant and 239/plant, respectively) (Kapoor, 2014). This study is supported by Toh et al. (2011) and reported that increased temperature enhances the growth of parthenium, enlarges canopy size and structure and accelerates population growth rate because of the shortened life cycle.

Enhancement of CO2 has a beneficial effect on C3 weeds rather than C4 weeds. C3 plants have rubisco enzyme which has both carboxylation and oxygenation activity, which mostly favours oxygenation at ambient CO2 level. But with increase in CO2, carboxylation takes place at faster rate leads to increase in photosynthesis and decrease in transpiration in C3 weeds. Furthermore, it has been documented that variability in growth response to elevated CO2 is due primarily to differences between plants with a C3 (33–40% increase) vs. a C4 (10–15% increase) photosynthetic pathway (Fuhler, 2003; Prior et al., 2003). The response of Commelina benghalensis growth variables to ambient (375 μmol mol-1) and elevated (ambient + 200 μmol mol-1) CO2 resulted into the production of plant height (102.45 cm), inflorescence number (317.62) and root length (275.48 m) at elevated CO2 compared to ambient CO2 (95.16 cm, 257.13, 246.51 m, respectively) (Price et al., 2009).

Awasthi et al. (2018) studied on the effect of increasing CO2 on green gram and weeds like Commelina diffusa and Euphorbia geniculata. Among the three species, Euphorbia geniculata emerged as most responsive to elevated CO2, showing higher relative growth rate, photosynthesis, dry weight and stomatal conductance. At elevated CO2, weed–crop interaction altered in favour of weeds leading to considerable yield loss of green gram. Zeng et al., 2011 worked on the effect of elevated CO2 on competition between a C2 crop (Oryza sativa L.) and a C4 weed (Echinochloa crus-galli L.). The study revealed that elevated CO2 (ambient + 200 μmol mol-1) significantly enhanced the biomass, tillers, leaf area index and net assimilation rate of rice compared to barnyard grass. Therefore, elevated carbon dioxide favours C3 crop or weed.

Another study, Nguyen et al., 2017 reported that parthenium weed growth and seed output were significantly increased under the elevated CO2 concentration (550 ppm) when compared to 390 ppm. Supporting to this, Bajwa et al., 2019 studied on the effect of elevated carbon dioxide concentration on growth and productivity of parthenium and concluded that the plants grew taller (41%), produced a larger number of leaves (13%) and flowers (39%) and higher dry biomass (34%) at elevated CO2 compared to the ambient CO2.

Soil enzymes are also playing an important role in the growth of plants by providing essential nutrients from the rhizospheres of the region. Climate change will favour the enzymatic activity in the weed rhizosphere than crop. Sarathambal et al., 2016 studied about the effect of elevated CO2 on soil enzyme activities in the weeds associated with rice-wheat ecosystem and reported that CO2 enrichment significantly increased the soil enzymes like dehydrogenase, fluorescein diacetate hydrolysis and urease activity in weeds rhizosphere than rice and wheat.

Rainfall and evaporation pattern of a region influences the weeds directly by interrupting the physiological functions involved in the process of seed dormancy and germination. Under water stress conditions, stomatal conductance decreases due to partial closure of stomata. C3 plants have greater competitive advantage due to higher water use efficiency and deep root system. Changes in precipitation patterns and water availability will alter plant size, seed production and dispersal and also leads to shift in vegetation. Weed shift is the important process that can be viewed in a region where change in rainfall pattern exists. Example: survival and outgrowth of cheat grass (Bromus tectorum) and yellow star thistle (Centaurea solstitialis) (Voller, 2006). In some cases, new weed species which are not problematic earlier, become invasive and show higher importance value index percentage. Importance Value is a measure of how dominant a species is in a given forest area. Example – In Cauvery delta, Leptochloa chinensis and Marsilea quadrifolia dominated the native weeds such as Echinochloa sp. over the years by virtue of their amphibious adaptation to alternating flooded and residual soil moisture conditions.
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(Kathiresan, 2014). It is to be noticed that under climate change, there will be a general shift to higher altitudes and towards the poles for most species, with the shift greatest for wet tropical species (Scott et al., 2008).

The effect of water stress on weeds can be studied by different scientists and reported about the tolerance level of weeds towards water stress conditions are higher than crop plants and weeds can produce small quantity of seeds even if situations are not favourable. Chauhan and Johnson (2010) studied about the growth and reproduction of Echinochloa colona in response to water stress and revealed that most stressed plants (irrigated at 12.5% of field capacity) still produced considerable biomass (8.5 g plant\(^{-1}\)) and seeds (>1,600 seeds plant\(^{-1}\)). They also reported about the response of weed and rice crop grown together on water stress conditions. The jungle rice to rice biomass ratio also increased from 4.7 at 100% of field capacity to 7.6 at 12.5% of field capacity, indicating the greater jungle rice vigour in water stress conditions.

Several weed species have adopted mechanisms like avoidance, escape or quiescence strategy to survive flood induced stress. In avoidance, the plants can complete their life cycle between two subsequent flood events and these periods are survived by dormant life stages (eg. Chenopodium rubrum). In escape strategy, modifications in anatomy and morphology of plants equip the plant to collect more oxygen from the surrounding and deliver it to internal tissues and these morphological changes include shoot elongation and aerenchyma and adventitious root formation (Bailey –Serres and Voesenek, 2008). For example, adaptation of Cyperus rotundus ecotypes in flooded soils suggests changes in metabolic or morphological growth processes that make these weeds more adapted to the flooded conditions of paddy fields i.e. the cross sectional area of stem occupied by aerenchyma tissue in low land conditions of this weed was twice than that of species in upland conditions and also low land Cyperus rotundus plants were over 30 % taller and 50 % heavier and their tubers were three times larger than those of upland species (Fuentes et al., 2010). Differ to escape strategy; quiescence strategy suppresses the morphological changes, produce stable functional traits and conserve carbohydrate reserves. This strategy depends mainly on anaerobic energy production and adjustment of metabolism (Bailey –Serres and Voesenek, 2008). Example - Alternanthera philoxeroides can recover fast after submergence because it has the capacity to maintain the integrity of the photosynthetic apparatus under stress conditions i.e. major portion of the carbohydrates will be reserved for post submergence activity, thus it can act as water proof plants (Ye et al., 2016). As weeds are smarter than crop plants, these can adopt any of these strategies earlier than crops in order to survive under flooded situations.

**Effect on weed management**

Current weed management practices have helped farmers to achieve reduction in weed population. Approaches like diversification of cropping systems, mulching and conservation tillage have added additional benefit for controlling weeds. Consequently, weed communities have changed and, in some cases, become resistant to commonly used herbicides, thus increasing the complexity of managing weeds (Derksen et al., 2002). Climate change has several consequences on weed management especially for biological and chemical control. As insects are cold-blooded organisms, the outside environment governs insect’s physiological processes very much and temperature is probably the single most important environmental factor influencing insect behaviour, distribution, survival and reproduction (Sujayanand and Karuppaiah, 2016). Elevated CO\(_2\) may reduce the nutritional properties of weeds and affect eating habits of insects (Casteel et al., 2012). Alterations in climate has been seriously affecting the feeding behaviour of successfully established biocontrol agents (BCA) in India and worldwide. Bhusal et al. (2020) revealed that above the optimal temperature (27-30\(^\circ\)C), the feeding attributes of Zygogramma bicolorata on parthenium decreased and there exists a possibility for decrease in body size and thereby weed control efficiency of adults with an increase in temperature. Similarly, Allen et al. (2014) reported that changing environmental temperature may create constraints on reproduction and development of Crytobagous salviniae. BCA of Salvinia molesta. Wei et al. (2015) also studied about the effect of different water regimes on Agasicles hygrophila. BCA of Alternanthera philoxeroides and suggested that drought can reduce the biological control of weed indirectly by interfering with plant–insect interaction.

The successful use of herbicides depends on environmental conditions prior to, during and after herbicide application. The response of weeds to herbicide applied at elevated carbon dioxide condition varies with species to species. Decreasing stomatal conductance with increased CO\(_2\) could reduce the uptake of both soil and foliar applied herbicides (Upasani et al., 2018). Ziska and Goins (2006) studied about the impact of elevated CO\(_2\) and weed population in glyphosate treated soybean and found out the potential consequences for CO\(_2\) induced changes in weed populations, biomass and subsequent glyphosate efficacy. In contrast, Marble et al. (2015) reported that predicted future CO\(_2\) levels will have little impact on the efficacy of single applications of halosulfuron or glyphosate for control of purple and yellow nutsedge at the growth stages ie., at 3 weeks following herbicide application, both weeds were adequately controlled by both herbicides and combinations at all rates tested, regardless of CO\(_2\) concentration (ambient + 200µmol mol\(^{-1}\)). Manea et al. (2011) reported that the efficacy of glyphosate on invasive exotic grass species is affected under elevated CO\(_2\) conditions. The mature invasive grasses (Chloris gayana, Eragrostis curvula, Paspalum dilatatum) that were sprayed with the recommended concentration (10 ml L\(^{-1}\)) of glyphosate had a significantly higher survival rate under elevated CO\(_2\) (675 to 715 ppm) compared with ambient CO\(_2\) (380 to 420 ppm).
Temperature can directly affect herbicide performance through its effects on the rate of herbicide diffusion, viscosity of cuticle waxes and physicochemical properties of spray solutions. Due to high temperature, viscosity decreases and diffusion of herbicide molecules inside the leaf tissue increases (Fausey and Renner, 2001; Varanasi et al., 2016). The response of weeds to different herbicide doses also depends on species under varied temperature levels. Ganie et al., 2017 studied about the temperature influence on efficacy, absorption and translocation of 2,4-D and glyphosate on two weed species. Required 2,4-D doses to achieve 50% and 90% control of Ambrosia artemisiifolia were 187 and 3,805 g ae ha⁻¹ at low temperature (20/11°C d/n) compared with 61 and 177 g ae ha⁻¹ at high temperature (29/17°C d/n), respectively primarily due to more translocation at high temperature. In another study, the differences in weed response to sulfonl urea herbicide under low temperature have been due to decreased foliar absorption of herbicide and have been reported that less absorption occurred at 5/3°C than at 25/23°C for Avena fatua and Aegilops cylindrica (Olson et al., 1999).

The persistence of herbicide in soil has been affected by temperature and moisture content of soil. The loss of herbicide is directly proportional to increase in temperature and moisture content. The half-life of pendimethalin was higher at 50% field capacity (108.28 days) than at saturation (35.45 days) and at higher temperature (27±2°C). The order of disappearance of pendimethalin and oxfluorfen at three moisture levels was saturation > field capacity > 50% field capacity (Siresesha et al., 2011). Therefore, loss will be more after a heavy precipitation. Similar to soil, temperature of water is also an important factor affecting herbicide efficacy. Lower temperature decreases the efficacy by forming sludge at the bottom of spray tank. Singh et al. (2010) reported that for the control of Phalaris minor, spraying of clodinafop formulations with water temperature of 8°C resulted in 57% mortality compared to 75% with water temperature of 25 or 40°C.

**CONCLUSION**

By considering all studies related to effect of climate change on weed–crop interactions, conclusions can be made that as weeds are more intelligent than crops, these can respond quickly to any change. Controlling weeds is likely to be more demanding and expensive under climate change. As India is also facing ill effects of environmental stresses, future weed management should be in such a way that artificial intelligence and remote sensing can be added along with traditional approaches. Integration of new methods of weed control like utilization of weeds as bio resources, composting, as fodder or phytoremediation are better options. Production of allelochemicals from weeds to control other weeds is also in emerging path. A better understanding of shift in weed flora and immediate identification of new species in a locality is needed. Earlier predictions can be made on weed shift, damages caused by them and better strategies can be adopted to remove them before it adds to weed seed bank.

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