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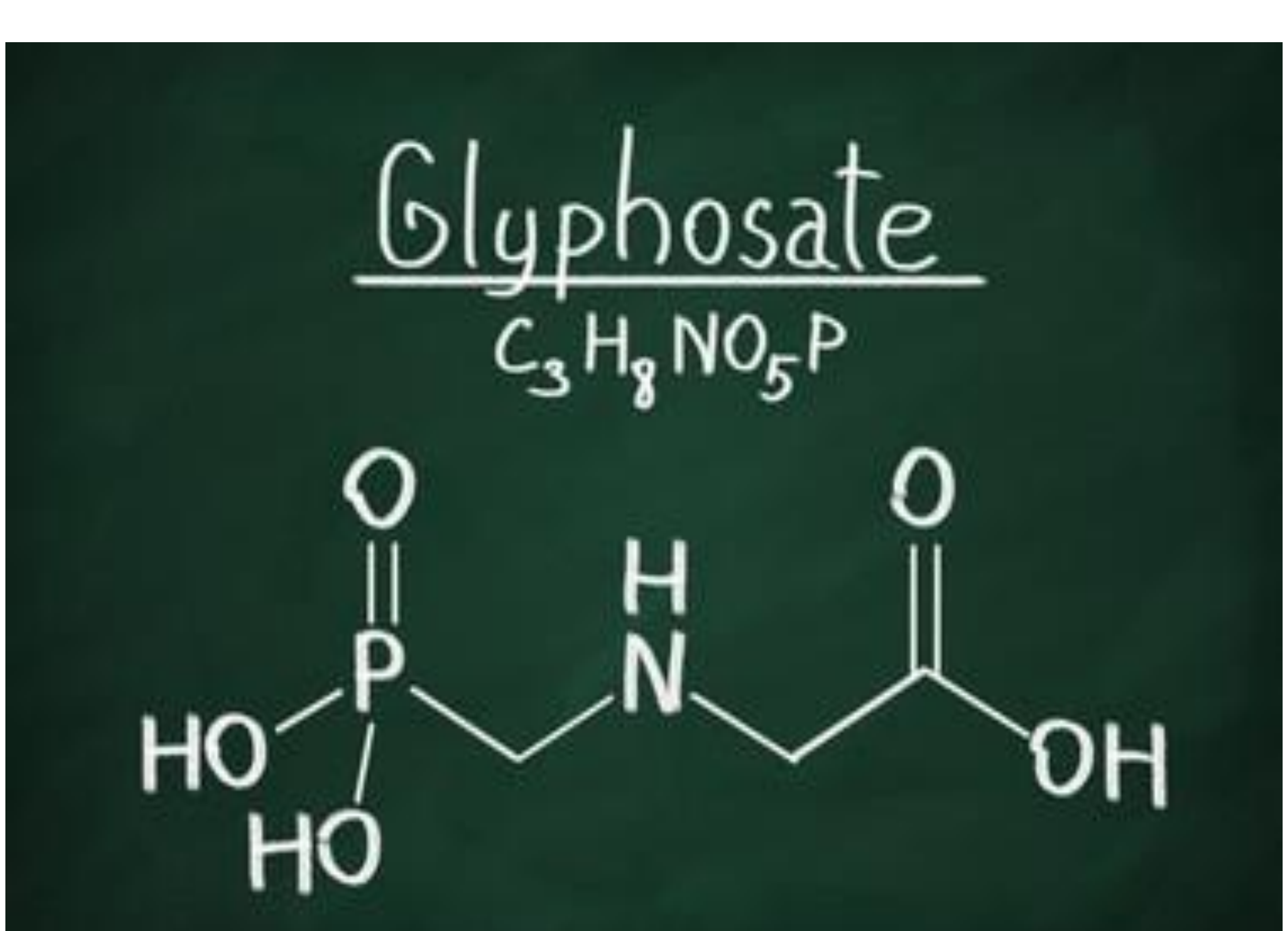

PERSPECTIVE

The Need for *Climate-Resilient* Integrated Weed Management (CRIWM) under future Climate Change

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This paper formed a major part of a Keynote Presentation made by A. N. Rao at the First International Conference, Weed Science Society of Bangladesh, e, held at Dhakka, Bangladesh, on 21 May 2022. The authors have added some additional commentary to increase the clarity and context of the presentation.

Abstract

Ensuring future food and nutritional security, while reducing poverty are significant global challenges. This is especially true in the Asian-Pacific region, characterized by rapid population growth, food shortages and landuse changes. The region is already affected by a changing climate with increased periods of droughts and rainfall in some countries. Efforts to increase crop productivity and reduce existing crop yield gaps are critically-important to meet the targeted food and nutritional security goals in the region. This requires identifying and addressing constraints, such as the changes in weed flora and alleviating the negative effects of weed abundance in cropping fields with sustainable technologies.

Climate-Resilient Integrated Weed Management (CRIWM) is a new term that has emerged to assist in this effort. CRIWM is an intensely-focused approach that aims to increase crop productivity sustainably, while simultaneously reducing the adverse effects of weeds and greenhouse gas emissions of agricultural practices. CRIWM can be used to re-energize educating all those involved in agriculture to plan for uncertainties in weed management outcomes under a changing climate. The approach requires doing what has been done so far in managing weeds even better. Targeted research must explore new combinations of already well-established methods (such as conservation farming, regenerative agriculture, soil health and cultural weed control practices, as well as biological and chemical weed control) with an eye for options to reduce reliance on any one technique alone. Precision weed control robotics and other 'climate-smart' innovations (such as the use of solar-powered equipment) appear crucial in planning for more effective weed management under climate change.

Keywords: Asian-Pacific Region, weeds, climate-resilience, Integrated weed management, IWM, CRIWM

Introduction

The growing world population, rapid economic development in many countries, and changes in dietary habits have combined to result in an increase in global food and nutritional demands. The total global food demand is expected to increase by 35% to 56% between 2010 and 2050, while the population at risk of hunger, mostly in developing countries, is expected to change by −91% to +8% over the same period. Under climate change scenarios, especially in a warmer future world, the ranges change slightly (+30% to +62% for the total food demand and −91% to +30% for the population at risk of hunger) (van Dijk et al., 2021).

Global warming and associated changes in temperatures and rainfall patterns, including more frequent and more intense extreme weather events (i.e. floods, droughts and cyclones) are likely to disrupt the global food production systems. Climate change modelling shows that yield losses of major world crops could be large under an uncertain, warmer and wetter climate, although specific effects depend very much on the individual crop, cropping system, growing regions and locations and other socio-economic factors (Jägermeyr et al., 2021).

Notwithstanding uncertainties, adapting to the predicted but inevitable changes in the global climate is a matter of utmost urgency. In most countries, agricultural production systems are expected to be affected, posing major challenges to the livelihoods and food security of billions of people (IPCC, 2021).

Greenhouse gas emissions of global agri-food systems are 16.5 (95 %; CI range: 11–22) billion metric tonnes (Gt CO_2 eq. yr^{-1}), corresponding to 31 % (range: 19-43 %) of the total human-caused (anthropogenic) emissions (Tubiello et al., 2022). These estimates show that food production systems, are not only vulnerable to global climate change but are also the second largest contributor to its causes.

Thus, serious adjustments to agriculture-related land use management practices and transformations are essential in adaptation responses and for climate change mitigation. In a highly uncertain future, science-based solutions will be required to anchor sustainable agriculture and increase food and nutrition security across the globe. The challenge is how to achieve this while protecting the ecology of agro-ecosystems and increasing the resilience of the environment to the changing climate.

From the beginnings of agriculture, colonizing species, occupying the same disturbed habitat (i.e. cropping fields) with crops, have long been a major constraint to crop production (Baker, 1991; Liebman et al., 2011; Storkey et al., 2021). Weedy taxa are, nevertheless, a key component of all agro-ecosystems, as they are primary producers within food production systems with a critically-important role in supporting biodiversity (Marshall et al., 2003; Storkey and Westbury, 2007; Altieri et al., 2015).

Weeds cause direct or indirect adverse effects on crop production, which can lead to severe crop yield losses (Table 1) and reduced quality of the harvested crop. Weedy species also interfere with agricultural operations (machinery and irrigation) and occasionally, their abundance, persistence and dominance, within agricultural landscapes, may also reduce the local plant biodiversity.

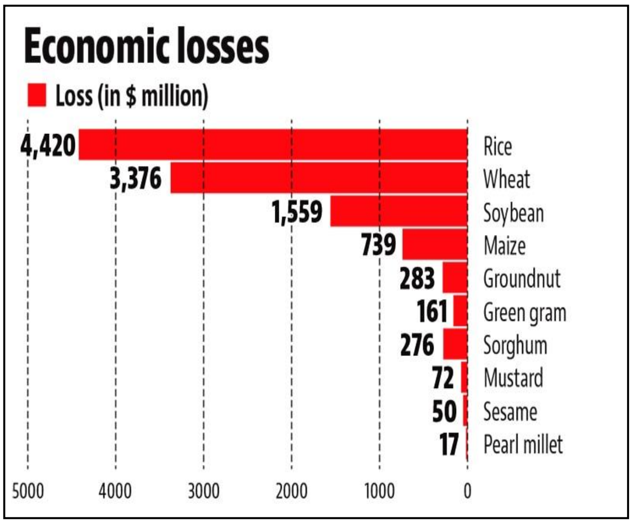
Table 1 Economic losses due to weeds in different countries and crops

Country	Yield Losses/ year ($)	Reference
Australia	5 billion	McLeod, 2018
Africa	4.3 billion	Kayeke et al., 2017
India (10 crops)	11 billion	Gharde et al., 2018
Canada (wheat)	0.37 billion	Flessner et al., 2021
USA (wheat)	1.14 billion	Flessner et al., 2021
USA (maize)	26.7 billion	https://wssa.net/wssa/weed/croploss-2
USA (sorghum)	24 billion	
USA (dry beans)	722 million	
USA (soybean)	17.2 billion	
USA (sugar beet)	1.3 million	

India alone is losing an average of $11 billion each year in 10 major crops (Figure 1) due to weeds, with variation yield losses caused by weeds varying with the specific crop, season and location (Gharde et al., 2018). The negative impacts of weeds on crop productivity are being increasingly experienced globally under climate change (Ramesh et al., 2017a). As shown in Table 1 and abundant research across the globe, crop yield losses due to weeds (averaging about 34%) exceed the losses caused by other pests and pathogens.

In a global review of major crop yield losses in wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), maize (*Zea mays* L.), potatoes (*Solanum tuberosum* L.), soybean [Glycine max (L.) Merr.], and cotton (*Gossypium hirsutum* L.), for the period 2001–03, across major agricultural regions, Oerke (2006) showed that losses due to weeds (34%) exceeded the losses caused by animal pests and pathogens (18 and 16%, respectively). Oerke (2006) and Oerke and Dehne (2004) also noted that these crop losses occurred despite the success of various herbicides and other crop protection chemicals. They suggested that higher losses would have most likely occurred if the farmers did not use crop protection chemicals.

As atmospheric CO_2 concentration increases, changes in temperature and rainfall are felt across countries. Such changes will influence the growth of both crops and weeds, as well as how we manage weeds (Chandrasena, 2009; Chauhan et al., 2012; Varanasi et al., 2016). A significant challenge will be to devise agri-food systems that can be climate-resilient, and concurrently shift the balance in favour of crops over weeds, as both will benefit from elevated CO_2 (eCO_2) and warmer conditions (Bir et al., 2014; Sun et al., 2021; Ziska, 2011; 2016; 2022).



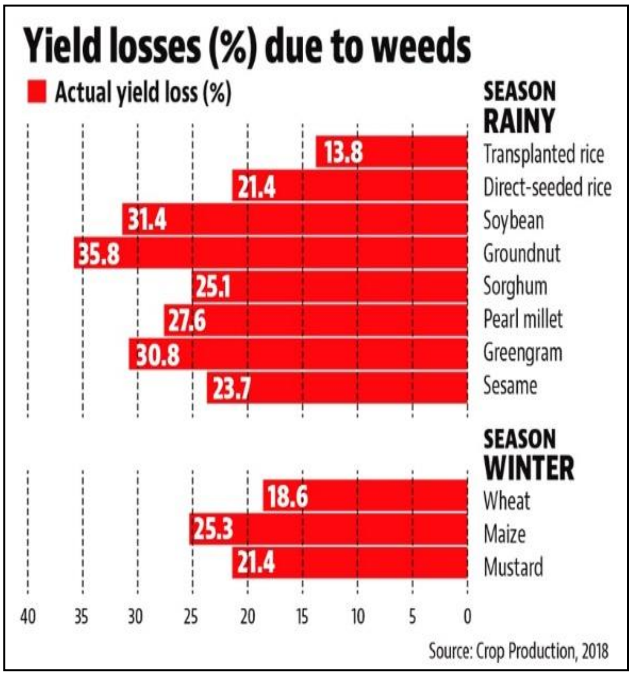


Figure 1 Losses caused by weeds vary with the crop, season and location in India (Source: Gharde et al. 2018)

In a recent review, Vila et al. (2021) argued that while the individual effects of environmental change and of effects of weeds on crop yields have been assessed for many global crops, the combined effects have not been broadly characterized. Conducting a meta-analysis of 171 observations, which measured the individual responses and combined effects of weeds and eCO_2, drought or warming on 23 crop species, Vila et al. (2021) found the combined effect of weeds and environmental change to be additive. The review by Vila et al. (2021) suggested that the effects of weeds alone on crop yields can be either similar to what they are now (i.e. average losses of 28% for a wide range of global crops and situations) or more detrimental than environmental changes (such as droughts) under climate change.

Such research, and those of others (Milberg and Hallgren, 2004; Oerke and Dehne, 2004). indicate that crop yield losses are likely to be quite significant, due to the increase in weed abundance, under future climate change. Hence, the management of agricultural weeds, to reduce their detrimental effects appears to be crucial, now, more so than ever before, to ensure global food and nutrition security.

Other pressures under which weeds should be more effectively managed come from the need for (a) low-input, sustainable production systems, (b) maintaining soil health in arable lands with efficient resource uses, (c) increased income for farmers and (d) conducting agricultural operations with decreased greenhouse gas emissions (Liebman and Davis, 2000; Altieri and Toledo, 2011; Altieri et al., 2011; Mwendwa et al., 2017). The need to preserve plant biodiversity, including a variety of beneficial weeds within agricultural landscapes and cropping systems, especially to support pollinators, is also becoming increasingly critical for sustainable agriculture (Nicholls and Altieri, 2012; Altieri et al., 2015).

Across the world, agricultural intensification and the changing climate have combined to result in significant changes in weed floras in different crops and cropping systems (Storkey et al., 2021). Weeds can rapidly evolve in life cycle strategies (Holt et al., 2013; Shaw, 2016) and other ways and thereby, better adapt to climatic variations than crops. They will also be evolving to resist human efforts to control them, including the use of herbicides (Ziska, 2011; 2016; Ziska et al., 2014; Clements and Jones, 2021a, b). The capacity of colonizing taxa to rapidly evolve is most profoundly demonstrated by the emergence of herbicide-resistant weeds, which have greatly increased in recent times (Heap, 2014; 2022).

Hence, it is essential to understand, across the timeline, the climate change effects on the changes in weed floras, weed adaptations, herbicide resistance, new bio-geographical distributions of arable weeds and interactions of weeds with crops and the environment, in different cropping systems. It is also important to continually review information on the effects of climate change on the efficacy of different weed management practices that can be implemented, as part of the adaptation process.

In this article, we have reviewed and synthesized some of the latest information on climate change effects on weeds and weed management. We also discuss potentially recent technologies and how 'Climate-resilient' and Integrated Weed Management (CRIWM) might be promoted as an approach to further prepare agri-food systems for the anticipated decreases in crop productivity and food supplies, as well as the challenges posed by weedy species.

Climate Change Effects and Weeds

Under climate change (mainly, a warmer world, with intermittent and prolonged droughts and highly unpredictable weather patterns with extreme weather events, such as floods and cyclones) weeds have the potential to invade new areas and dominate human-modified ecosystems, including agri-food production systems. The evidence from weed research in the past three decades confirms the capacity of weedy taxa to adapt relatively rapidly to any changes in the future climate (Patterson, 1995; Alberto et al., 1996; Ziska and Duke, 2011; Ziska, 2022).).

Many weedy taxa, with wide geographical distributions, exhibit large *intra-specific* variations in most functional and phenotypic traits (Vellend et al., 2007; Hulme, 2008; Chapman et al., 2013). This is an adaptive response to the wide variation in biotic and abiotic factors they face. Such selection pressure can lead to the evolution of morphologically and functionally different ecotypes, including 'agro-ecotypes', as a response to environmental variables (Wong et al., 2020; Bachofen et al., 2021).

Weedy taxa also undergo rapid genetic changes via mutations and/or other genetic material exchanges, such as hybridization and introgression (Clements and DiTommaso, 2011; 2012) [1]. Other rapid changes in weeds could also occur through epigenetic modification, which alters chromatin without changing DNA sequences (Jones, 2012).

Much evidence is now available to show that colonizing taxa can change their genetic makeup as a response to a changing environment (Hulme, 2008; Wong et al., 2020; Bachofen et al., 2021). The outcomes of such genetic changes are likely to lead to small-scale changes in their genomes, which produce different *biotypes* or *ecotypes* of the same species, as closely related species exchange genes, through hybridization and introgression.

As Vellend et al. (2013) and Wong et al. (2020) showed, in many situations, pioneer taxa are significant evolutionary forces themselves, forcing other co-existing and closely-related congeners in plant communities to change and adapt to varying environmental conditions. It is highly likely that as climate change effects increase on a global scale and are felt in different ecosystems, the adaptive responses of plants will be led by weedy taxa.

In one well-studied example, Paterson et al. (2020) recently showed how a strong colonizer – johnsongrass [*Sorghum halepense* (L.) Pers.], a polyploid species (2n=40). Johnsongrass was formed by the hybridization of grain sorghum [*Sorghum bicolor* (L.) Moench] (2n=20) and wild sorghum [*Sorghum propinquum* (Kunth) Hitchc.] (2n=20). Johnsongrass has *Sorghum bicolor*-enriched allele composition and striking mutations in 5,957 genes that differentiate it from representatives of its progenitor species (Paterson et al., 2020).

Occasionally used as forage and food (seed and flour), over several centuries, johnsongrass spread from its tropical, West Asian origin, across much of Asia, Africa, Europe, North and South America, and Australia. While grain sorghum remained confined to cultivation, *S. halepense* readily naturalized and now occurs across vast landscapes, in both agricultural and non-agricultural habitats (Sezen et al., 2016). It is a good example of the capabilities of colonizing taxa for rapid adaptation and evolution well beyond those of the parental progenitors.

A significant volume of research has emerged in recent decades to show that the same adaptive capabilities will most likely allow such taxa to spread more widely under a warmer and wetter future climate (Paterson et al., 2020; Wallingford et al., 2020). Range expansion of many weedy taxa will also be expedited by changing precipitation regimes and extreme weather events, which increase weed seeds and propagule dispersal and establishment across large landscapes (Clements and Jones, 2021a, b).

Atmospheric CO_2 concentration, a key GHG and a component of climatic change continues to increase and is predicted to be around 550 µmol mol^{-1} (550 ppm) by 2050. The response to eCO_2 and increased temperatures by weeds and crops will depend on their photosynthetic pathways and how quickly they may adjust and adapt to changed environmental conditions. It is generally accepted that higher atmospheric CO_2 is likely to stimulate the growth of C_3 plants which are likely to respond with increased net photosynthesis and yield, compared to C_4 plants (Alberto et al., 1996; Chandrasena, 2009).

The expected future environmental changes, such as rising CO_2 and global warming will influence the competitiveness between crops and weeds (Ziska 2010; Ziska et al., 2014; Ziska, 2022), although the effects are likely to vary with the nature of weeds and crops (Chongtham et al., 2019; Ziska et al., 2019).

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[1] *Hybridization* is the process of crossing two closely related organisms to produce a *hybrid* with mixed gene alleles (*heterozygosity*). It is a natural phenomenon as well as a technique breeders use. *Introgression* (*Introgressive Hybridization*) refers to the transfer of genetic material between species, following hybridization, and backcrossing to the parental species. These mechanisms of genetic material exchange are common in Nature and especially among domesticated animals and plants.

Weed taxa will more than likely benefit from a changing climate as they have the genetic makeup and adaptive capacity to grow and thrive in inhospitable environments. It is also likely that eCO_2, combined with warmer and possibly wetter and fluctuating conditions, will benefit a wide variety of weeds much more than crops and other slow-growing plants (Chandrasena, 2009; Holt et al., 2013).

Nevertheless, physiological and biochemical characteristics of crops and weeds – whether they are C_3 or C_4 plants - will be the key determinants of their individual responses to eCO_2 and other climatic effects, such as variable rainfall patterns and available water for growth, affected by droughts (Patterson, 1995; Hatfield et al., 2011; Ziska, 2011).

Several books (Ziska and Dukes, 2011) and reviews are available on the responses of crops and weeds and their likely interactions under climate change (Patterson, 1995, Chandrasena, 2009, Clements and DiTommaso, 2011; 2012, Rodenburg et al., 2011, Naidu and Murthy, 2014, Peters et al., 2014, Singh et al., 2016, Ramesh et al.; 2017 a, b, Ziska et al., 2014; 2019).

The effects of weeds on crops under future environmental changes will depend on the individual species' photosynthetic performances, metabolic pathways and other significant biochemical responses (Vila et al., 2021). Overall, under eCO_2 and warmer scenarios, both C_3 and C_4 weeds are likely to be more competitive in C_3 and C_4 crops. Although weeds and crops have the same photosynthetic pathways, under eCO_2, weeds will be harder to manage (Ziska, 2010; 2022). Elevated CO_2 concentrations would favour highly competitive C_3 weeds, such as lesser canary grass (*Phalaris minor* Retz.) and wild oat (*Avena ludoviciana*) in wheat (C_3) and weedy rice in rice (both C_3). In contrast, greater responsiveness of C_3 crops (e.g. rice and wheat) to CO_2 would benefit them when competing with C_4 weeds (Patterson, 1995, Rodenburg et al. 2011).

The evidence from available research is that significantly warmer and intermittently wetter or drier conditions will benefit C_4 species more than C_3 species (Patterson, 1995; Chandrasena, 2009; Valerio et al., 2011). Higher temperatures, due to global warming, may increase the growth rates of C_4 weeds. The C_4 photosynthetic pathway provides its greatest advantage under hot arid high sunlight conditions. C_4 plants also have a higher water use efficiency than C_3 plants. C_4 weeds also produce more biomass with robust roots, and seeds, than C_3 weeds, even under prolonged droughts (Rodenburg et al., 2011; Ziska et al., 2014; 2019; Singh et al., 2016, Ramesh et al., 2017a, b).

Under climate change, significant range-shifts in arable weeds and other environmental weeds are likely to occur, resulting in the spread of colonizing taxa into new areas (Wallingford et al., 2020). With climate-suitability modelling, such as CLIMEX, a wealth of evidence is now emerging on potential range-shifts of species under a changing climate (Kriticos et al., 2006; Wallingford et al., 2020).

In one example, Kistner and Hatfield (2018) predicted future increases in temperatures will expand the range of palmer amaranth [*Amaranthus palmeri* (S.) Wats.], (a C_4 species) northward into parts of Canada and Northern Europe. In another well-studied example, under a warmer climate with wetter and drier, intermittent cycles, the growth and reproductive output of parthenium weed (*Parthenium hysterophorus* L.) is predicted to greatly increase (Nguyen et al., 2017). Evidence is also emerging that metabolic pathways in parthenium may have already been altered by eCO_2, resulting in higher concentrations of parthenin, which is potentially implicated in its 'invasive success' (Rice et al., 2021).

The generalist '*all-purpose*' genotypes, including '*Jack-of-all-trades*' and '*Masters-of-None*' life cycle strategies (i.e., phenotypic plasticity, ecotype formation), combined with hybridization and other gene exchange mechanisms and specialized strategies like mimicry, allow pioneer species to evolve rapidly (Baker, 1991; Hulme, 2008).

As identified in the various recent reviews (Rodenburg et al., 2011; Naidu and Murthy, 2014, Peters et al., 2014, Ramesh et al.; 2017a, b, Ziska et al., 2014; 2019; Ziska and Dukes, 2011), how to incorporate climate change adaptation approaches into existing weed management programs is a key challenge. In addition, as argued by Christie (2014), raising awareness of the vulnerabilities of specific cropping systems, as well as broader agricultural landscapes to climate change, is becoming crucial. Many countries, including the USA, Australia and New Zealand, have embarked on identifying possible preemptive action against 'high-risk' weeds (banning, control and removal), occupying vulnerable sites (McGlone and Walker, 2011; Duursma et al., 2013).

Climate Change Effects on IWM Components and their Resilience

Building on standard IWM practices (Altieri and Toledo, 2011; Owen et al., 2015), "*Climate-Resilient Integrated Weed Management"* (CRIWM) involves a combination of weed management practices that could be *integrated* to absorb, utilize, or even benefit from perturbations caused by climate change. CRIWM solutions aim to combine environmental information (climatic and weather data), knowledge about weeds (life cycles, biology and ecology), and all available cultural practices and new technologies to persistently control weeds in an ecologically and economically sustainable manner.

In our view, it is possible to develop CRIWM only when the impacts of climate change on each of the established weed management methods are better understood and the climate-resilient components of those methods are identified. Our review finds that published information and data are insufficient to draw definite conclusions on the effects of eCO2, temperature and precipitation under climate change on several IWM components, as shown in Table 2.

We also agree with the viewpoint expressed by Birthisel et al. (2021) recently that it is crucial to better understand climate change effects on the '*many little hammers*' of ecologically-based weed management approaches (i.e. IWM). In the sections below, we discuss the likely impacts of climate change on each of the IWM components, summarizing the significant and expected changes that may influence the effectiveness of different weed control practices.

Table 2 Possible effects of climate change on components of Climate Resilient Integrated Weed Management (CRIWM)

WEED MANAGEMENT METHOD	↑[CO_2]	↑Temp	↑H_2O	↓H_2O
PREVENTATIVE MANAGEMENT - SEED BANK DEPLETION				
Stale seed bed	0	+	- +	+
Soil solarization	0	+	- +	- +
Harvest weed seed control	- +	0	-	+
Short duration cover crop	- +	0	+	0
Summer fallow	0	0	0	+
Seed predation	0	0	0	0
REDUCING SEEDLING RECRUITMENT				
Plastic mulching	0	+ -	+	+
Natural mulching	0	+	+	+
Cover crop mulch	0	+	+	+
CROP COMPETITIVENESS				
Competitive crops and cultivars	0	0	0	- +
Increased plant density	0	0	0	- +
Altered spatial arrangement	0	0	0	- +
Intercropping and living mulch	0	0	+	- +
Cover crops	0	0	+	-
Improved irrigation placements	0	0	-	+
Improved fertilizer applications	0	0		
Transplanting	+	- +	+	+
PHYSICAL WEED CONTROL				
Tillage and Cultivation	-	-	-	+
Flaming	-	0	- +	-
Flooding	0	0	0	0
Mowing	-	0	-	0
Grazing and Herbivory	-	- +	0	0
Biocontrol	0	0	0	0
Hand weeding	0	-	0	0

+ indicates positive change (green colour), − indicates negative change (red colour), ± indicates mixed positive and negative changes, 0 indicates insufficient data (white colour). Source: Modified from Birthisel et al. (2021)

Manual weeding

Labour-intensive and costly hand weeding is still common in many developing countries (Figure 2). Hand weeding is not just time-consuming; it is onerous and imparts high drudgery and stress on the labourers (bending all the time to remove weeds). Hand weeding is especially difficult if the soil surface is not moist and loose. It is particularly costly where labour is in short supply and wages are high. Hand weeding is also often quite unsuccessful because of difficulties in identifying and removing certain weeds, such as grass weeds at the initial stages (e.g. weedy rice, *Echinochloa* spp.) in rice.

As the world becomes warmer with more frequent hot days and heatwaves across the world, the risk of mortality and illness increases for workers in open agricultural fields during periods of extreme heat (Klein et al., 2007; IPCC, 2021). As a result, the efficiency and propensity for hand weeding will more than likely decrease in all developing countries. India will lose more than 101 billion hours of labour every year, the highest of any country in the world.

Figure 2 Manual weeding, common in developing countries, will become harder in a warmer world

An effective adaptation strategy is to move work-hours from the middle of the day to early in the day – but as the planet warms further, even this strategy will become less effective. What is likely to be more effective is a combination of moving the working hours of labour and some form of mechanization.

Mechanical Weed Control

Mechanical weed control (Figures 3, 4 and 5), using various implements, requires less labour than hand weeding. In developing countries, farmers use various tillage equipment, including the running-blade harrow or the disk harrow in dryland cropping fields, as a component of IWM. Although fuel costs will be a key factor, in a warmer future climate farmers will have to increasingly rely on such machinery, not just for tillage and ploughing of the hardened earth but also to achieve better weed control. Labour shortages also will force farmers to adopt increasing mechanical weed control methods.

A primary challenge would be to innovate and design affordable machinery that would be suitable for wider adoption by farmers in developing countries and are 'climate-resilient' (i.e., be able to effectively operate in warmer and wetter conditions, less fuel-consuming with fewer GHG emissions).

The use of improved machinery as weeding tools are likely to save labour (about 20-40 man-days per hectare) and ensure more effective and timely weed control. Seeding and/or planting crops in rows is a prerequisite for mechanical weeding. In developed countries, improved tillage and cultivation tools are widely used (Brown and Gallandt, 2018).

We predict that as global warming will affect all forms of tillage and cultivation, a warmer and wetter future may require increasingly mechanized equipment and 'smarter' machinery even in all developing countries.

Figure 3 Cono-weeder used in rice in India

Figure 4 Inter-row cultivation using a mechanical weeder and animal power. India

However, the more intensive tillage requirements become, the more likely that they will increase GHG emissions from soils and from agricultural operations (Mooney and Sjögersten, 2022). Well-known tillage techniques, using heavy disk harrowing (Figure 5) may have to be modified for less intensive tillage practices in the future.

Figure 5 Heavy tillage with machinery may need to be modified under a warmer and wetter future climate

Heavy tilling of the soil with various types of ploughs and other machinery exposes carbon buried in the soil to oxygen in the air, allowing microbes to convert it to CO_2. Tillage is a standard practice in most cropping situations, before sowing crops, but the question is being increasingly asked - *what if farmers could avoid this step?* Recent research in the UK indicated that zero-tillage, or minimum tillage, which are well-established practices, could be crucial in both reducing GHG emissions and increasing soil carbon. Such methods appear crucial in mitigating climate change effects (Cooper et al., 2021).

The use of tillage for weed management can be minimized by practising 'need-based tillage' for reducing weed abundance by using improved weed detection technologies (WDT) with camera sensors, artificial intelligence (AI) and computer-controlled, mobile robot platforms. In recent decades, the industry has seen such innovation-driven opportunities to incorporate strategic tillage in different cropping systems to target widely-dispersed weeds in the fields or isolated weed patches.

There is currently a great deal of global industry interest in incorporating artificial intelligence (AI), 'deep-learning', highly sensitive cameras and computerized, 'smart' technologies into mechanical tillage equipment (Bruciene et al., 2021; Coleman et al. 2022). Light weight and low-speed autonomous vehicles, equipped with advanced sensor systems for weed control within crop rows are becoming common. These include Robocrop intra-row cultivator (Figure 6), a Robovator intra-row cultivator, and an intelligent camera-based Steketee-IC [2] (Fennimore et al., 2016) are already well-developed and increasingly used in several advanced and industrialized countries.

Intelligent inter and intra-row weeding machinery (Chandel et al., 2021) and robotic weeding systems (Quan et al., 2022), combining deep learning technology with a targeted weeding mode are being developed in several countries with advanced technologies and investments. We expect these technologies to be modified significantly and made more affordable in developing countries in the next decade or so. Achieving increased work efficiency with mechanization using solar power-based machinery, such as herbicide sprayers (EcoRobotix, 2022; Figure 8), and walking power weeders, such as those developed in India (Kachhot et al., 2020; Figure 9), are most certainly important parts of the CRIWM solutions in the years to come.

Figure 6 Robocrop Inter-row Cultivator (source: https://garford.com/products/robocrop-inrow-weeder/)

Figure 7 Steketee-IC 'Intelligent' Weeder for row crops (Source: https://www.steketee.com/about-us/)

Figure 8 Solar-powered Robot used for herbicide spraying in row crops (Source: EcoRobotix (2022)

[2] The intelligent camera (IC) steering works with an algorithm based on the principle of "Deep Learning". The Steketee-IC Weeder is an automatic hoeing machine, which distinguishes crops and weeds and ensures reliable weed removal even within sown crops and with high weed infestations. A compressor provides the pneumatic pressure to move sickle-shaped knifes actively intra-row and inter-row, to remove weeds.

Figure 9 Solar-powered Weeder promoted in India to replace traditional tillage methods and fuel-driven equipment (Source: Kachhot, et al. 2020)

Preventative measures

Preventative weed management methods are well established within the discipline, although practical applications vary greatly in different countries, with different cropping and agri-food systems (Rao et al., 2007; 2017). However, there is an urgent need to understand the effects of climate change on individual IWM components that affect preventative weed management, such as weed seed production, persistence and dispersal of weeds via agricultural operations. Within cropping systems, this will allow planning of effective preventative measures, such as how to stop new weed introductions to cropping fields via seed, and how to reduce weeds from reproducing, once they are in the fields.

Possible preventative measures that need to be adopted in a particular cropping system and location need to be selected based on the weed floras prevalent at the site, and the likely changes those populations may undergo, under climate change.

A recently popularized method in preventative weed management is Harvest Weed Seed Control (HWSC), which destroys weed seeds, which get harvested with the crop. HWSC techniques and associated machinery have enabled the routine use of an alternative weed control technology, at a novel weed control timing, applicable in global grain cropping fields (Walsh and Powles, 2022).

Driven by the significant threat of widespread populations of annual, rigid ryegrass (*Lolium rigidum* Gaud.) with multiple-herbicide resistance, the first HWSC system – the *Harrington Seed Destructor* (HSD) was developed by a West Australian farmer. It harvests weed seeds along with the cereal grains but separates and grinds the small weed seeds, rendering them unable to germinate (Walsh and Powles, 2022). As the cereal grains (in this case, wheat) are harvested and the chaff separated, the HSD feeds it to a high-speed mill that pulverises the chaff, which includes weed seeds that would otherwise pass through the harvester and be returned to the field. The seed destructor has been shown to destroy up to 90% of weed seeds in cereal fields.

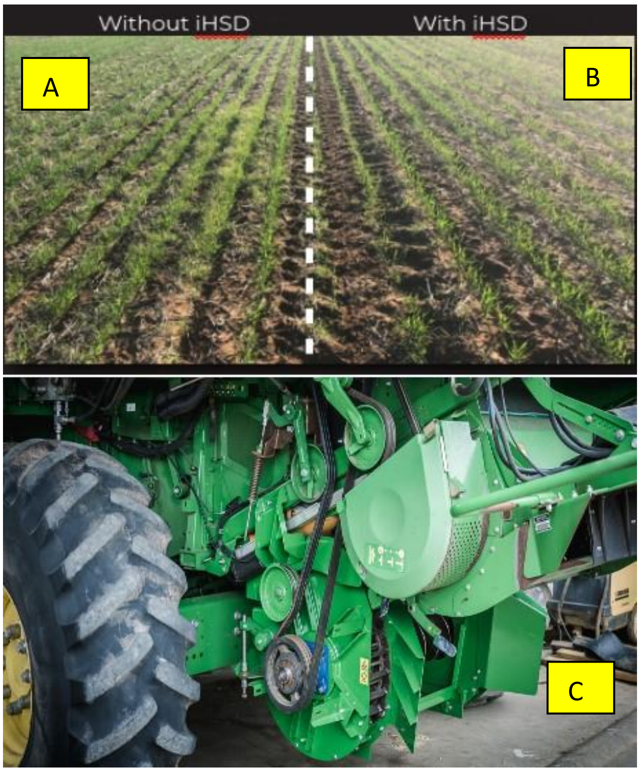

Figure 10 An Australian wheat field harvested without (A) and with (B) the use of a (C) HSD attachment to the Harvesting Machine. Note the significantly reduced weed population that developed in the field, after the HSD (https://ihsd.com/)

According to Walsh and Powles (2022), the use of HWSC has likely contributed to lower annual ryegrass population densities, and thus, mitigates the impacts of herbicide resistance in those fields, as well as slowing further evolution of resistance. In addition, low weed densities enable the introduction of site-specific weed control technologies and the opportunity to target specific in-crop weeds with non-selective, alternative weed control techniques. Given the potential of weed species, such as ryegrass, to adapt to all forms of weed control and evolve their defences, HWSC treatments also need to be judiciously used in grain cropping systems to ensure their ongoing efficacy (Walsh and Powles, 2022).

After the success of the *Harrington* system, several other similar equipment and attachments have been developed in Australia and the USA (Walsh and Powles, 2022). We note that these sophisticated systems are quite expensive (approximately, US $ 50-60,000) and possibly unaffordable to farmers in most developing countries.

Nevertheless, developing countries will have to also consider the options of separating the much smaller weed seeds after grain harvest and developing HWSC systems that suit their specific needs. The successful operation and adoption of such machinery, however, depends on the crop production terrain and the dynamics of the weed flora, as affected by climate change. It is also possible to predict that, at least in tropical countries, if prolonged wetter periods occur under climate change, they will constrain the operation of sophisticated machinery, such as HWSC.

Enhanced Crop competitiveness

i. Intercropping

Inter-cropping (multiple-cropping) is widely practised in Asia, Africa, Latin America and Oceania, by farmers as a means of increasing crop productivity per unit of land area and minimizing the risk of crop losses, due to uncertain climatic conditions.

Smallholders, with limited capital and resources to invest in farming, often combine two contrasting crops, such as a legume and a cereal, to ensure higher overall productivity than either species grown alone. Inter-cropped mixtures can use resources, such as space, water, soil nutrients and sunlight, more effectively than monocultures (Rao and Ladha, 2011; Rao et al., 2017). Crop mixtures also leave behind nutritious crop residues that encourage different kinds of microflora, which degrade organic matter and perform other biological transformations in the soil. Inter-cropping is also an effective strategy to introduce more biological diversity and stability into agro-ecosystems (Altieri and Toledo, 2011).

The abundance of arable weeds is generally lower in intercrops, as the design of these systems favours the growth of crops with different root systems and plant morphologies. Crop mixtures enhance soil physical properties, smother weeds and increase soil plant nutrients in the soil through the addition of biomass and residues. In the case of adverse weather conditions, such as a delay in the onset of rains and/or lengthy dry periods, inter-cropping systems provide the advantage that at least one crop will survive to give economic yields, thereby serving as insurance against unpredictable weather patterns, which are likely to increase under future climate change scenarios (Machado, 2009).

ii. Competitive Crop cultivars

Competitive crop cultivars are crucial components of IWM in agri-food systems (Ramesh et al., 2017a, b; Mwendwa et al., 2017). Implementing climate change adaptation technologies, such as drought-tolerant crop cultivars and water-saving irrigation regimes, will help increase the competitiveness of crops against weeds under rainfed production systems (Bir et al., 2014).

In irrigated rice, water-saving methods can be designed involving intermittent or continuous periods of aerobic conditions, instead of the traditional weed-suppressive floodwater layer. Such adaptations will help reduce GHG emissions and also increase resource use efficiency (Ladha et al. 2015, Chakraborty et al., 2017). However, location-specific (‘site-specific) weed management strategies need to be developed for different production systems, combining, drought-adapted and competitive crop cultivars, to reduce the likely increase in weed competition under a changing climate (Chandrasena, 2009). are likely to play a critical role in such situations (Rao et al., 2007; Soriano et al., 2017).

iii Cover Crops

Annual cover crops, such as legumes, are usually killed by mowing or herbicide applications at a sufficiently late stage in their development and by cutting close to the ground (Singh et al., 2007; Rao and Ladha, 2011). The mowed cover crop residues form an *in situ* mulch, which physically hinders weed seed germination and seedling establishment.

The biomass of decaying crop residues, such as wheat, maize, barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.), oat (*Avena sativa* L.) and sorghum, also release inhibitory chemicals. These chemicals inhibit weed seeds from germinating and may also reduce the growth of weed seedlings (Altieri et al., 2011). Maintaining crop residues, including those of cover crops, especially during the critical weed-free period required for specific crops, are likely to make post-plant cultivation, herbicide use or hand weeding unnecessary, or much reduced, and yet lead to acceptable crop yields (Liebman et al., 2001; Jat et al., 2021). Legume cover crops, planted in zero-till fields, fix atmospheric N_2, reduce soil erosion and mitigate the effects of drought in the long term. Mulches from cover crops also conserve soil moisture and improve the soil’s water-holding capacity (Altieri et al., 2011). The selection of location-specific cover crops is increasingly becoming important in adapting farming for future climate change effects.

Under warmer and wetter conditions, cover crops are likely to be easier to establish in upland crop rotations. Most will be effective in suppressing weed seedling emergence. However, more specific, country-based and cropping system-specific studies are needed to establish how much above-ground biomass of residues is needed to suppress weeds and the variations in the tolerance of weed species to cover crop residues (Mwendwa et al., 2017).

Conservation Agriculture practices

Conservation Agriculture (CA) comprises a set of management practices that cause minimal soil disturbance while protecting the soil with crop residues (green manures and mulch) and also includes crop rotation. CA-based technologies, such as zero, strip or reduced tillage, direct-seeding and/or cultivations using permanently-raised beds, may facilitate improved crop establishment and timely sowing. Such practices can significantly increase crop yields, protect soil health, reduce irrigation water requirements, lower production costs, and boost farmer income (Ladha et al., 2015; Jat et al., 2021).

The FAO (2014) recognizes the tangible benefits of CA, which allow growers to manage greater areas of land with reduced energy and machinery inputs while achieving significant benefits in crop yields and reducing soil erosion and soil impoverishment, especially in climate-vulnerable, lower rainfall regions. CA practices suppress weed seedling emergence, allowing crops to gain an early advantage in establishment and growth (Jat et al., 2021). Chaudhary et al. (2016) recently showed how CA practices, including reduced tillage, direct-seeding and crop residue management, make farming systems more resilient to climatic change. Mooney and Sjögersten (2022) also explained the potential for up to 30% reduction in GHG emissions by CA practices, such as minimum tillage or no-till methods, which involve direct-seeding.

(i) Diversified Crop rotations and Mulching

The beneficial effects of crop rotations depend on the selection of crops. For example, a rotation of a legume and a row crop, followed by a tuber or cereal crop may offer the following benefits in sequence: N_2 fixation and improved soil N; breaking-up of soil, stimulating weed seed germination and suppression of weeds by smothering (Jat et al., 2021).

Crop rotations add considerable amounts of nutrients and organic matter to the soil, thus improving soil health. Within crop rotations, weed suppression can be achieved by high planting densities, increased depth of seeding and other practices. Different crops, rotated, interrupt the life cycles of difficult-to-manage perennial weeds, and promote annual weeds to germinate at various times but with fewer individuals. Rotating different crops, sometimes with varying fallow periods, alters the weed composition in the fields, associated with the different and rotated crops (Machado, 2009; Rao and Ladha, 2011; Rao et al., 2017).

Diversified crop rotations, along with various forms of green manuring and mulching, should form an important component of CRIWM, as they reduce the abundance and growth vigour of many species, especially, annual weeds. Such practices also assist in increasing the yields of rotated or sequential crops. The retention of residues of component crops on the soil surface suppresses weed seed germination, either by the release of allelopathic compounds or by imposing a physical barrier to emerging seeds.

The selection of climate-adapted competitive crop varieties, mixed or intercropping complementary crops and genetically-diverse crops in crop rotations help in better resource capture by crops. Precision fertilizer applications, and drip irrigation to crops grown in rotation, help in better resource utilization.

Under a warmer and wetter climate, increased precipitation is likely to have a positive effect on weed seed germination and its reduction by mulches and residues of cover crops. However, those effects are likely to be negative influences on the effectiveness of irrigation and fertilizer placement. On the other hand, warmer conditions will have positive effects on natural crop residue mulching and cover crop residues, while they may have mixed impacts on the efficacy of techniques, such as plastic mulching.

(ii) Reduced- or No-tillage

Reduce tillage or no-till systems have various advantages, especially in managing populations of annual weeds. However, some weeds, especially perennials, tend to grow and flourish in such CA systems. CRIWM strategies include the wider adoption of the ‘stale seedbed’ technique with minimum soil disturbance (Boyd et al., 2006) [3], soil solarization, using polyethylene sheeting, planting weed-competitive crop cultivars in narrow rows with high seeding rates, the use of plant residues as mulch and the judicious use of an effective post-emergence herbicide (Rao, et al., 2007; Rao and Ladha, 2014). Nevertheless, under warmer and intermittently wetter future climates, especially in regions affected by frequent flooding, many of these CA techniques will be much harder to implement.

Diversified Farming Systems

Diversified Farming Systems (DFS) aim to integrate ecological and economic benefits for sustainable agriculture (Rosa-Schleich et al., 2019). At a farm level, they aim to reduce negative environmental externalities and enhance ecological benefits by integrating biodiversity into agricultural production. Research indicates that DFS systems (with grains, fruit, vegetables, animal fodder, trees and livestock, cultivated in the same field) outperform (by 80%) conventional systems and are especially suited for inter-cropping and polycultures, which are common in developing countries. The DFS system

[3] In the ‘Stale seedbed’ technique, the seedbed is no longer freshly and heavily tilled at the time of crop planting. The untilled bed has aged or become ‘stale’ by planting time. Planting is done usually by drilling and placing crop seeds deep. The shallow weed seeds, emerging are killed by (a) very shallow tilling, (b) an effective herbicide, (c) thermal weeding, or (d) by physical coverings.

used must have multifaceted means to reduce weeds and include various IWM methods.

One such DFS is the '*Rice-Fish-Duck*' System in China, which is a traditional rice production system that incorporates fish, ducks, and the cultivation of different vegetables within the terraced rice fields. Other components of the system are tree species, used as fuelwood, food and medicines. Weeds, algae, aquatic insects, benthos, insect pests, water mice, water snakes, birds, and other soil and water microbes are also essential components of this complex system (Lu and Li, 2006).

The fish – Nile Tilapia (*Tilapia nilotica* L.) and European carp (*Cyprinus carpio* L.) in this system consume insect pests of rice and weeds, while the ducks consume snails, weeds, filamentous green algae, floating aquatics, such as *Azolla* spp. Animal faecal matter enriches the water with nutrients, occasionally triggering eutrophication in stagnant water. However, by consuming biomass, the fish and ducks reduce methane emissions, which are otherwise produced by decomposing vegetation by up to 30%, as compared with conventional farming.

DFS are much understudied. However, adapting to climate change would require more emphasis on finding such integrated and traditional systems that can reduce the competition crops face from weeds while mitigating inputs (Koohafkan and Altieri, 2016).

Biological Control

Biological control of weeds has been a powerful tool to manage weeds, where specific natural enemies (insects, fungi, bacteria or viruses) are used against particular weed species. While biocontrol agents have not been found for all major global weeds, the sub-discipline is well-developed within Weed Science. There are many well-documented success stories, which also discuss opportunities and constraints (Charudattan and Dinoor, 2000; Charudattan, 2001; Harding and Raizada, 2018).

However, evidence is emerging that plant-herbivore interactions and their complex inter-relationships within ecosystems could be affected by climate change (Descombes et al., 2020). Sun et al. (2020) showed that the effects of climate change on the effects of biocontrol agents on weeds may either be positive or negative. In their studies on the herbivory of ragweed (*Ambrosia artemisiifolia* L.) by a bio-control agent - the beetle *Ophraella communa* LeSage (Coleoptera: Chrysomelidae), increased resistance to herbivory arose through a shift in plant metabolomic profiles without genetic changes.

The authors argued that this change was most likely triggered by the trans-generational induction of stronger plant defences. Importantly, while increased resistance was costly at ambient temperatures, warming removed this constraint and ragweed showed a propensity to better defend itself from the natural enemy (Sun et al., 2021). Such studies show that the efficacy of biocontrol agents in managing weeds in agri-food systems will be modified by changing climatic factors. Research is limited in this area of biocontrol, possibly due to funding limitations. As Sun et al. (2021) suggested, understanding the mechanisms of how weeds and their natural enemies interact in changing abiotic environments and future climate scenarios will be quite a challenge.

Herbicides

Herbicides are the most predominant tool used against weeds in developed countries, especially in monocultures of the world's major crops (wheat, corn, soybean and cotton). However, their usage is fast increasing even in developing countries (Gianessi, 2016; Brookes, 2019). Herbicides continue to be a dominant component of weed management in all major crops in Australia, China, Thailand, and Vietnam but are less predominant in India, Pakistan, Bangladesh, Sri Lanka, Indonesia, and the Philippines. In these emerging economies, herbicides are more widely used in commercial plantation crops and much less used in major crops.

In Thailand and Malaysia, in particular, even though all forms of weed control methods are used, herbicides are becoming the predominant tool, used in most crops. Of the total active ingredients of herbicides used, glyphosate accounts for 50% of all herbicides used in Australia, 13% in China; 37% in India; 73% in Indonesia; 33% in Thailand; 36% in Vietnam (Brookes, 2019).

It is important to note that the agrochemical industry has been severely constrained and has changed dramatically in the past two decades. No new herbicides with new modes of action (MOAs) have been discovered for almost 40 years (Duke and Dayan, 2021). The slowing down of the herbicide discovery is due to several factors, including (a) drastic consolidations of the herbicide and pesticide industry, (b) a substantial devaluation of the non-glyphosate herbicide market after glyphosate-resistant crops were introduced, (c) more stringent regulatory requirements for new products, and (d) the diminishing returns of new herbicide discovery approaches (Westwood et al., 2017).

The evolution of herbicide-resistant weeds has been dramatic, and the number of resistant weeds has been increasing every year in all countries where herbicide use is prevalent (Heap, 2022). At the same time, the efficacy of herbicides has been markedly reduced by climatic change-related factors (i.e. eCO2 and higher temperatures) (Ziska, 2010, 2016, 2020), which means that a '*rethink*' on weed management is in order (Waryszak et al., 2018).

Matzrafi et al. (2016) and many others have predicted an increased risk of the evolution of herbicide-resistant weeds under predicted climatic change conditions. In recent studies, Wedger et al. (2022) recently demonstrated how weedy rice (*Oryza* spp.) – a de-domesticated form of rice - in the USA, has dramatically changed due to crop-weed gene exchanges through hybridization and introgression. In their article, Wedger et al. (2022) suggested:

> *"The shifting landscape of rice agriculture has resulted in a new generation of weedy rice. The Clearfield™ cropping system reduced the average field infestations (of weedy rice) drastically, but two decades of herbicide applications, in the presence of hybrid rice gene-flow bridges, has resulted in weedy rice that is herbicide resistant and likely more competitive than historical populations. The rapid adaptation of weedy rice to herbicide applications should serve as yet another example of the dangers of relying on single methods of control for agricultural pests".*

The dangers of relying too much on a single method of weed control, such as herbicides, have been clear for at least four decades, as evident in the increased numbers of herbicide-resistant weeds and greater weed problems in agri-food systems, across the globe. Mooney and Sjögersten (2022) suggested that energy uses, such as more intensive tillage, will most likely increase, along with increasing GHG emissions, if increasing numbers of weed species become resistant to herbicides and other interventions, under a changing climate.

Increased precipitation, due to climate change, may cause increased herbicide run-off and greater herbicide residues in water bodies, thus aggravating contamination and risks to human health and non-target organisms. Such effects, and the herbicide resistance debacle, necessitate the reduction of herbicide use, as a component of CRIWM.

To reduce herbicide use, there has been a significant increase in the use of artificial intelligence (AI) with the sensing capability to intelligently activate spraying tools. 'Site-specific' and precision herbicide applications to low-density weed populations are currently facilitated by sensor-based spray booms, which are highly effective (Allmendinger et al., 2022). Adapting future farming to climate change requires making such systems (currently limited to advanced economies) more affordable to developing countries and varied agri-food production situations

Coleman et al. (2022) recently described an *OpenWeedLocator* (OWL), which is an open-source, low-cost and image-based device for fallow weed detection. The system improved the detection and treatment of weeds, but also reduced the operational costs of whole-farm spraying by up to 90%. In OWL technology, weed detection sensors capture infrared reflection from green tissue and deliver herbicides as the boom passes over the plant. Such targeted applications considerably reduce the amounts of herbicides required to be applied in a field, offering both economic and environmental benefits (Coleman, et al., 2022).

Another way to reduce the potential harmful effects of herbicides is to take into consideration the *Environmental Impact Quotient* (EIQ), a method that measures the environmental impact of pesticides (Kovach et al. 1992). An updated calculator for Field Use EIQ is now available (Grant, 2020), which allows herbicides with minimal EIQ values (Table 3) to be profitably used, minimizing any negative effects.

Overview and Conclusions

The latest IPCC Reports (IPCC, 2021) indicate that the world must prepare itself for "*Widespread and long-lasting heatwaves, record-breaking fires and other devastating events, such as tropical cyclones, floods and droughts*". These will have major impacts on socio-economic and cultural development and the environment, especially in developing countries. In our view, urgently responding to climate change must be the focus of all agricultural enterprises and agri-food production systems, recognizing that agriculture is a significant contributor to GHG emissions.

Climate change is a critical confounding factor that can affect agriculture and food security in many different ways. Climate-resilient food systems, including CRIWM, are needed to ensure food security and support GHG emissions mitigation efforts. The FAO (2016) recognizes how vulnerable developing countries and especially smallholder farmers, are to the predicted climate change effects.

In planning for the future, the FAO (2016) recently identified the following as essential and complementary components of future farming:

- **Conservation Agriculture** (CA), promoting minimal soil disturbance, surface mulches, crop rotation, and the integrated production of crops, trees and animals;
- **Maintaining healthy soil**, through integrated soil nutrition management, which enhances crop growth, bolsters stress tolerance and promotes higher input-use efficiency;
- **Improved crops and varieties** adapted to smallholder farming systems, with high yield potential, resistance to biotic and abiotic stresses and higher nutritional quality;
- **Efficient water management** that obtains '*more crop per drop*' and energy-use efficiency, while reducing agriculture-related water pollution; and

- **Integrated Pest Management (IPM)**, based on good cultural practices, more resistant varieties, natural enemies, and judicious use of relatively safer pesticides when necessary.

Table 3 Environmental Impact Quotient (EIQ) values of herbicides used in rice

Herbicide	Farm Worker	Consumer + Leaching	Ecology	EIQ Total (Farm Worker+ Consumer+ Ecological)/3
2,4-D	8	8	34	16.67
Bispyribac-sodium	6.90	4.55	22.95	11.47
Cyhalofop-butyl	8	3	64.60	25.20
Chlorimuron-ethyl	8	7	42.60	19.20
Halosulfuron methyl	12	6	42.60	20.20
Metsulfuronmethyl	8	8	34	16.67
Oxadiargyl	6	2	26	11.33
Pendimethalin	12	5.5	73.0	30.17
Penoxsulam	12	9.35	34.80	18.72

The recommendation from the FAO is that implementing such practices is the only way to meet *Sustainable Development Goals* and global food security. These approaches will "*increase cereal production, keep ecosystems healthy, strengthen resilience to climate change, and progressively improve land and soil quality*" (FAO, 2016).

We agree that raising the productivity and incomes of smallholders, will promote the inclusive economic growth needed to free millions of rural people from abject poverty. Linking smallholder production to well-designed social protection programmes will also ensure food and nutrition security for the most vulnerable and help eradicate or reduce hunger, especially in developing countries.

Science tells us what is causing global warming: CO2 and other greenhouse gases emitted largely by relentless human activities. Science also tells us what the impact of global warming will be: melting ice caps and rising sea levels; melting glaciers and disruption of weather patterns and water supplies; disruption of agriculture; and the possible extermination of millions of species of animals, plants and insects who may not have the time to adapt to such changes.

Climate Change Mitigation components of CRIWM

Climate change mitigation requires policies and technologies that reduce the sources of GHG emissions while enhancing the sinks of GHGs. This approach needs to be based on technological changes and substitutions that reduce inputs and emissions per unit of output (Klein et al., 2007).

The most effective mitigation options for GHG emissions in 'climate-Smart' agriculture are improved sustainable cropland management, such as improved agronomic practices, improved nutrient and irrigation water uses, minimum tillage and CA techniques, which include crop residue management and cover crops, all of which effectively and profitably combine to manage weeds (Jat et al., 2021).

Climate Change Adaptation components of CRIWM

Climate adaptation is a complementary strategy to climate mitigation—reducing GHG emissions from energy uses and land use changes to minimize the pace and extent of climate change (Klein et al., 2007). The selection of location-specific components of CRIWM should be based on the weeds associated with the agri-food systems.

Climate change will likely affect multiple interconnected aspects of farming systems, with substantial implications for weed management. Some of the most significant interactions are shown in Figure 11. Concerning managing weeds under a changing climate, climate adaptation components of CRIWM should include the following:

1. Selection of location-specific, competitive crop cultivars that are more tolerant of extreme conditions (heat and drought and flooding).

2. Selection of cultivars, which are resistant to diseases and pests and a variety of soil conditions.

3. Flexibility to adjust nutrient and irrigation supplies to cropping fields, and/or herbicide applications, depending on the location-specific need, changing weather conditions and associated weeds.

4. Altering the timing or location of cropping activities, such as planting date to effectively use resources and implement other management strategies at the farm level for improved crop productivity while minimizing weed growth.

We envisage climate resilient adaptation as '*doing what we always did, but better and more effectively'*, given that there is already an unfolding climate change crisis. Adaptation is a MUST as humans are running out of other options. Some measures, given above, may be constrained by available technologies (i.e. crop cultivars and equipment, and/or reliable supplies), costs involved, and inadequate knowledge of how to implement adaptation practices on the farm level. Farmers' responses to adaptation are also affected by what they are used to, traditional beliefs, long-standing cultural practices, and other socio-economic factors, such as the level of trust in government support, accessibility to knowledge and farming incentives.

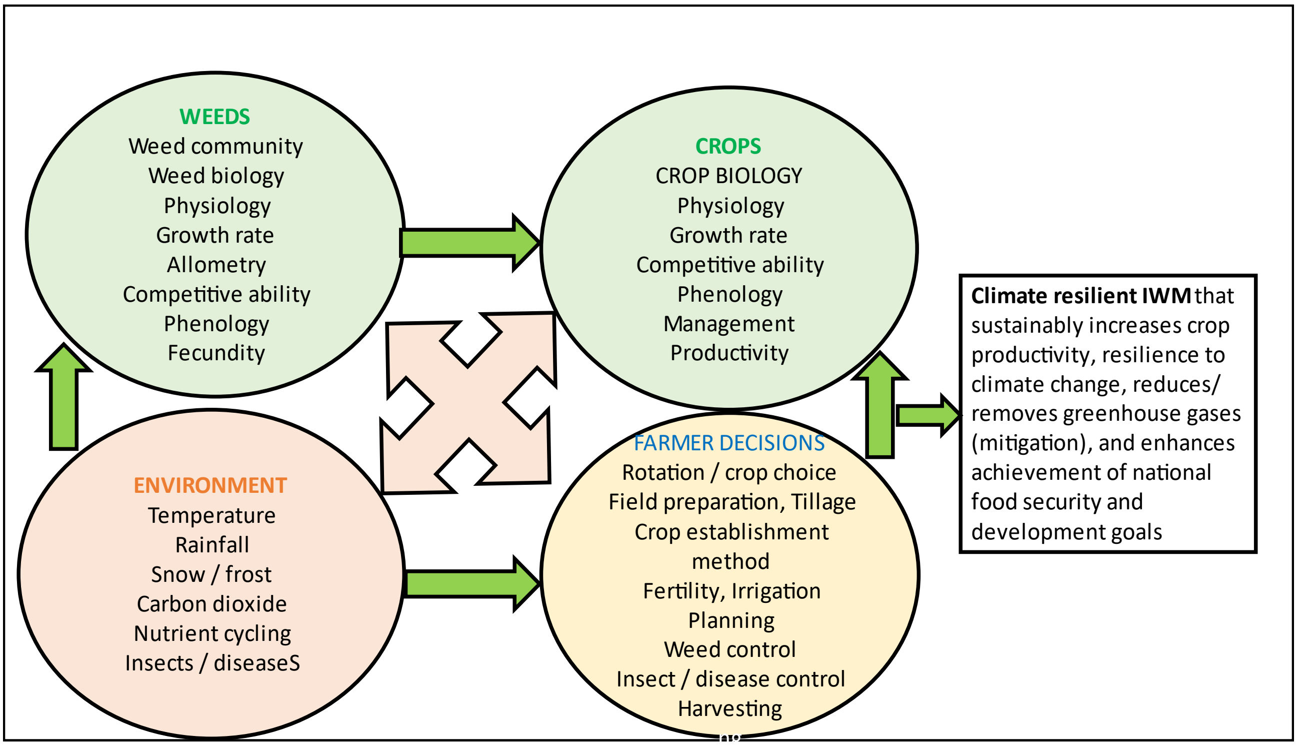

Figure 11 Crop-weed-environment interactions in agri-food systems will help in location-specific components of climate-resilient integrated weed management

However, given that *taking no action is not an option*, the adaptation components of weed management discussed above should be part of the solutions we seek to reduce the vulnerability of agri-food systems to climate change. While improving the effectiveness of managing weeds, in CRIWM, it is also essential to convey the message to farmers that weeds are only one component that may limit the productivity and profitability of farming.

In our experience, in well-managed cropping fields, using well-established, resilient crop cultivars, weeds are not necessarily the most significant factor constraining yield outputs. Those other socio-economic factors, related to farming communities and the support they receive, are indeed what limits sustainable agricultural production and profitability.

Weedy taxa and their populations are extremely resilient and have the genetic makeup to adapt to a changing climate more so than any other group of plants. It is inevitable that weed floras will change, both within agricultural landscapes, and areas outside agriculture, in human-modified environments (Wallingford et al., 2020).

Monitoring the weed flora to identify major weeds that are likely to change and thereby threaten increased crop losses is an important part of planning for the future. Being flexible in weed management approaches, using new weed detection technologies that reduce GHG emissions, as much as possible, and making such technologies affordable to developing countries, are also critically important.

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How may Climate Change affect the activity of Glyphosate on Weeds? Some reflections

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Abstract

The evidence of changes in the global climate being felt by all of the bio-physical environments on the Earth is undisputed. Well-established literature, some of which is summarized herein, shows that the climate change effects will modify agro-ecosystems, including the multiple interactions between crops and weeds. From the perspective of weed management, there is compelling evidence that climate change effects will alter the growth of both C3 and C4 weeds and C3 and C4 crops in their interactions in cropping environments. Such responses will not just modify the outcomes of weed-crop competition, but also affect the efficacy of weed management methods, including the performance of herbicides.

Glyphosate [N-(phospho-methyl) glycine] is unquestionably the world's most used and successful herbicide. Published research, over at least three recent decades, indicates that glyphosate's efficacy and activity on specific weeds may increase or decrease in the wake of elevated atmospheric carbon dioxide (eCO_2) concentrations, global warming and associated climate change effects (such as increased or decreased rainfall and droughts). Changed glyphosate activity under climate change has been attributed to several factors. These include modified plant morphology and physiology (e.g., lower number of stomata, increased leaf thickness and modified cuticle permeability, etc.), which affects plant uptake and also changes in translocation of the herbicide to metabolically-active target sites.

However, there is also evidence that, under some conditions, glyphosate activity on specific weedy taxa or groups of weeds may not be adversely affected by the dominant climate-modifying factors. In this article, we appraise some of the published evidence on glyphosate and reflect upon those factors and how the growth and vigour of weedy taxa might affect the efficacy of glyphosate, under eCO_2 and a warmer global climate. In our view, aside from the broad generalizations, the effects of eCO_2 and warming on glyphosate efficacy on major weeds cannot yet be discerned without more directed research.

Keywords: Climate change, eCO_2, global warming, weeds, crops, glyphosate, herbicidal activity

Introduction

Global climate change is now undisputed and has already caused shifts in temperature, rainfall and other weather patterns across the globe, putting animals, plants and human societies at risk (Stern, 2006; Blasing, 2016). The reasons for climate change are human activities, including the relentless burning of fossil fuels, deforestation, and the rising concentration of greenhouse gases (GHGs), i.e., methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs) in the atmosphere.

These three gases are the primary cause of the greenhouse effect, while synthetic CFCs are responsible for the depletion of the ozone (O_3) layer. While enormous quantities of CO_2 are released mainly from the burning of fossil fuels, the other GHGs – methane and nitrogen oxides - are largely released by agriculture and industry. (IPCC, 2001; 2022).

Recent increases in GHGs (Table 1) show that over the past 200 years, human activities have introduced a huge concentration of GHGs into the atmosphere. Because GHGs absorb the infrared radiation (IR) discharged from Earth's surface, they are now contributing to the warming of the Earth's atmosphere much more than they did previously. However, climate projections suggest significantly increased warming by 2100, especially over land. There will also be changes in global precipitation patterns (IPCC, 2001; 2022).

Concentrations of GHGs will also keep on increasing in the 21st Century, due to the activities of a constantly growing human population. The consumption of non-renewable energy resources will also continue for several years. Even if the GHG emissions were decreased immediately, their amount would hike for some time because of the long-term persistence of these gases in the atmosphere and passive uptakes by impact-reducing agents, like the vast oceans and the great vegetation communities (biomes) of the world, which include the forests and grasslands (IPCC, 2021; 2022).

Carbon dioxide emissions are directly attributed to human activities, playing the most significant role in climate change. Atmospheric CO_2 concentration has now risen to above 415 ppm; it was about 300 ppm in the early ages of the industrial era (IPCC, 2022). The *Intergovernmental Panel on Climate Change* (IPCC) predicts that CO_2 concentration will rise to 700 ppm at the end of the 21st Century. Soaring concentrations of CO_2 [eCO_2], as a GHG, will have a profound, direct impact on the global temperature, although a part of warming is also contributed to by CH_4 and other GHGs.

Every 1000 Gt (Giga Tons) of cumulative CO_2 discharges is evaluated to probably cause an increase of 0.27°C-0.63°C in global surface temperature with the best estimate of 0.45°C (IPCC, 2022). It is expected that CH_4 is contributing almost 18% to the total global warming and this is still continually increasing.

If the increasing GHG emission trends are not arrested, the mean temperature of the globe is predicted to rise 1.4-5.8°C by the end of this century, which is an alarming figure that puts many thousands of plant and animal species, as well as humanity, in peril (IPCC, 2021; 2022).

Table 1 A summary of Greenhouse gas concentrations and rates of change*

	CO_2	CH_4	N_2O	# CFC
* Pre-industrial (1750-1800)	280 ppmv	700 ppbv	275 ppbv	0
* Concentration in 1994	358 ppmv	1714 ppbv	311 ppbv	503 pptv
* Rate of change in concentration (up to 1994)	1.5 ppmv/yr	13 ppbv/yr	0.75 ppmv/yr	18-20 ppmv/yr
** Concentration in 2022	413 ppmv	1909 ppbv	335 ppbv	511 pptv
** Rate of change (most recent 12 years)	2.4 ppmv/yr (0.6% per year since 2010	8.8 ppbv/yr (0.5% per year since 2010	0.99 ppbv/yr	Not available
* Atmospheric life (yrs)	50-200	12-17	120	102

* Source: IPCC, 2001; 2022; ppm – parts per million; ppb- parts per billion; ppmv or ppbv– by volume; # Chloro-fluoro-carbons, CFCs, are synthetic gases, discovered in the 1920s and used as refrigerants, propellant sprays, and foaming agents substitute. They are the primary cause of ozone layer depletion.

** Sources: (1) Our World in Data (**https://ourworldindata.org/greenhouse-gas-emissions**); T.J.Blasing (2016). *Carbon Dioxide Information Analysis Centre* (CDIAC). The Most Recent Greenhouse Gas Concentrations (**https://cdiac.ess-dive.lbl.gov/pns/current_ghg.html**); IPCC (2022); (2) The Global Carbon Project (GCP) [1] (**https://www.globalcarbonproject.org/carbonbudget/22/highlights.htm**).

[1] **The Global Carbon Project** is a Research Project of ***Future Earth*** and a research partner of the ***World Climate Research Programme***. It was formed by the international science community to establish a mutually agreed knowledge-base to support the policy debate and action to slow down and ultimately stop the increase of GHGs in the atmosphere.

Plant growth and metabolic processes, especially photosynthesis, will respond directly to eCO_2, as well as to a warmer climate and other associated changes in climate, such as droughts, extreme hot periods or cold spells, or intermittent, heavy, wet-weather events. Influential reports (Parry, 1990; 1998; Rosenzweig and Hillel, 1998; Luo and Mooney, 1999) and research articles (Ainsworth and Rogers, 2007; Hatfield and Prueger, 2015) have explained in detail how such global climatic changes could modify plant growth rates, developmental processes (phenology), and several physiological processes, such as stomatal conductance, water use efficiency, and CO_2 fixation.

Variations in agricultural production will arise due to direct impacts of eCO_2, higher temperatures, soil moisture deficits and higher exposure of plants to O_3, and combinations of these factors. These factors would have direct effects at the whole plant level, or indirect effects, at the system level, for instance, by modifying crop weed interactions, changing nutrient cycling processes, as well as the incidence of insect pest damages and plant diseases (Fuhrer, 2003).

The predictions are that climate change may cause a decrease in agricultural yields of some of the world's major crops, such as wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.) and maize (*Zea mays* L.) and these effects would be significantly felt in regions and countries that are also most vulnerable. As a consequence of changes in agro-ecosystems, there is a high likelihood of increasing food insecurity across many regions of the world as climate change occurs (Wang et al., 2018; Neupane et al., 2022).

There is also considerable evidence that climate change will have a direct influence on both the abundance and persistence of colonizing taxa (weedy species) in human-modified environments. The spread and geographical distribution of many globally-important weeds are also likely to increase as their ranges expand. Such effects are likely to have major flow-on effects on how weeds will compete with crops in a warmer and CO_2-enriched environment and on weed management in both agricultural and non-agricultural settings (Carter and Peterson, 1983; Patterson, 1985; 1995a, b; Alberto et al., 1996; Patterson et al., 1999; Bunce, 2000; 2001; Ziska, 2000; 2003a, b; Ziska and Dukes, 2011; Chandrasena, 2009; Varanasi et al., 2016; Ramesh et al, 2017).

Ziska and other researchers in the USA first demonstrated that changes in climatic conditions may decrease the efficiency of certain herbicides (Ziska and Bunce, 1997; Ziska et al., 1999; Ziska and Teasdale, 2000; Ziska and Dukes, 2011). They attributed the changes, variability and unpredictable effects on variations in the uptake, translocation, metabolic detoxification, vacuolar sequestration, and other mechanisms by which plants metabolize herbicides (Ziska and Dukes, 2011; Shaner et al., 2012; Varansi et al., 2016). Since the studies intensified in the 1990s, a wealth of evidence has emerged, demonstrating the likely general (adverse) effects of climate change on crop yields (Wilcox and Makowski, 2014; Wang et al., 2018; Raza et al., 2019) and the possible stimulation of growth of many weed species (Ziska, 2003; Ziska et al., 2004; Ziska and Dukes, 2011; Clements et al, 2014; Jabran and Dogan, 2020; Siddiqui et al., 2022).

However, data and information available on climate change effects on the field performance and activities of specific herbicides are somewhat limited, especially on the most widely used global herbicides, which include glyphosate [N-(phosphonomethyl) glycine]. Weed scientists agree that glyphosate is perhaps a '*once-in-a-century'* herbicide, based on its efficacies on a broad spectrum of weed species, commercial success in many countries, and popularity among farmers and weed control practitioners in diverse applications (Duke and Powles, 2008).

The objective of this review is to re-appraise the major findings of the published literature and reflect upon our own research on potential climate change effects on managing weeds with glyphosate. Glyphosate is likely to continue as the world's most used herbicide (Benbrook, 2016; Van Bruggen, et al., 2018; Green, 2018) in the current decade and beyond.

Duke (2018) explained that "*much has happened since the last such review ten years ago [Duke and Powles, 2008], but nothing has happened to detract from the "once-in-a-century herbicide" descriptor that we gave it then*". Glyphosate, however, is under intense scrutiny for its environmental and health effects (Duke, 2018; Kanissery et al., 2019).

Projections are that in the current decade glyphosate usage will still grow at about 5% per annum[2]. As reviewed herein, studies on the interactions between eCO_2, warming and other factors affecting glyphosate efficacy have also continued with high intensity in the last decade with some studies focusing heavily on the likely mechanisms of glyphosate tolerance by treated plants.

[2] The glyphosate market was valued at US$9.016 billion in 2020. It is expected to grow at a CAGR of 5.1% per year to reach US$12.771 billion by 2027 (**https://www.researchandmarkets.com/reports/5576420/)**.

Major effects of Climate Change

The vast global climate change knowledge repository shows that the changes in the global climate will have flow-on impacts on people's livelihoods, agriculture, and natural ecosystems (Parry, 1990; 1998; Drake and Gonzàlez-Meler, 1997; Rosenzweig and Hillel, 1998; Dukes and Mooney, 1999; Luo and Mooney, 1999; Stern, 2006; Ziska, 2008; Hatfield and Prueger, 2015; Tollefson, 2021).

Table 2 provides a summary of likely effects, of which the first two are relevant to predicting how weeds may respond to climate change and the implications for weed management in both cropped and non-cropped areas. Due to climate change, if the natural habitats of native plant species and vegetation communities undergo significant changes, some weedy species will prosper in those conditions because they have the genetic makeup and inherent adaptations to survive in diverse and stressful conditions (Chandrasena, 2009; Ziska and Dukes, 2011).

Changes that are already on the planet, such as extended periods of elevated temperatures and droughts, increased rainfall and extreme weather events such as floods, cyclones and tornados), are all habitat disturbances. Inevitably, such disturbances will favour the growth of fast-growing, opportunistic, colonizing taxa, which are likely to move into and dominate those habitats (Dukes and Mooney, 1999; Ziska and Dukes, 2011; Hatfield and Prueger, 2015).

In reviewing climate change effects on US Agriculture, Hatfield et al. (2014) summarized the following as the most likely future effects:

- In the last 40 years, there has been an increase in interruptions in agricultural productivity and it is expected to continue throughout the next 25 years. The majority of crops and livestock will face growing negative impacts by mid-century or beyond.
- Several agricultural areas will suffer greater declines in crop and livestock production from stresses, due to the disruptions caused by plant and animal diseases, weeds, insect pests, and other stresses induced by climate change.
- Recent losses of agricultural land and water resources due to extreme weather conditions especially increasing rainfall will continue to pose problems for irrigated and rainfed agriculture unless they are mitigated by the adoption of new resource conservation methods.
- Agriculture and associated socioeconomic systems have already begun to adapt to the current climate change scenarios; however, more modernization and investments will be required to keep the pace of this adoption process as climate change unfolds over the next 25 years.
- The impact of climate change on agriculture will lead to serious concerns about food security, both in the U.S.A. and worldwide, by variations (decreases) in final crop yields and (increases) in commodity prices and also significantly affect food storage, processing, transportation and selling.
- Implementing adaptation initiatives to climate change can help in delaying and decreasing some of the well-established negative impacts.

Effects of eCO_2 on plant growth

Plants will feel the effects of eCO_2 directly through their physiological processes. Elevated CO_2 will affect how they 'fix' CO_2 in photosynthesis and how their stomatal pores respond by opening more or closing. Higher rates of photosynthesis and more efficient gaseous exchange (through stomata) will increase plant growth rates (Carter and Peterson, 1983; Ziska and Bunce, 1997; Dukes and Mooney, 1999; Luo and Mooney, 1999; Ziska and Dukes, 2011; Lee, 2011).

Reviews by Griffiths et al. (2013), Lundgren et al. (2014) and Christin and Osborne (2014) have discussed C_4 photosynthesis, comparing the efficiencies of C_4 plants with C_3 plants and other mechanisms of CO_2 fixation. The most common CO_2-fixation mechanism in plants is C_3 photosynthesis, present in 95% of all species. It involves CO_2 capture and conversion into a 3-carbon sugar (glyceraldehyde-3-phosphate) by the enzyme RuBisCo (Ribulose-1,5-bisphosphate carboxylase-oxygenase). The second-most important mechanism - the C_4 pathway - firstly 'fixes' CO_2 into 4-carbon sugars (oxaloacetic acid and malic acid) and involves a different enzyme (phospho-enol-pyruvate carboxylase, PEP-carboxylase). A third pathway, common in succulents, is *Crassulacean Acid Metabolism* (CAM photosynthesis).

The efficiencies of the different photosynthetic pathways are governed by RuBisCo and PEP-carboxylase enzymes, which have different affinities to CO_2. How cells are arranged inside leaves affects the efficiency of CO_2 assimilation by chloroplasts in leaves. C_4 plants have a special type of leaf anatomy, called *Krantz* anatomy in which chloroplast-bearing bundle-sheath cells surround the veins, which supply food and water to leaves. This cell arrangement (an internal 'CO_2 pump') allows CO_2 to be fixed by those special cells and efficiently transfer photosynthetic products from their chloroplasts to the adjacent transport system (phloem) (Griffiths et al., 2013; Lundgren et al. (2014).

As a consequence of the more efficient CO_2 fixation pathway in C_4 species, increasing the external CO_2 concentration above the ambient levels could be expected to have small or negligible effects on the net photosynthesis in C_4 plants. Nevertheless, higher photosynthetic rates, growth stimulation and enhanced biomass production for C_4 plants have been recorded with eCO_2 levels. Such responses are generally due to changes in resource partitioning, accelerated phenology (i.e. floral development, prolonged leaf senescence and enhanced water potentials resulting from stomatal closure at eCO_2 (Carter and Peterson, 1983; Patterson, 1995a; b; Ziska and Bunce, 1997).

While not all plants may respond equally, the combined effects of eCO_2 and higher temperatures will alter a plant's ability to compete with another species, in any given environment (Ziska and Bunce, 1997; Drake and Gonzàlez-Meler, 1997; Ziska and Dukes, 2011). The evidence is that eCO_2 could make some species stronger, enabling them to use both water and nutrients more efficiently and better tolerate stresses, such as drought and fluctuating temperature (Carter and Peterson, 1983; Ziska and Bunce, 1997; Luo and Mooney, 1999; Bunce, 2001; Ziska and Dukes, 2011).

There is a sizable number of previous articles that have attempted to determine the effects of eCO_2 on several C_3/C_4 crop/weed combinations (Patterson et al., 1984; Ziska and Bunce, 1997; Ziska, 2000, 2001, 2003). Unsurprisingly, results reveal that C_4 plants show less response to eCO_2, whether they are a weed or crop than C_3 plants. Further, most research appears to indicate that C_3 weeds are likely to have greater negative impacts on the growth rate and biomass of both C_3 and C_4 plants under eCO_2 than do C_4 weeds.

However, while most studies suggest a larger relative response of C_3 to C_4 plants under eCO_2, it should not be assumed that C_4 plants are incapable of responding to higher CO_2 levels. Species-specific responses to eCO_2 and warmer conditions in C_4 plants are strongly indicated by research. The positive responses of C_4 plants also appear to be independent of any improvement in water relations even in the absence of drought (Ziska and Dukes, 2011).

Colonizing taxa, whether C_3 or C_4, already express innate abilities to withstand environmental stresses. This means that they will most likely benefit more from higher temperatures and eCO_2 than their non-weedy relatives and other slow-growing plants (Luo and Mooney, 1999). Such changes will assist the spread and distribution of many species across the globe, in terms of both altitude and latitude, and their persistence and competitiveness in different habitats (Ziska and Bunce, 1997; Ziska, 2000; 2003; Ziska and Teasdale, 2000; Ziska and Dukes, 2011; Lee, 2011).

Effects of elevated temperature on plant growth

Temperature regulates plants' physiological processes, acting as a determining factor for seed germination, and phenological processes, such as flowering, fruiting and seed formation, all of which are likely to be affected by climate change. Changes in temperature, particularly the frequency and duration of periods of elevated temperatures and eCO_2 may combine to produce important modifications to seasonal rainfall patterns, droughts, local weather, and regional climates, and periods of moisture stress across large landscapes (Parry, 1990; 1998; Rosenzweig and Hillel, 1998; Bunce, 2001).

With global warming, plants, in many parts of the world, will experience not just stress due to higher temperatures but also moisture deficits. However, the way plants feel these effects are unlikely to be uniform in various regions. In the tropics, warming, even by a few degrees, will increase evapo-transpiration from plants to a specific point where the growth rate of some species would suffer due to lower moisture content. However, shifts in rainfall patterns (intermittent and heavy rainfall events and flooding) could balance such responses, under a changing climate scenario.

Temperature is the prominent factor that affects plant growth at high (above 50 ^{0}N) and mid-latitudes (above 45 ^{0}N). In such cold regions, warming would extend the growing season of plants, although the effects on any plant species will be influenced by other factors, such as rainfall. The responses will vary from region to region, and from species to species (Luo and Mooney, 1999; Bunce, 2000; 2001).

Climate change research also shows that the beneficial effects of eCO_2 on most crops might be negated by warming and associated changes, such as extended periods of droughts or intermittent, heavy rainfall events. Persistently higher temperatures will have a considerable impact on the growth rates and phenology of plants (Lee, 2011), such as the flowering time and duration in mass-flowering crop species, as well as the success of pollination, via insects. Similar effects would be felt by weedy taxa, but they would be better adapted to respond to such changes.

In a well-studied example from Australia, Scott et al. (2014) reported that buffel grass (*Cenchrus ciliaris* L.), a C_4 grass, was able to acclimate and grow at warmer temperatures (growth at 35°C versus 25°C) in Australia. The climate suitability modelling prediction is that the spread of buffel grass southwards on the Australian continent is inevitable, as the species shows the capacity to rapidly acclimate and persist under warmer conditions. Although buffel grass is a desirable pasture grass, this range shifting is likely to lead to greatly increased future management costs as it begins to occupy conservation areas and other habitats away from pastures (Scott et al., 2014; Webber et al., 2014).

Combined effects of eCO_2 and warming on plant growth

Over the past two decades, attempts have been made to better clarify crop losses due to weeds that may occur under climate change as plant growth is strongly affected by both CO_2 concentrations and temperature. Research indicates that crop yield losses are likely to be quite significant, due to greater abundance, growth vigour and persistence of weedy taxa in most agro-ecosystems, under future climate change (Ziska, 2000; 2003; Milberg and Hallgren, 2004; Oerke and Dehne, 2004; Oerke, 2006; Ziska and Dukes, 2011; Hatfield et al., 2011; 2014; Liu et al., 2017; Gharde et al., 2018; Neupane et al., 2022).

Evaluating the impacts of elevated temperature and CO_2 on two annual C_3 and C_4 weeds – common lambsquarters (*Chenopodium album* L.) (C_3), and foxtail grass [*Setaria viridis* (L.) P. Beauv] (C_4) in climate chambers, Lee (2011) found that both factors affected the germination, phenology and growth stages of the species. Germination and flowering time were more affected by a 4°C increase in temperature than eCO_2 (1.8 times above ambient CO_2). Higher temperatures delayed seedling emergence by 26 and 35 days, respectively, for lambsquarters and foxtail grass. The flowering times were also delayed by 50 and 31.5 days, respectively for the two species.

The higher temperature alone greatly reduced the biomass and seed production of both species with the effects being more dramatic for the C_4 species. However, eCO_2 compensated for the disadvantage caused by warmer conditions, resulting in increased biomass and seed production of both species. Again, the stimulation of growth by the combined warmer and eCO_2 conditions was more dramatic for the C_4 weed than for the C_3 grass. (Lee, 2011).

Climate chamber studies by Temme et al. (2015) also showed differential responses of 28 C_3-species, including several weeds (16 forbs, 6 woody, and 6 grasses) to low CO_2 (160 ppm), ambient (450 ppm) and eCO_2 (750 ppm) conditions. The study focused on the leaf growth responses [measured by specific leaf area; leaf area ratio; leaf-mass fraction], relative growth rates and allocation of resources to root systems. Fast-growing species benefitted from eCO_2 by increasing their plant biomass but suffered significantly under low CO_2 (160 ppm). Interestingly, *fast growers grew relatively fast and slow growers grew relatively slowly irrespective of CO_2 levels*. For all species, eCO_2 increased the relative growth rate (RGR) by 8% but low CO_2 had a much more profound effect, decreasing the RGR much more significantly (by 23%).

The differential responses of contrasting plant morphological groups prompted Temme et al. (2015) to state that "*winners will continue to win*" under eCO_2. In their view, flowering plants, which evolved over the past 100-125 or so million years have not had sufficient time in evolutionary terms to adjust their physiology and metabolism (i.e. RuBisCo enzyme-related) to the changing CO_2 levels. In their view, in the future, the dramatic changes in the CO_2 levels will ultimately determine how individual species, their populations and vegetation communities evolve and change [3],

In a recent review, Vila et al. (2021) stated that although the individual effects of climate change and of effects of weeds on crop yields have been evaluated for many global crops, their combined effects have not been well studied. Conducting a meta-analysis by observing 171 cases, which measured the individual responses and integrated effects of weeds and eCO_2, drought or high temperature on 23 crop species, Vila et al. (2021) found the integrated impact of weeds and climate change to be additive and the effects of weeds alone on crop yields can be either similar to the ones that are now (average losses of 28% for a range of global crops and situations) or more detrimental than environmental changes (such as droughts), under climate change. Hence, the management of arable weeds, to reduce their harmful effects on crops, is becoming even more crucial now than ever before, to ensure global food security (Vila et al., 2021).

[3] Fossil evidence shows that the Angiosperm evolution occurred in the late Cretaceous Period, about 125-100 million years ago.

In addition to increased growth, photosynthetic rates and changes in resource allocation to shoots or underground parts, seed production in many annual weeds could also increase or decrease as the climate warms up and CO_2 levels rise. In one well-studied example, Navie et al. (2005) reported that parthenium (*Parthenium hysterophorus* L.) produced 16,000 seeds per plant under a warm temperate regime (32/24°C) but significantly increased its seed production (19,000 seeds per plant) under a cooler temperate regime (25/16°C). Nguyen et al. (2017), in recent research, confirmed that eCO_2 and warmer conditions, as well as intermittent wetter and drier cycles, under climate change, would greatly enhance the growth and reproductive output of parthenium weed.

Our work, in Turkey (Jabran and Dogan, 2020), with prickly lettuce (*Lactuca serriola* L.), false barley (*Hordeum murinum* L.) and cheatgrass (*Bromus tectorum* L.) showed that warmer conditions (25/15 °C day/night vs. 20/10 °C day/night) and eCO_2 (800-900 ppm) stimulated the growth and biomass production by all three species. The growth stimulation by eCO_2 alone was also more significant than that caused by the higher temperature regime alone.

However, we detected significant interactions of the two climate change factors with nitrogen (N) fertilizer applications [controls with no added N, vs. 60 kg/ha (medium) or 120 kg/ha (high)]. Nitrogen applications stimulated the leaf growth and biomass production of prickly lettuce and cheatgrass more than that of false barley. Based on these results, we identified a clear need to study 'species-specific' interactions of not just the primary climate change factors (CO_2 and temperature) but also with external inputs in agriculture, such as N fertilizers and moisture regimes, under future climate scenarios.

Differential response of Weeds and Crops to elevated CO_2

Over the past three decades, much research has focused on the effects of elevated CO_2 levels on crops and weeds with these different photosynthetic pathways. Of the 15 crops, which supply 90% of the world's calories, 12 are C_3 plants. These include rice, wheat and soybean. The other 10%, including maize, sorghum [*Sorghum bicolor* (L.) Moench], proso millet (*Panicum miliaceum* L.), pearl millet [*Cenchrus americanus* (L.) Morrone] and other millets) and sugar cane (*Saccharum officinarum* L.), are C_4 crops.

The majority of weeds in the world are C_3 plants. Measurements show wide variations in the way weeds respond to higher CO_2, both within populations of the same species and between species. In general, C_3 weeds increase their biomass and leaf area under eCO_2 more than C_4 weeds. Other factors, such as higher temperature, high sunlight, and availability of abundant water and nutrients also affect the weeds' responses (Patterson, 1985; Patterson, 1995a, b).

Elmore and Paul (1983) showed that 14 out of 18 of the *'World's Worst Weeds'* are C_4. Overall, C_4 plants constitute a small portion of the total population of plant species in the world (less than 1000 out of 250 000). The *Weed Science Society of America's Composite List of Weeds* comprises about 2000 species, in 500 genera, and 125 plant families. Of these, at least 146 species, in 53 genera, and 10 families, have the C_4 pathway. In percentage terms, this is 17-fold higher than the C_4 plants among the total world plant population, which indicates the significance of the C_4 pathway for weedy taxa (Elmore and Paul, 1983).

While C_4 plants are photosynthetically more efficient under eCO_2 than C_3, research suggests that eCO_2 levels will stimulate the growth of both C_3 crops and C_3 weeds. A doubling of CO_2 may even cause a 10-50% yield increase in some C_3 crops, which is highly beneficial. Given that C_4 plants are already photosynthetically efficient, eCO_2 levels may not affect them much. Therefore, yield increases in C_4 crops under eCO_2 scenarios are likely to be much lower (only up to about 10%) or none at all (Patterson, 1995a, b; Patterson et al., 1999; Ziska, 2001; 2003a).

Among the 14 most aggressive global weeds are tropical grasses, which are C_4 plants, including barnyard grasses (*Echinochloa* P. Beauv. spp.), paspalum (*Paspalum* L. spp.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], Bermuda grass [*Cynodon dactylon* (L. Pers.], cogongrass [*Imperata cylindrica* (L.) P. Beauv.], goosegrass [*Eleusine indica* (L.) Gaertn.] and johnson grass [*Sorghum halepense* (L.) Pers.]. While all such species may not show increased growth under higher CO_2, Patterson (1995a, b) and Patterson et al. (1999) suggested that they could become much harder to control because, as C_4 plants, they are well tolerant to heat and moisture stress than C_3 species. Therefore, the simple notion that climate change will only benefit C_3 plants may not be entirely accurate (Patterson, 1995a, b; Patterson et al., 1999).

In some early research, Ziska and Bunce (1997) compared the effect of eCO_2 (720 ppm), on the biomass production of six major C_4 weeds - redroot pigweed (*Amaranthus retroflexus* L.), barnyard grass [*Echinochloa crus-galli* (L.) P. Beauv.], fall panic grass (*Panicum dichotomiflorum* Michx.), foxtail grasses [*Setaria faberi* Herm. and *Setaria viridis* (L.) P. Beauv.], johnsongrass and four C_4 crops – amaranth (*Amaranthus hypochondriacus* L.), sugar cane, sorghum and corn. The photosynthetic rates of eight of the ten species increased by 20% and the increase for C_4 weeds was double that of the C_4 crops, at higher CO_2, which produced significantly higher biomass.

The general view (Ziska and Dukes, 2011) is that weed-crop competition, irrespective of whether they are C_3 or C_4 species, could become more intense under future climate change, particularly under rising concentrations of CO_2. Ziska (2003b) had earlier reported that in a 'weed-free' environment, eCO_2 (250 ppm above ambient) caused a remarkable rise in leaf size and weight of sorghum (a C_4 crop) but had no remarkable impact on the seed yield or above-ground biomass comparative to ambient CO_2 levels.

At ambient CO_2 levels, the presence of velvetleaf (*Abutilon theophrasti* Medik.), a C_3 weed, had no effect on either the sorghum grain yield or total dry matter production. However, at eCO_2, a 3-fold increase in velvetleaf growth and biomass caused significant yield and biomass losses in sorghum. In comparison, redroot pigweed (C_4), growing at ambient CO_2, caused a remarkable reduction in the aboveground dry matter production of sorghum but not grain yield. Although, at eCO_2, the C_4 weed became much more aggressive and caused significant losses in both sorghum grain yield and dry matter, indicating potentially higher yield loss in a commonly grown C_4 crop from weedy competition in a future climate with eCO_2 (Ziska, 2003b).

Such research has clearly established that under eCO_2 and warmer conditions, growth rates and dry matter accumulation of both C_3 and C_4 weeds could increase, particularly if other favourable conditions prevail (i.e. moisture). In one study from Southeastern USA, Runion et al. (2008) reported significantly increased growth of sicklepod (*Cassia obtusifolia* L.; C_3 legume) and Johnsongrass [*Sorghum halepense* (L.) Pers.; a C_4 grass] under eCO_2 (575 ppm) when compared with ambient CO_2 (375 ppm). Under eCO_2, both plants allocated more resources to leaf and shoot growth than to reproductive structures and became more competitive (Runion et al., 2008).

Climate Change effects on Glyphosate – an Appraisal

The overwhelming evidence from research indicates that climate change will most likely have a significant effect on the biology and ecology of weedy species, as well as their abundance and persistence. Climate change will also most likely directly affect herbicide applications and herbicide effectiveness in field situations. Effects will most likely occur through altered plant (leaf or stem) uptake, translocation (via phloem or xylem) and metabolism of herbicides at the cellular level, including detoxification or sequestration (Chandrasena, 2009; Ziska and Dukes, 2011; Clements et al., 2014; Ziska, 2016; 2020; Fernando et al., 2016; Ramesh et al., 2017; Siddiqui et al., 2022).

The early studies (Bunce, 2000) had already shown that rising CO_2 concentration could cause many changes in plant leaves, including a reduction of stomatal numbers and stomatal conductance by up to 50% in some plants. With eCO_2, cuticles on plant leaves may also become waxier and thicker and less permeable even to surfactant-assisted, formulated herbicides. Such changes in leaf morphologies, along with changes in cuticular wax chemistries may reduce the uptake of foliar-applied herbicides with concomitant decreases in the efficacy of foliar-applied herbicides, most of which are phloem-mobile and translocate following a typical ''source-to-sink" pattern (Ziska et al., 2000; Ziska, 2003; 2008; 2016; 2020).

Glyphosate is undoubtedly the world's most-used and best-known herbicide (Dukes and Powles, 2008; Sammons and Gaines, 2014; Van Bruggen, et al., 2018; Green, 2018).). As a non-selective, foliar-applied, systemic chemical, glyphosate controls a wide range of weeds in both agricultural and non-agricultural settings. Glyphosate's history proves that it has been a remarkably successful weed control tool that has performed well under diverse conditions all over the world (Duke and Powles, 2008; Benbrook, 2016; Heap and Duke, 2017; Duke, 2018).

Once absorbed through leaves and stems, glyphosate is highly mobile inside the plant body, being translocated to meristematic tissues, such as developing leaves, shoots, and roots. Glyphosate affects plants by suppressing chloroplast enzymatic activity inside the shikimate pathway, resulting in the build-up of shikimate (shikimic acid). The specific enzyme inhibited by glyphosate is EPSPS (5-enolypyruvylshikimate-3-phosphate synthase). It is also known that under optimum growth conditions, nearly 20% of total photosynthetically-fixed carbon is predicted to move through the shikimate pathway.

The inhibition of the enzyme and the pathway then causes a reduction in the biosynthesis of aromatic amino acids, many aromatic secondary metabolites, plant proteins and hormones essential for growth (Shaner et al., 2012). The phytotoxic effects that result from the above effects of glyphosate include wilting of leaves, chlorosis, necrosis, and plant death, which generally occur within one to three weeks after glyphosate applications (Shaner et al., 2012; Sammons and Gaines, 2014; Heap and Duke, 2017).

However, published research indicates that under future climate change scenarios, the efficacy of glyphosate may increase, decrease or remain constant, depending upon the types of weeds treated, rates and timings of applications and other local, influential factors that affect the growth of the targeted species. Some of the most significant findings are summarized in **Table 3** and discussed briefly below.

In some of the earliest studies, Lewis Ziska and co-workers (Ziska et al., 1999) demonstrated that under eCO_2, a C_3 weed – lambsquarters was considerably tolerant of glyphosate at the recommended control rate. In contrast, redroot pigweed, a C_4 species, was well controlled by the recommended rate of glyphosate, or one-tenth of it. The main reasons for the differential response of the C_3 and C_4 species to glyphosate might be the effects on plant morphology and physiology, brought about by eCO_2. Plant size alone could not explain the tolerance between the two levels of CO_2 in the C_3 weed's recalcitrance, indicating that under eCO_2, physiological changes may have occurred. Based on the results, Ziska et al. (1999) predicted that the control of some C_3 weeds with glyphosate could become more difficult under future climate change.

Pline et al. (1999) also showed that foliar uptake of ^{14}C-glyphosate by 'Roundup-ready' (RR) soybean (*Glycine max* L.) grown at 15 or 35°C was similar up to 7 days after treatment (DAT). However, translocation was significantly higher at 35°C than at 15°C, indicating the potential for glyphosate injury to the genetically-modified crop, supposed to be glyphosate-resistant.

Long-term exposure of couchgrass [*Elymus repens* (L.) Desv. ex Nevski.] to eCO_2 (720 ppm) significantly increased its resistance to glyphosate, which became difficult to control (Ziska and Teasdale, 2000). Ziska (2001) showed early evidence that eCO_2 increased leaf area sizes and biomass of C_3 weeds and predicted that such a change would assist C_3 weeds, such as common cocklebur (*Xanthium strumarium* L.) to evolve glyphosate resistance.

Sharma and Singh (2001), working with Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.]. showed that the uptake and translocation of ^{14}C-glyphosate were significantly higher at 22°C or 95% relative humidity (RH) than at 16°C and 35°C, or 45% and 70% RH. Such findings indicate that with global warming, changes in humidity could lower the overall efficacy of some herbicides.

In another example, Zhou et al. (2007) found that glyphosate efficacy was considerably reduced when applied on drought-stressed velvetleaf. Adding to this research, Mithila et al. (2008) showed that the lowered efficacy of glyphosate on velvetleaf and lambsquarters under low N was primarily due to reduced herbicide acclimatization to meristems. The authors argued that low N may reduce the net acclimatization of carbon in plants, which results in a reduction in the net transport of sugar molecules, and also glyphosate, taken up by the treated weeds. In their view, decreased glyphosate efficacy under low soil N in some weed species would explain why some weeds survived glyphosate treatments in field situations (Mithila et al., 2008).

Manea et al. (2011) also reported that glyphosate efficacy in controlling three out of four C_4 grass weeds - Rhodes grass (*Chloris gayana* Murb.), African love grass (*Eragrostis curvula* Schard.) and dallis grass (*Paspalum dilatatum* Poir) was significantly reduced under eCO_2. In contrast, smutgrass (*Sporobolus indicus* R. Br.) was well controlled by glyphosate under both ambient CO_2 and eCO_2. The authors suggested that glyphosate efficacy was equivalent to the number of plant tissue in which it has to act; i.e. a significant amount of biomass would dilute glyphosate within the plant, making it less effective. As a result, if the growth of some C_4 grasses is stimulated by eCO_2, they would resist glyphosate and increased glyphosate rates would be required for their control (Manea et al. (2011).

While some studies report that eCO_2 and elevated temperatures affect the growth of weeds, and reduce glyphosate efficacy, not all studies agree with such a finding. In one study, Marble et al. (2015) recorded that the growth of hard-to-control, globally important, C_4 sedges - purple nutsedge (*Cyperus rotundus* L.) and yellow nutsedge (*Cyperus esculentus* L.) increased under eCO_2 (608 ppm) compared with ambient CO_2 (405 ppm). However, at three weeks, a single application of glyphosate or halosulfuron, either alone or in mixtures, at recommended rates, controlled both sedges adequately, regardless of CO_2 concentration.

In our view, the results of the study (Marble et al., 2015) were influenced by the age of the treated plants, which were only four weeks old at the time of treatment. We concur with the authors that more mature plants or hardier nutsedge populations (possibly with greater numbers of underground tubers) may require more than one herbicide application, but these may not necessarily be higher glyphosate rates. Whether or not eCO_2 affected the translocation of glyphosate or halosulfuron to the tubers or roots of the sedges was not determined in the study, which was a limitation.

Table 3 A Summary of findings in climate change-related studies on the effects of eCO_2, temperature and other factors affecting glyphosate activity

Study	Significant findings of modified (reduced) activity	Probable reasons
Pline et al. (1999)	• Uptake and translocation of glyphosate to meristems was significantly higher at 35°C (HT) than at the lower 15°C temperatures (LT), indicating increased glyphosate injury to Roundup-Ready (RR) soybean at higher temperatures.	• Increased translocation out of leaves at HT.
Sharma and Singh (2001)	• Temperature and relative humidity (RH) both influenced glyphosate uptake and translocation by Florida beggarweed (*Desmodium tortuosum*), which was optimally controlled at 22°C and 95% RH.	• Increased uptake and translocation at higher temperatures and RH.
Ziska, Teasdale and Bunce (1999)	• Irrespective of CO_2 (ambient 360 ppm vs. elevated 720 ppm), the growth of redroot pigweed (*Amaranthus retroflexus*), a C_4 species, was significantly reduced by a lower glyphosate rate (0.112 kg ai ha^{-1}) and was fully killed by a higher rate (1.12 kg ai ha^{-1}). At eCO_2, the lower glyphosate rate had no effect on the growth of a C_3 species - lambsquarters (*Chenopodium album*), while the higher rate reduced its growth, but did not eliminate the weed.	• Increased biomass production and vigour resulting in possible dilution of the herbicide in tissues.
Ziska and Teasdale (2000).	• Sustained growth, photosynthesis and increased tolerance to glyphosate observed in a C_3 perennial weed, quackgrass (*Elytrigia repens*), grown at elevated carbon dioxide.	• Dilution of the herbicide in the large biomass and tissues.
Reddy (2000)	• Glyphosate control of the woody redvine (*Brunnichia ovata*), was greatly affected by post-treatment temperature. Uptake and translocation were highest in plants maintained at 35/30 ^{0}C (14/10 h, day/night) and were lowest in plants maintained at 25/20 ^{0}C. Translocation of glyphosate out of leaves continued up to 8 DAT.	• Increased translocation out of leaves at a higher temperature
Ziska, Faulkner and Lydon (2004)	• In Canada thistle, under eCO_2 (ambient + 350 ppm CO_2) both root and shoot biomass increased. Root growth was stimulated more strongly by eCO_2 than shoot growth. Reduced glyphosate efficacy at eCO_2 treatments was not due to differential herbicide uptake. Instead, tolerance was more a dilution effect, related to the large stimulation of roots, relative to shoot biomass, at eCO_2.	• Increased biomass production, resulting in dilution of the herbicide in tissues.
Zhou et al. (2007)	• Drought and flooding conditions lowered the efficacy of glyphosate on button weed due to the weed suffering from stressful conditions.	• Reduced uptake and translocation
Mithila et al. (2008)	• Reduced glyphosate efficacy on velvetleaf and lambsquarters, grown under low N, was a result of decreased herbicide translocation to meristems under N stress.	• Decreased translocation.
Manea et al. (2011)	• eCO_2 stimulated the biomass production of all four C_4 grasses tested. Under eCO_2, glyphosate control of smut grass (*Sporobolus indicus*) was unaffected. • But, the control of Rhodes grass (*Chloris gayana*), African love grass (*Eragrostis curvula*) and dallis grass (*Paspalum dilatum*) were significantly reduced.	• Dilution of g*lyphosate* in the larger biomasses of the grasses under eCO_2.
Marble et al. (2015)	• eCO_2 increased the growth and vigour of purple and yellow nutsedge shoot and underground growth. Glyphosate efficacy was, however, not affected.	• Increased uptake and translocation.
Zhang et al. (2015)	• Glyphosate-susceptible (GS) and glyphosate-resistant (GR) goosegrass (*Eleusine indica*) biotypes showed a differential response to eCO_2 (800 ppm) when compared with ambient CO_2 levels (400 ppm). • eCO_2 increased the glyphosate tolerance in the S biotype, but reduced the resistant level in the R biotype, due to reduced photosynthesis, and decreased carboxylation efficiency at eCO_2 levels compared with atmospheric CO_2 levels.	• Modified uptake and translocation.
Ganie et al. (2017)	• Glyphosate-resistant and glyphosate-susceptible common ragweed (*Ambrosia artemisifolia*) and giant ragweed (*Ambrosia trifida*) biotypes were both more effectively controlled by glyphosate at higher temperatures (HT, 29/17 ^{0}C d/n) compared with lower temperature (LT, 20/11 ^{0}C d/n). Glyphosate translocation was much higher at HT for common ragweed, while in giant ragweed, both uptake and translocation were significantly higher at HT compared with LT.	• Increased uptake and translocation.

Table 3 (continued)

Study	Significant findings of modified (reduced) activity	Probable reasons
Jabran and Doğan (2018)	• Growth, leaf and biomass production of cheatgrass, false barley and prickly lettuce increased under both eCO_2 and higher temperatures. All three species were well controlled by glyphosate at standard and double rates. • More than 80% control of plants grown under eCO_2 and higher temperatures was also achieved by lower glyphosate rates	• Modified uptake and translocation.
Bajwa et al. (2019)	• Growth and reproduction of parthenium increased under eCO_2, but its control by glyphosate was not affected by eCO_2. Herbicide injury developed more slowly at eCO_2 (700 ppm), compared to ambient (400 ppm), which showed that under eCO_2, glyphosate translocation was initially slow. However, the survival rate of treated plants was higher under eCO_2, compared with ambient CO_2 at recommended (0.8 kg a.i. ha^{-1}) and lower rates of glyphosate.	• Modified uptake and translocation.
Matzrafi et al. (2019)	• Glyphosate translocated quickly from leaves of Canadian fleabane and lambsquarters to shoot meristems and roots under eCO_2 [ambient 400 ppm vs. eCO_2 720 ppm], increased temperatures [18/12°C vs. 32/26°C], and the combination of both factors in both species. • The combined effects of both factors led to higher survival rates as compared to each factor alone. Early induction of reproduction and loss of apical dominance occurred in glyphosate-treated plants under high temperatures and eCO_2 levels.	• Modified translocation and tissue-specific sequestration, leading to decreased sensitivity.
Cowie et al. (2020)	• Parthenium growth was stimulated by eCO_2 (Plants grown under 600 and 800 ppm accumulated 23% and 55% more biomass compared to ambient CO_2). • Glyphosate treatments significantly reduced plant biomass (81%, 78% and 76% respectively, in the 400, 600 and 800 ppm treatments).	• Modified photosynthetic responses

The effects of eCO_2 stimulating the growth of shoot systems also lead to more resources being partitioned to underground parts of plants, such as taproots, tubers or rhizomes. Evidence of this effect was described in some early research. For example, in Canada thistle (*Cirsium arvense* L.), the stimulation of underground biomass (taproots) resulted in inadequate control of the weed by standard glyphosate rates (Patterson et al., 1999; Ziska et al., 2004). Ziska's early studies (2003a) showed growth stimulation of several weeds by eCO_2, and greater subterranean biomass production by Canada thistle (+72%) and spotted knapweed (*Centaurea maculosa* Lam.) (+60%). Despite species-specific responses, the consensus of these studies is that CO_2–induced increases in root or rhizome biomasses could make perennial weeds, particularly grasses, much harder to control under eCO_2.

Shaner et al. (2012) explained that glyphosate efficacy would be different in C_3 and C_4 weeds and pointed out that as a result of eCO_2 some C_3 weeds can evolve glyphosate-resistant more easily as compared to the C_4 weeds. Glyphosate-resistant populations of goosegrass (*Eleusine indica*), a C_4 grass, have been increasing in prominence in many tropical Asian countries and in parts of China (Chen et al., 2015). Studying these in China, Zhang and co-workers (2015) recorded a highly significant differential response in glyphosate-resistant (R) and glyphosate-susceptible (S) goosegrass biotypes to eCO_2 (800 ppm vs. ambient 400 ppm). Elevated CO_2 caused an 11% increase in glyphosate tolerance in the S biotypes but reduced the resistant level in the R biotypes by 60%.

Clearly, eCO_2 had a greater impact on the biochemical processes of the goosegrass R biotype, which were adversely affected by eCO_2 (lower photosynthetic performance, stomatal limitations and shoot biomass). Such effects resulted in the decline of their glyphosate tolerance and were largely explained by reduced photosynthesis and decreased carboxylation efficiency at high CO_2 levels compared with ambient CO_2 levels (Zhang et al., 2015).

Zhang et al.'s results, however, sharply contrasted with those of Manea et al. (2011) who had earlier recorded increased resistance to glyphosate in several, growth-stimulated C_4 grasses. Glyphosate resistance is likely to impart a considerable cost for resistant plants through several tolerance mechanisms. Reviewed elsewhere (Shaner, 2009; Roso and Vidal, 2010; Shaner et al., 2012; Salas et al., 2012). Sammons and Gaines, 2014; Fernando et al., 2016), the mechanisms of glyphosate tolerance include the following: (a) biochemical changes, such as increased EPSPS enzyme concentrations in different tissues; (b) unknown transport protein-related factors that may affect the critical phloem-loading step in tolerant plants; (c) reduced movement of the herbicide through the transpiration flow (in the xylem, after entering through the stem); (d) the inability of the herbicide to re-enter the phloem; (e) metabolic detoxification of glyphosate; (f) sequestration of glyphosate within chloroplasts and/or cells associated with phloem; and (g) enhanced production of EPSPS in some tissues and regions.

However, it is also clear that such physiological mechanisms of glyphosate tolerance may be modified by plant growth under eCO_2, warming and other climate change factors (such as moisture stress). The outcomes are largely uncertain, and generalizations are difficult to make with the current status of knowledge, except that some responses appear highly variable and could well be species-specific.

In our research, over two typically cool growing seasons (2013-2015) in Turkey (Jabran and Dogan, 2018), we studied the interactions of higher temperatures, eCO_2 and glyphosate on the growth and control of cheatgrass, false barley and prickly lettuce. Study treatments included: (1) ambient CO_2 (400-450 ppm) and temperature (20/10 ^{0}C day/night); (2) elevated temperature (25/15 ^{0}C day/night) + ambient CO_2; (3) eCO_2 (800-900 ppm) + ambient temperature and (4) eCO_2 + higher temperature. We found that eCO_2 and higher temperatures combined to consistently increase the total biomass and leaf area production of all three species, relative to ambient, control conditions. Growth stimulation by eCO_2 was stronger than any negative effect of higher temperature and also explained the increased growth under the combined conditions (Jabran and Dogan, 2018).

Different glyphosate rates provided somewhat variable control of the three weeds. The standard rate (1.44 kg a.i. ha^{-1}) and its double rate (2.88 kg a.i. ha^{-1}) completely and consistently controlled the weeds under all climatic conditions. The lower rates of 0.72 and 1.08 kg a.i. ha^{-1} also achieved >80% kill of all three weeds under all the climatic conditions, leading to our finding that eCO_2 did not change the efficacy of glyphosate (Jabran and Dogan, 2018)

Elevated CO_2 levels appear to clearly improve the growth and development of plants. The effects are likely to be caused by (a) improved photosynthetic rates, (b) reduced photorespiration, (c) increased water availability, through decreased cuticle thickness and lower stomatal numbers, and (d) improved source-to-sink transport, sink size and biomass production. However, higher temperature day/night regimes may adversely affect the growth rate of plants by having opposite effects, such as increasing evaporation, transpiration and metabolism rates.

Ganie et al. (2017) found that glyphosate resistance was sensitive to temperature in both susceptible and resistant biotypes of common ragweed (*Ambrosia artemisifolia* L.) and giant ragweed (*Ambrosia trifida* L.). All biotypes were well controlled by glyphosate as resistance decreased under higher temperatures (29/17 ^{0}C d/n) compared with lower temperatures (20/11 ^{0}C d/n). This finding led to the recommendation that glyphosate should be applied on warmer days in spring and mid-to-late afternoons in the growing seasons (Ganie et al., 2017).

Elevated temperature and eCO_2 levels both cause low sensitivity of many weeds to glyphosate, possibly due to low absorption and translocation rates (Matzrafi et al., 2019). Recently, Matzrafi et al. (2019) showed that the sensitivity of both Canadian fleabane (*Conyza canadensis* (L.) Cronquist. and common lambsquarters to glyphosate was much less under eCO_2, warmer conditions, and the combination of both factors. The higher temperature had a greater effect on plant survival than eCO_2 on both species. Moreover, the combination of elevated temperature and eCO_2 resulted in the loss of apical dominance and rapid necrosis in treated plants.

The reason for reduced glyphosate activity was the rapid translocation of the herbicide out of treated leaves to shoot meristems and roots in plants subjected to higher temperatures and eCO_2. This caused decreased sensitivity of the plants and reduced glyphosate efficacy, possibly due to altered herbicide translocation and/or tissue-specific sequestration. The authors suggested that over-reliance on glyphosate for weed control under changing climatic conditions may result in more weed control failures (Matzrafi et al., 2019).

In more recent studies, similar types of responses have been observed in other C_3 weeds, such as lambsquarters, thornapple (*Datura stramonium* L.), *C. arvense*, and parthenium (Bajwa et al., 2017; 2019). In recent research, Bajwa and co-workers (2019) showed that the growth and reproduction of parthenium increased under eCO_2, but its control by glyphosate after 21 DAT was not affected by the growing conditions under higher CO_2. Herbicide injury developed more slowly at eCO_2 (700 ppm), compared to ambient CO_2 (400 ppm), which showed that under eCO_2, glyphosate translocation was initially slow. The survival rate of treated plants was also higher under eCO_2, compared with ambient CO_2 at recommended (0.8 kg a.i. ha^{-1}) and lower rates of glyphosate.

In other recent studies, Cowie et al. (2020) confirmed that parthenium showed higher growth and reproduction rate under eCO_2. Compared to parthenium, grown under ambient CO_2 (400 ppm), plants at 600 and 800 ppm CO_2 produced 23.4% and 54.5% more biomass, respectively. Glyphosate treatment, however, dramatically declined plant biomass at all three CO_2 treatments 400, 600 and 800 ppm, by 81%, 78% and 76% respectively.

From the physiological point of view, glyphosate-treated plants showed a severe reduction in chlorophyll content (by >90%) and several photosynthetic efficiency parameters (i.e. maximum quantum efficiency; photon absorption and electron transport). However, these effects were slower to develop in plants cultivated under eCO_2. Low efficacy of glyphosate also occurred but only with plants grown under eCO_2 and this effect was mainly due to improved biomass production. The recovered parthenium plants also grew up to reproductive maturity and produced seeds, which leads to the possibility that under eCO_2 conditions, parthenium may become harder to control by glyphosate (Cowie et al., 2020).

Conclusions

Research on how climate change factors may affect glyphosate activity has produced some significantly mixed results. These have been hitherto explained based on differences in (a) plant growth – increased biomass production under eCO_2 and resource partitioning to underground parts, (b) changes in leaf morphologies, plus changes in cuticular and epicuticular waxes, affecting uptake by either leaves or stems; (c) translocation in the phloem and xylem, affected by physiological processes; (d) possible detoxification and/or sequestration of glyphosate in different tissues (largely in glyphosate-tolerant plants).

Photosynthetic responses of plants to eCO_2 and warming, as well as the interactions of plant growth and metabolism in the presence or absence of N fertilizers and or moisture deficits also complicate the results. Overall, we agree that the mechanisms by which glyphosate activity might be adversely affected by the rapidly changing climate factors are still unclear and may be ‘species-specific’, as has been previously suggested by Mithila et al. (2008).

Studies are yet to demonstrate whether higher temperatures would lower the viscosity and increase the permeability of cuticular and epicuticular lipids, thereby enhancing the foliar uptake of glyphosate or other herbicides through the cuticle.

Climate change components, especially eCO_2 levels, generally cause stomata to close and reduce stomatal conductance (a measure of stomatal opening, the rate of CO_2 entering, or water vapour exiting through stomata), while increasing leaf areas. As suggested by Ziska (2016) and Varanasi et al. (2016), a decline in stomatal conductance and a reduction in the demand for aromatic amino acids may also affect glyphosate activity after it has entered a plant. Their view is that declined protein levels produced in plant tissues under eCO_2 could directly reduce the efficiency of enzyme-inhibiting herbicides, including glyphosate.

Under climate change, the combined effects of eCO_2 and higher day/night temperature regimes are likely to increase the growth, biomass and vigour of many weeds in most situations. These effects could also affect herbicide efficiency either through reduced uptake rates of active ingredients or by increased biomass, which enables plants to better withstand the effects of the herbicide. In general, elevated temperatures alone may have either neutral, negative or slightly positive effects on the growth of weed species as they balance their physiological demands of water and nutrients required for growth against the stresses caused by higher temperatures. While individual plant responses will inevitably be constrained by the resources available to them (Mithila et al., 2008; Manea et al., 2011), they will be modified by other climate components.

Because of the predicted changes in plant physiology and morphology, the activity of foliar-applied herbicides, such as glyphosate, is likely to be modified. If the foliar uptake of glyphosate is decreased, under climate change, due to changes in cuticle thickness and permeability in leaves or other structures, it could result in reduced translocation and efficacy of glyphosate on weeds that are usually susceptible to glyphosate.

If climate change effects result in greatly enhanced biomass production and changes in resource allocation to shoots and roots or other subterranean parts in some weeds, such as both C_3 and C_4 grasses, it could lead to differential translocation of the herbicide to active sites. Dilution of the herbicide in larger biomasses could be a strong reason for the differential responses.

It is well-known that the combined effects of factors i.e., CO_2, soil moisture, sunlight, relative humidity and temperature can differentially impact the plant absorbance, translocation, metabolism and action of phloem-mobile herbicides, such as glyphosate. It is also clear that variations in soil N levels can impact plant growth and development, which in turn may have an effect on biochemical and physiological processes, such as the absorbance, translocation, and activity of herbicides. This is why it is essential to well understand the complex influences of eCO_2, global warming, and other influential and changing factors (such as N fertilization and moisture regimes), on the growth and herbicide tolerance of weeds (Chandrasena, 2009; Ziska and Dukes, 2011; Varanasi et al., 2016; Ziska, 2016; Ramesh et al., 2017; Jabran and Dogan, 2018).

In our view, supported by others (Duke and Powles, 2008; Benbrook, 2016; Heap and Duke, 2017), the extensive use of glyphosate is not likely to slow down but continue in the next decade or so in most countries. Given this glyphosate use trend and the current discourses on environmental risks associated with it, research must strive to better understand the factors that significantly influence glyphosate activity. As Kanissery et al. (2019) recently argued, research must focus on increasing understanding among glyphosate users about its careful utilization and this necessitates further studies to avoid, mitigate or eliminate the problems due to its overuse.

Our studies also have shown clearly that when plants can respond to eCO_2 with a higher growth rate and large, leafy biomass production, such effects can improve their tolerance of glyphosate and possibly other herbicides. This suggests that in a world with higher concentrations of CO_2, increased application rates of glyphosate might be required, which could have significant economic and environmental consequences. Nevertheless, our review, and those of others (Ziska and Dukes, 2011; Varanasi et al., 2016; Ziska, 2016; Ramesh et al., 2017), find that interactions among a range of factors operating in the field may have unpredictable effects on herbicide activity.

Available literature also indicates that the effects of climate change components can be highly variable, not only within groups of herbicides with the same mode of action but also varies with different modes of action Making a generalized statement about each mode of action continues to be difficult. More detailed studies on the effects of climate change components and their relations on all frequently used herbicides and their activity on selected, globally-important weedy taxa is essential to understand the consequences for future weed management under climate change scenarios.

Based on this review, more generally, we recommend further research to focus on the interaction of future climate factors on glyphosate activity on climate-hardened weedy plants and not juveniles (such as used by Cowie et al., 2020), and species representing major families and/or groups of weeds.

As Waryszak et al. (2018) recently suggested, the evidence from a spate of research on climate change factors affecting the activity of glyphosate and other herbicides needs that over-reliance on herbicides for controlling weeds needs a "*rethink*" under eCO_2 and associated changes. Although our own research found contrary evidence, the increased resistance of many species to glyphosate warrants further research regarding the effects of climate change variables on the herbicide's activity on target weeds and other factors that are known to affect its overall effectiveness.

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SHORT COMMUNICATION

Lantana (*Lantana camara* L.) biocontrol agents in Australia with possible options for India and Sri Lanka

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Abstract

The focus of this short article is the biocontrol agents of the globally-important species - lantana (*Lantana camara* L.), which was introduced as an ornamental plant during the 18th and 19th Centuries across continents. Lantana is now naturalized in most continents and causing problems in human-modified landscapes and is also spreading fast into conservation areas and forests. Currently, where it needs to be controlled, a variety of methods are available, which include manual, mechanical and chemical control, as well as fire. However, none of these methods, even when applied in combinations (integrated) have been sufficiently effective on a landscape level or can be sustainably applied to control large and dense infestations. It appears that future lantana management must be oriented towards re-investing in biocontrol simply because it is not feasible to control lantana over the long term using conventional methods. Numerous biocontrol agents have shown considerable promise but have not been well utilized in countries that have increased risks of further spread.

Efforts to manage lantana in Australia are still continuing, with a well-developed National framework, an integrated approach and investment in additional biocontrol agents. South-Asian countries, especially India and Sri Lanka, can certainly benefit from Australian experiences in lantana management and R&D investments in biological control. This is especially so since research on host specificity and the effectiveness of agents would have already been conducted. This would require that both countries, and also, possibly some African countries, re-appraise the risks of lantana and make an increased effort at biocontrol to manage those risks, especially in natural ecosystems and conservation areas, heavily disturbed by tourism activities.

Keywords: Lantana biocontrol agents, host specificity, invasive, *Teleonemia scrupulosa*, *Uroplata girardi*

Introduction

Lantana camara L. (Verbenaceae) is a globally-important weed found in over 80 countries or island groups. Lantana has the potential to significantly affect flora and fauna biodiversity, as well as have negative impacts on agriculture and the economy (Swarbrick, 1985; Swarbrick et al., 1995; DNRM&E, 2004; Gooden et al., 2009a; b).

Lantana's dual reproductive strategy of profuse seed production and extremely robust and vigorous vegetative reproduction contribute to its fast spread, regrowth and persistence at any infested site, year after year. Frugivorous birds and small mammals consume the berries and also spread lantana seeds over medium or long distances, making lantana difficult to control and presenting a significant dilemma to land managers (Gosper and Vivian-Smith, 2003; Buckley et al., 2006; Zalucki et al., 2007; Bhagwat et al., 2012; Kannan et al., 2013a, b).

Land-clearing for timber and farming combined with the construction of roads, railways and linear infrastructure (oil, gas and water pipelines, and powerlines) across large landscapes, were the main causes of the initial spread. Roads and facilities construction for tourism inside nature reserves, nursery trade, neglected properties and urban gardens also contribute greatly to lantana becoming further established in new areas (Day et al., 2003a;b; DNRM&E, 2004; Urban et al., 2011).

Dutch explorers introduced the plant into the Netherlands in the 1600s from Brazil (Stirton, 1977; Spies and du Plessis, 1987). It was then hybridized in glasshouses in Europe before its introduction to other countries as an ornamental. Subsequent hybridization has resulted in over 600 varieties or forms, During the colonial period, many aesthetically pleasing species, such as lantana, were transferred between colonies. These were seen as 'exotic novelties' (Kannan et al., 2013a; b). As a result, many former British colonies share similar issues with potentially 'invasive' ornamental plants brought in by colonial settlers. Collecting exotic plants for newly established public or private botanical gardens was a novelty within the colonies and was a well-remunerated occupation, promoted by plant acclimatisation societies (Janick, 2007).

Over the past two decades, research in Australia has demonstrated that large and continuous lantana stands, above a threshold of about 75% cover, would significantly modify the biological environment around the stands. Such large lantana stands significantly alter native species compositions of all growth forms around them. Fewer canopy trees occur among the heavily lantana-infested sites, which cause substantial changes in vegetation from tall open forests to low, lantana-dominated shrublands and open areas (Gooden et al., 2009a;b).

The spread of lantana in tropical and sub-tropical forests, agricultural landscapes, nature reserves and conservation areas, including biodiversity hotspots, has been of great concern, not just in Australia (Day et al., 2003a, b; Zalucki et al., 2007), but also in India (Sharma et al., 2005; Kannan et al., 2013; Singh and Singh, 2015), Sri Lanka (Sampson et al., 2018) and numerous African countries (Simelane et al., 2021). Therefore, a re-appraisal of available management options is timely.

Lantana: Management efforts

The key to good management of lantana is constant vigilance to prevent its spread into new areas. Repeated control of new regrowth is also critical to its long-term management success. Control of new infestations should be a priority because lantana can expand its range during good seasons but does not necessarily die out during poor conditions (Day et al., 2003a;b; Zalucki et al., 2007).

The Australian guidelines and experiences indicate that the 'golden rules' of lantana management should be (a) control infestations early but in stages; (b) prioritize infestations, based on site characteristics (size and distribution of infestations and feasibility of control), and (c) integrate suitable methods for each site, depending on accessibility and available resources (DNRM&E, 2004).

Lantana infestations can be controlled with herbicides, manual and mechanical means or by the use of fire, followed subsequently by the planting of competitive native species (DNRM&E, 2004). However, in many infested areas, the sheer size of the infestations makes these methods impractical. Mechanical grubbing, slashing and hand pulling are really only suitable for relatively small areas, while controlled fire and burning can only be used over large areas away from plantations or where other valuable species are growing.

The most commonly applied lantana control methods in developing countries are manual methods, combined with some forms of mechanical removal using backhoes, drag chains and tractors. Herbicide use for lantana management is uncommon in developing countries mainly because they are unaffordable for control treatments over very large tracts of infested lands. Although labour costs have been increasing steadily everywhere, compared with developed countries, there is still a greater availability of labour for hire in developing countries for tedious weed control work, such as those required for lantana management, especially in conservation areas.

Despite these well-established methods, their integration into programs that can successfully deliver on-ground control of lantana has been difficult everywhere. In many situations, manual, mechanical and chemical control methods are not feasible for full implementation and long-term management. Lantana infestations, growing on steep hillsides or along creeks, are often inaccessible for herbicide treatment or mechanical removal, and fire is not an option in some native forests or in orchards or plantation forests (Day et al., 2003a; b). Therefore, in many situations where lantana is a problem, biological control options are the only viable long-term solution to its management.

Lantana: Biological control agents

Biocontrol efforts to manage lantana started in 1902 in Hawai'i, with research later conducted in Australia (Day et al., 2003a; b; Zalucki et al., 2007; Day and Zalucki, 2009; Day 2012) and South Africa (Urban et al., 2011; Simelane et al., 2021). Since then, 44 agents have been deliberately released in 33 countries, with 28 agents getting established in at least one country. However, through the natural spread, biological control agents for lantana are now found in 65 countries worldwide (Winston et al., 2014). Despite intense efforts in many countries, biocontrol of lantana has only ever been partially successful, and the weed is presently not adequately controlled anywhere where it had been introduced in the past (Zalucki et al., 2007; Winston et al., 2014).

Lantana biocontrol agents in Australia

Since 1914, 29 insect species and one pathogen have been tested for their specificity and then introduced in Australia. Twenty of those biocontrol agents established; however, these releases have had only limited success (Day et al., 2003a; Day, 2012; Winston et al., 2014). Biocontrol agents have in many cases, at least seasonally, decreased the volume of individual plants, making other control methods considerably easier.

One of the main reasons for lantana's weediness and for the limited success of biocontrol is the capacity for hybridization between varieties of *Lantana camara* and closely related species in the genus (Spies and du Plessis, 1987; Simelane et al., 2021; Lu-Irving et al., 2022;). Lantana's origin as a hybrid ornamental plant complicates the search for its centre of origin and thus, the searches for potential agents. Agents collected from similar lantana species or varieties to those lantana varieties in the target countries, or that have a broad host range, have been more successful at establishing (Day et al., 2003a, b). Another reason for limited control is that lantana can be found in a wide range of climatic regions, often occurring where biocontrol agents are not adapted (Day et al., 2003a, b).

Field surveys for potential biocontrol agents have been conducted in Mexico, Central America, the Caribbean, and Brazil, and agents have been collected from several different lantana species. These agents have been host-tested and released in Hawaii, South Africa, Australia, several countries in east Africa, south and east Asia, and the Pacific (Winston et al., 2014). The most important and damaging agents in Australia are given in **Table 1**.

The lantana lace bug - *Teleonemia scrupulosa* (Stål.) (Figure 1), the leaf-mining beetles - *Uroplata girardi* (Pic.) (Figure 2) and *Octotoma scabripennis* (Guérin-Méneville) (Figure 3) are all widespread and damaging biocontrol agents. These agents have contributed to the partial control of lantana in many regions of Australia. They should be a high priority for release in countries initiating or enhancing biocontrol of lantana (Day et al., 2003 a; b).

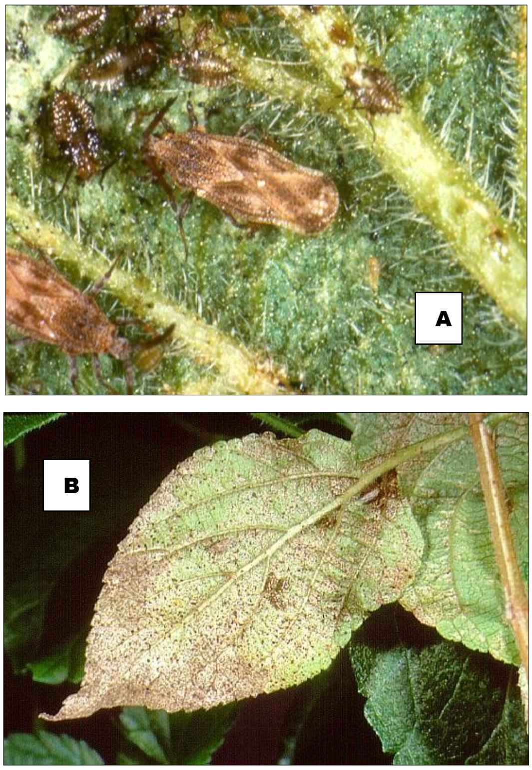

Figure 1 (A) Lantana lace bug- *Teleonemia scrupulosa* (B) Leaf damage caused by *T. scrupulosa*

Figure 2 (A) Lantana leaf-mining beetle *Uroplata girardi* (B) Leaf damage caused by *U. girardi*

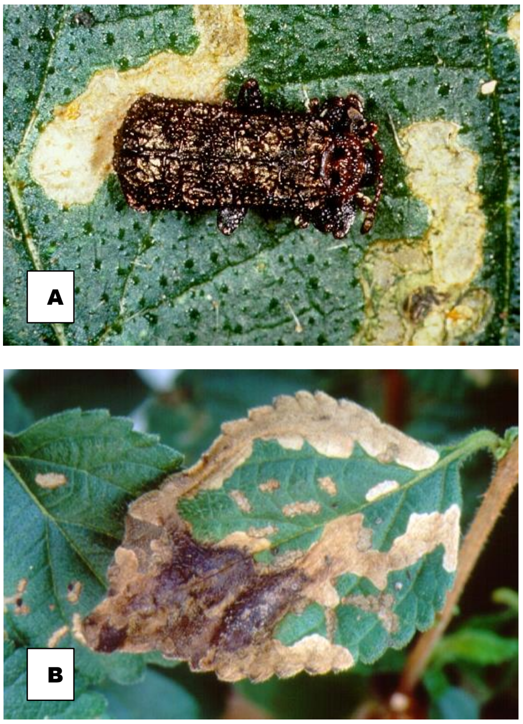

Figure 3 (A) Leaf mining beetle *Octotoma scabripennis* (B) Leaf damage caused by Octotoma scabripennis

Other damaging lantana biocontrol agents in Australia, include the gall-forming bud mite - *Aceria lantanae* (Cook) (Figure 4), the leaf-mining flies - *Calycomyza lantanae* (Frick) and *Ophiomyia camarae* Spencer, a defoliator moth - *Hypena laceratalis* (Walker) and the pathogenic rust - *Prospodium tuberculatum* (Speg.) Arthur.

Figure 4. Damage caused by the lantana flower gall mite, *Aceria lantanae*

Although these agents do not fully control lantana, they may make valuable contributions in countries and regions where few other biocontrol agents are currently present (Day et al., 2003 a; b).

Table 1 A summary of the main lantana biocontrol agents in Australia *

Agent Family	Agent Scientific Name	Agent Origin	First Released	Province/Area Released	Established?	General Impact
Agromyzidae	*Calycomyza lantanae*	Trinidad	1974	NSW, Qld	Yes	Variable
Agromyzidae	*Ophiomyia camarae*	USA	2007	Qld	Yes	Variable
Agromyzidae	*Ophiomyia lantanae*	Mexico	1914	NSW, Qld	Yes	Slight
Chrysomelidae	*Octotoma scabripennis*	Mexico	1966	NSW, Qld	Yes	Moderate-high
Chrysomelidae	*Uroplata girardi*	Brazil	1966	NSW, Qld	Yes	Moderate-high
Erebidae	*Hypena laceratalis*	Kenya	1965	NSW, Qld	Yes	Slight-moderate
Eriophyidae	*Aceria lantanae*	USA	2012	NSW, Qld	Yes	Variable
Miridae	*Falconia intermedia*	Jamaica	2000	Qld	Yes	Variable
Pucciniaceae	*Prospodium tuberculatum*	Brazil	2001	NSW, Qld	Yes	Variable
Tingidae	*Teleonemia scrupulosa*	Mexico	1936	NSW, Qld	Yes	Moderate-high
Tortricidae	*Crocidosema lantana*	Mexico	1914	NSW, Qld	Yes	Slight

* Source: Winston et al., 2014

Lantana biocontrol agents in India and Sri Lanka – An update

Biocontrol of lantana in India was first attempted in 1921 when the seed fly *Ophiomyia lantanae* was introduced. Since then, five other agents have been deliberately introduced. Four of these agents have been established. Six other agents have spread naturally into the country (Table 2). Sri Lanka has never deliberately introduced a biocontrol agent for lantana, but five agents have been reported to have spread into the country and established (Table 3).

Unfortunately, detailed studies on their distribution and impact on lantana in either country have not been undertaken (Winston et al., 2014). However, lantana remains a significant weed in both countries and additional biocontrol agents that have been reported to be damaging in other countries could be introduced if either or both countries were amenable to biocontrol (Tables 4 & 5). These agents have been tested for specificity before release and are now causing variable to high impacts on lantana in other countries such as Australia, South Africa and Hawai'i where they have been established (Day, 2012; Winston et al., 2014; Simelane et al., 2021).

Table 2 The status of lantana biocontrol agents in India *

Agent Family	Agent Scientific Name	Agent Origin	First Released	Province Released	Established?	General Impact
Introduced						
Agromyzidae	*Ophiomyia lantanae*	Mexico	1921	KA	Yes	Unknown
Chrysomelidae	*Octotoma scabripennis*	Mexico	1972	UP, MP	Yes, UP, MP	Unknown
Chrysomelidae	*Uroplata girardi*	Brazil	1972	UP, MP	Yes, UP, MP	Unknown
Crambidae	*Salbia haemorrhoidalis*	Trinidad	1971	-	No	Not Established
Noctuidae	*Diastema tigris*	Trinidad	1971	-	No	Not Established
Ortheziidae	*Orthezia insignis*	Mexico	1921	KA	Yes	Unknown
Naturally Occurring						
Agromyzidae	*Calycomyza lantanae*	Mexico	2018	Yes	Unknown	Unknown
Agromyzidae	*Ophiomyia lantanae*	Mexico	1921	Yes	None	None
Erebidae	*Hypena laceratalis*	Kenya	2018	Yes	Unknown	Unknown
Ortheziidae	*Orthezia insignis*	Unknown	1915	Yes	None	None
Pterophoridae	*Lantanophaga pusillidactyla*	Mexico	1919	Yes	Unknown	Slight
Tingidae	*Teleonemia scrupulosa*	Mexico	1941	Yes	Countrywide	Slight
Tortricidae	*Crocidosema lantana*	Mexico	1986	Yes	KA, TN	None

Source: Winston et al., 2014; UP (Uttar Pradesh); MP (Madya Pradesh); KA (Karnataka); TN (Tamil Nadu)

Table 3 The status of lantana biocontrol agents naturally occurring in Sri Lanka

Agent Family	Agent Scientific Name	Agent Origin	Date 1st Recorded	Established	General Impact
Agromyzidae	*Calycomyza lantanae*	Mexico	2013	Yes	Unknown
Agromyzidae	*Ophiomyia lantanae*	Mexico	1933	Yes	Unknown
Ortheziidae	*Orthezia insignis*	Unknown	1893	Yes	Heavy
Pterophoridae	*Lantanophaga pusillidactyla*	Mexico	1920	Yes	Unknown
Tingidae	*Teleonemia scrupulosa*	Mexico	2013	Yes	Unknown

Table 4 Effective lantana biocontrol agents that could be introduced into India

Agent Family	Agent Scientific Name	No. of countries where the agent is present	Impacts Elsewhere	Notes (presence or absence in Asia)
Acari	*Aceria lantanae*	7	Variable to high	Not present in Asia; Shows preferences for some lantana forms over others
Agromyzidae	*Ophiomyia camarae*	14	Variable to high	Not present in Asia; Causes defoliation in the tropics
Miridae	*Falconia intermedia*	2	Medium to high	Not present in Asia; Shows preferences for some lantana forms over others
Tephritidae	*Eutreta xanthochaeta*	1	Variable to high	Not present in Asia; Prefers drier areas.

Source: Winston et al., 2014

Table 3 Effective lantana biocontrol agents that could be introduced into Sri Lanka

Agent Family	Agent Scientific Name	No. of countries where the agent is present	Impacts Elsewhere	Notes (presence or absence in Asia)
Acari	*Aceria lantanae*	7	Variable to high	Not present in Asia; Shows preferences for some lantana forms over others
Agromyzidae	*Ophiomyia camarae*	14	Variable to high	Not present in Asia; Causes defoliation in the tropics
Chrysomelidae	*Octotoma scabripennis*	7	Variable to high	Present in India; Causes widespread defoliation
Chrysomelidae	*Uroplata girardi*	24	Variable to high	Present in India and the Philippines; it causes widespread defoliation
Miridae	*Falconia intermedia*	2	Medium to high	Not present in Asia; Shows preferences for some lantana forms over others
Tephritidae	*Eutreta xanthochaeta*	1	Variable to high	Not present in Asia; Prefers the drier areas

Source: Winston et al., 2014

What Can be Done about Lantana Infestations?

The interest in lantana management in India has been steadily increasing, which indicates that infestations are spreading across many regions and provinces (Sharma et al., 2005; Kannan et al., 2013a, b; 2016; Singh and Singh, 2015). The evidence in India is that relatively small infestations may be easily controlled and removed with manual and mechanical means. However, it is almost impossible to eradicate large infestations, which are decades old and deeply entrenched in forests and mountainous areas with steep slopes. Nevertheless, the general feeling among forest managers and volunteers working on lantana control in India is that long-term planning and community involvement (Kannan et al., 2016; ATREE, 2020) are critical to ensure that further spread is reasonably contained.

Developing management strategies for a highly robust, successful and naturalized species, such as lantana, is quite challenging. In managing lantana in high-value conservation areas, biodiversity hotspots and National Parks, such as in India, Sri Lanka and Australia, the clear benefit is the reduction of further spread, which then allows native species, including grasses, to regenerate. However, these benefits must be weighed and balanced with the costs involved, including the environmental risks (i.e. creating more disturbances) and other risks of conducting control programs to humans, other animals and plants.

In Sri Lanka, lantana infests many urban and rural areas and has been listed as a weed of national significance (Marambe and Wijesundera, 2021). In the last two decades, disturbances caused by the construction of roads and infrastructure, and tourism-oriented facilities, have allowed lantana to establish in national parks and conservation areas on a scale previously not recorded (Sampson et al., 2018). Haphazard lantana control interventions in nature reserves pose a risk of harm to both humans and animals, such as wild elephants and wild buffaloes. To intervene in lantana control or not is a delicate balancing act. Unfortunately, tourism revenue is essential in many developing countries.

A long-term vision and planning are required for many sites, such as the *Udawalave National Park*, in Sri Lanka, where, as noted by Sampson et al. (2018), the Asian elephant density and grazing pressures from other animals, such as buffaloes, are high. At such sites, if the spread can be effectively monitored and mapped, even a 'wait-and-see' approach of no active management intervention might be appropriate, instead of aggressive mechanical or manual control at the risk to animals and weed control staff. In South India too, a precautionary approach may be required in some National Parks, such as tiger reserves, based on understanding the 'site-specific' characteristics of infested areas, and adequate monitoring of lantana spread.

In any such lantana management project, attempts must focus on mitigating the primary causal factors of spread (for instance, disturbances caused by road construction, tourist traffic and facilities etc.). In these ecologically sensitive areas, biological control can play an integral part in managing weeds, as biocontrol agents are specific and attack only the target species. Biological control also works over time, so there is little degradation of landscapes. A re-appraisal of the existing biological control agents and exploring the potential of those that are likely to succeed under Indian and Sri Lankan conditions is highly desirable going forward, to reduce the risks of further spread and impacts of lantana.

Learnings from Australia and elsewhere

Managing lantana in Sri Lanka and India will always be challenging. In both countries, lantana control in specific situations, at specific sites, should only be undertaken with due consideration for the harmful effects of taking action vs no action.

Where control of small infestations or eradication are needed, some degree of herbicide use and physical removal will have to be employed with suitable safeguards. However, to manage lantana across the landscape, biological control utilizing host-specific and effective agents is the most cost-effective and sustainable method.

Mandatory property inspections, increasing the awareness of local communities and stakeholders of (invasion) pathways and taking consistent control action, where possible, with local and regional collaboration across boundaries, are key components of lantana management strategies.

Reactive management is common even in Australia, which boasts well-developed weed management approaches, policies and systems. Proactive monitoring and management over large landscapes are not very common and should be an essential part of the attempt to reduce the spread of species, such as lantana in any country.

The Australian experiences of successful lantana management have the following essential elements: (a) Collaboration across jurisdictional borders (i.e. States and Territories) via a declaration of lantana as a 'Weed of National Significance' (WONs), making the selling, moving and propagation of lantana illegal, and a Nationally-recognized *Lantana Management Plan* (DNRM&E, 2004); (b) Education and awareness training for weed managers and other land managers; (c) Keeping the public informed through effective communications (Newsletters, magazine and newspaper articles); and (d) coordination of actions via stakeholder engagement. This includes, for instance, convincing dialogues with Government Departments, corporations, industry and private landowners on the 'duty of care' (legislative requirements) and also the benefits vs. costs of managing lantana on their lands. Finally, as part of active management across landscapes, biological control forms an integral part of control programmes. This is evident in the 30 biocontrol agents deliberately introduced into Australia, since 1914.

Management of expanding lantana infestations needs to be mostly site-specific, especially within large, infested areas affecting biodiversity hotspots, national parks, wildlife corridors, infrastructure corridors (water and gas pipelines, roads and railways) or urban bushlands that are open for further infestations. Actions need to be taken even down to specific, property-level infestations. The 'containment zones' and site prioritization approaches, well developed and applied in Australia (Grice et al., 2010), should be applicable in any country that needs to take lantana management action.

Communications, policies, local government involvement, Public involvement and outreach, funding etc are all elements that would ensure success with a species, such as lantana. It goes without saying that funding available from governments, and industry is always finite and there is a limit to the time and efforts of individuals who volunteer their time for managing weeds in urban bushlands.

As a result, especially with species such as lantana, funds and effort need to be spent on weed management activities that result in the most positive outcomes for (a) biodiversity benefits; (b) management of assets and amenities that the public use, and (c) for protecting underlying ecological systems we all rely upon. Demonstrating the effectiveness of control activities and positive outcomes of well-coordinated programs ensures continuous funding from funding sources, including stakeholder agencies (such as road and railway authorities and water corporations), industry and private landholders, as well as governments.

In conclusion, it can be said that with the continual decline in resources, it is imperative that each country develops strategic approaches to weed management. This would include determining country priorities, monitoring the effectiveness of weed control action and also being flexible in approaches (i.e. adaptive management). Rather than just taking control action per se for its own sake, an outcome-orientated approach is critical for managing species, such as lantana, especially within large and infested conservation areas. The prevention of further spread with a multi-faceted approach is essential to contain lantana and to do so, biocontrol agents are critical.

In Australia, biocontrol is widely accepted as a useful tool to manage many weeds. However, biological control is not widely accepted or practised in either India or Sri Lanka. Landholders and governments do not have the means to control lantana and many other widespread weeds, leading to many weedy species increasing their spread and distribution with increasing impacts on biodiversity and agricultural practices. Therefore, biological control could be a highly useful and cost-effective tool to manage lantana and other important and widespread weeds in India and Sri Lanka.

To ensure that lantana management delivers conservation outcomes and does not add further conflicts, data and information on other species at risk, including plants, animals and humans) also need to be incorporated into biological control and long-term management programmes. To achieve a favourable outcome, there will be a range of challenges at each infested site and trade-offs that may need to occur. The critical issue in making decisions about trade-offs is: what would be the consequences of taking control action or no control versus the associated risks.

Australian experiences show that lantana eradication is more likely to be successful if the infested area is small, perhaps less than 100 hectares. Therefore, it is important to detect any new lantana infestations early in their spread as it can make the critical difference between eradication being feasible and the need to resort to less effective control methods. Distribution and mapping have been poor in almost all countries, as a result of which lantana has become entrenched.

Apart from India and Sri Lanka, there are many other countries where lantana is a significant problem, yet there are very few or no biocontrol agents present. These countries could also benefit from introducing other host-specific and effective biocontrol agents to help manage lantana.

Furthermore, 27 countries are deemed climatically suitable to support lantana yet are reported to not contain the weed. It is recommended that these countries do not allow its importation, even of so-called horticultural varieties that are 'claimed' to be sterile (Day et al., 2003a; b; Zalucki et al., 2007).

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