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).

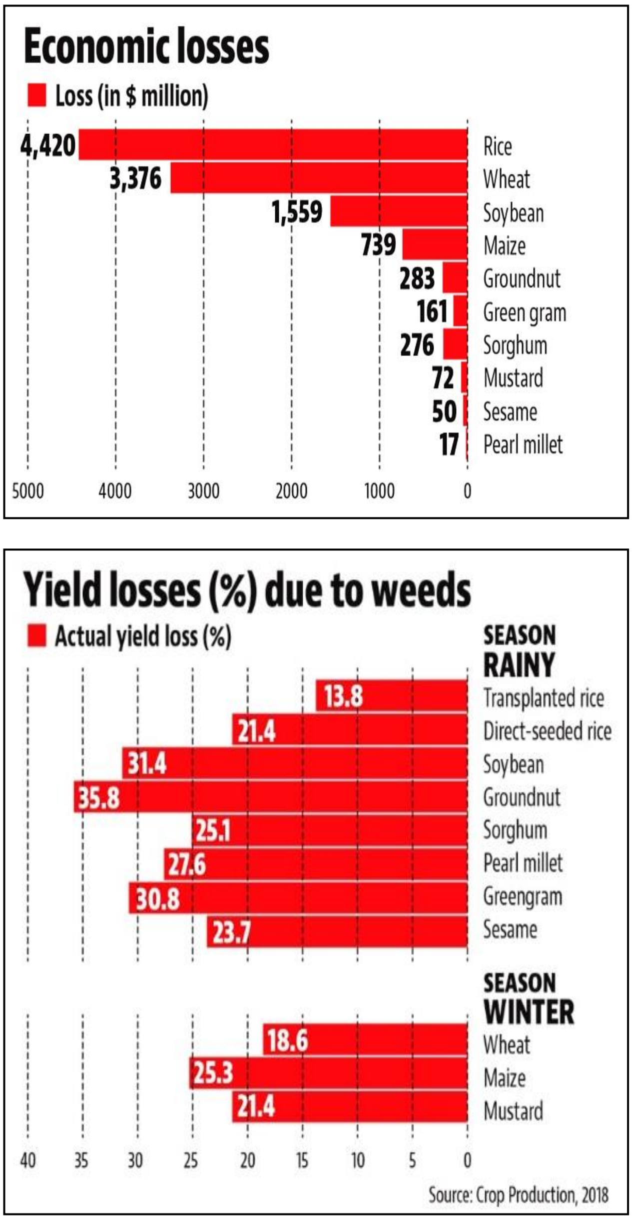

Figure 1 Losses caused by weeds vary with the crop, season and location in India (Source: Gharde et al. 2018)

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).

[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	↑[CO2]	↑Temp	↑H2O	↓H2O
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.

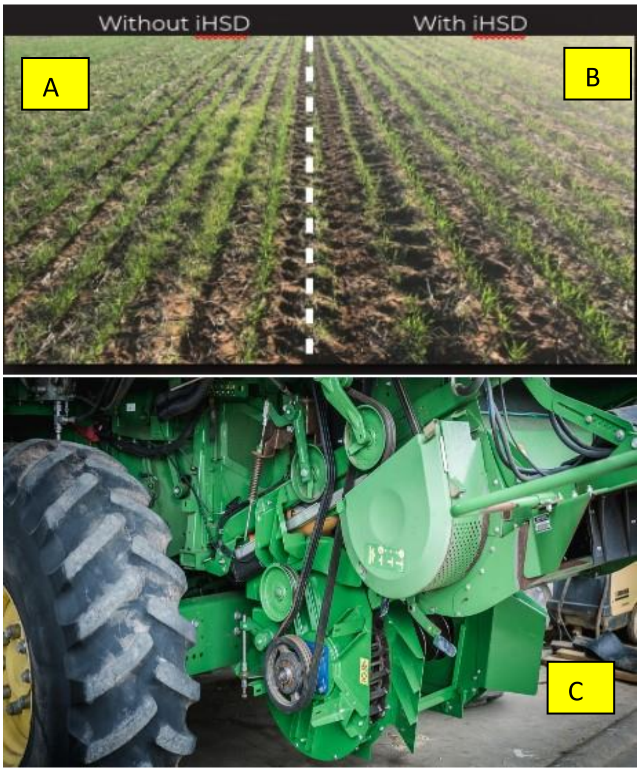

Figure 10 An Australian wheat field harvested without (A) and with (B) the use of a (C) HSD attachment to the Harvesting Machine. Note the significantly reduced weed population that developed in the field, after the HSD (https://ihsd.com/)

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.

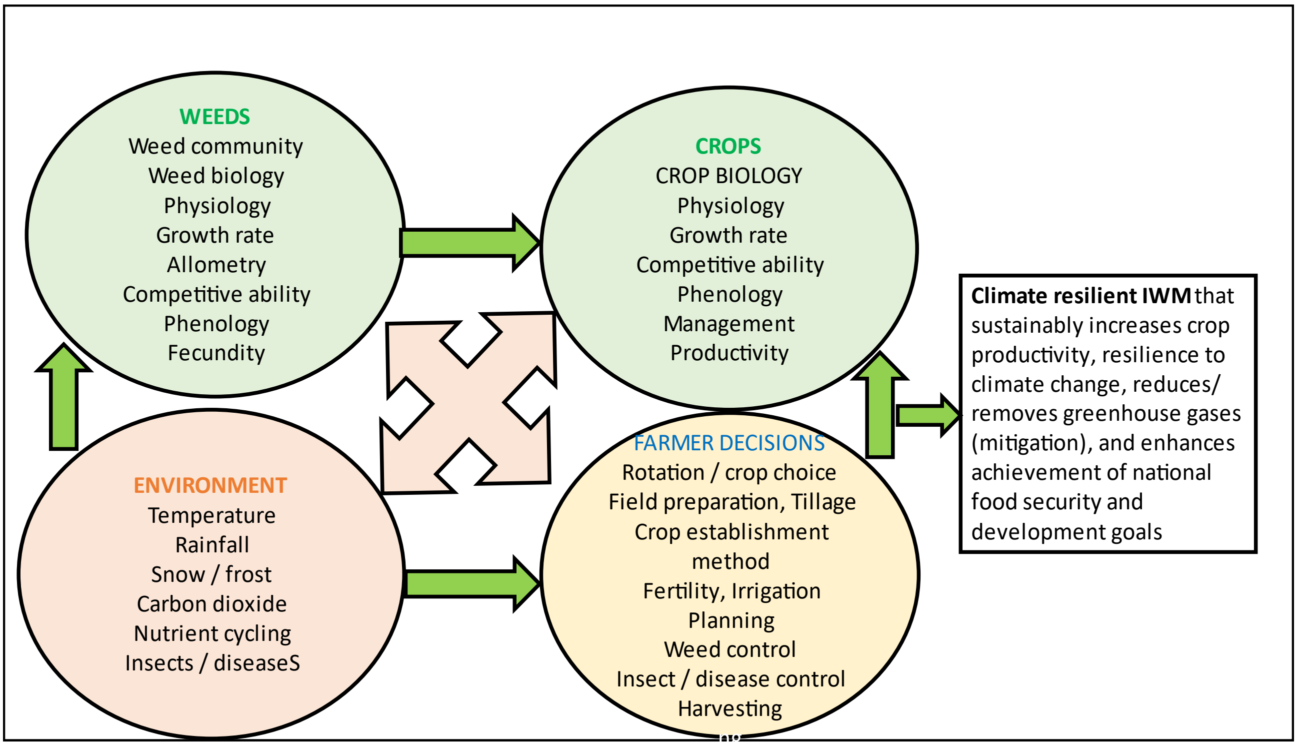

Figure 11 Crop-weed-environment interactions in agri-food systems will help in location-specific components of climate-resilient integrated weed management

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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