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REVIEW ARTICLE

The future of weed science

Robert L. Zimdahl

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ABSTRACT

Agricultural scientists, farmers, ranchers, and the agriculture industry remain confident of their basic faith in the possibility of continued increasing production through intelligent use of ever more efficient agricultural technology and research. Increasing production has been and remains the accepted way to achieve the moral obligation of feeding a growing population. Therefore, the weed management scenario has become one of the important factors. This brief essay questions if agriculture's moral justification will hold as widespread, rational scientific and moral arguments about human and environmental harm, public fear of technology, and concern about food quality dominate.

Keywords: Ecology, Education, Ethics, Evidence, Faculty, Facts, Future, Goals, Herbicides, History, Island empire, Management, Opposition, Paradigm, Pesticides, Production, Public health, Questions, Sustainability, Teaching, Technology, Risk, Values, Weed.

INTRODUCTION

We can, of course, be deceived in many ways.
We can be deceived by believing what is not
true; but we certainly are also deceived by not
believing what is true.
Kierkegaard - Works of Love.

I have chosen to begin with a topic clearly related to climate change and weed management that will affect weed science's future and global food security. My topic - agricultural ethics1 is a philosophical reflection on the future of weed science and agriculture, It is a challenge to you. Comments on weed science research and technology will follow (Section III).

AGRICULTURAL ETHICS

Universities routinely include ethical study in the curriculum for medicine, law, business, and the environment. Agriculture, the essential human activity and the most widespread human interaction with the environment does not. The agricultural science curriculum lacks consideration and study of the effects of agriculture on society and the environment. Ethics has not been institutionalized in Colleges of Agriculture, agricultural professional organizations, or the agribusiness industry. That is not to say there are no professional ethical standards.

Many assume agriculture has an adequate ethical foundation. The assumption is not questioned. There has been too little investigation and too little critical thinking about the lack of and need for an ethical foundation.

Agriculture has scientific challenges: achieving sustainability, maintaining production, pesticide and antibiotic resistance, invasive species, loss of biodiversity, biotech/GMOs, and pollution. Those involved in agriculture believe development and use of more energy dependent technology is always good and more will be better. It will address the need for production, address the problems caused by the unintended consequences of present technology, and alleviate public concern.

I do not mean to imply that we should abandon science and technology. We humans, the earth's dominant species, are not just figures in the landscape — we are shapers of the landscape (Bronowski 1973, p.19). Having achieved this power, we should think carefully about whether what we do is desirable. Although all involved in agriculture know what they are doing they should think about what they may be undoing.

The moral imperative is to produce food and fiber to benefit all humanity. Production is what must be sustained. Agricultures producers, suppliers, and researchers regardless of their employer should ask if

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production is a sufficient criterion for judging the consequences of all agricultural activities. Does increasing production justify everything agriculture does? Does it achieve sustainable production practices? Does the quest to increase production solve or even address agriculture's moral dilemmas?

Agricultural scientists have assumed that as long as their research and the resultant technology increased food production and availability, they and the end users were somehow exempt from negotiating the moral bargain that is the foundation of the modern democratic state (Thompson 1989). It is unquestionably a moral good to feed people. Therefore, it is assumed, anyone who questions agriculture's morality or the results of its technology simply doesn't understand the importance of what is done and how it is done. It is assumed that agricultural practitioners are technically capable and that the good results of their technology will make them morally astute.

When those involved in agriculture claim credit for improving production and keeping food cost low, they must also accept society's right to hold them responsible for problems often regarded as externalities. They need to ask and be prepared to respond to what has not been asked often enough. What could go wrong? What has gone wrong? What are the appropriate responses?

We live in a post–industrial, information age society. No one will ever live in a post-agricultural society. Continuing to justify all agricultural activities and technology by the necessity of achieving the moral obligation and production challenge of feeding a growing world population has not been and will not be a sufficient defense for agriculture's negative environmental and human effects. We are disturbing and changing the climate and our planet's ecosystems at a pace and scope never seen in human history (Friedman 2016).

What is the problem? Feeding the 11 billion expected to be on the planet at the end of this century is undeniably a good thing. Is it a production problem? Of course it is. But enough food is produced now to feed the global population3. Nevertheless about 810+ million people still go hungry every day. After steadily declining for a decade, world hunger is on the rise, affecting 1 of 9 of the world's people. From 2019 to 2020, the number of undernourished people grew by 150 million, a crisis driven largely by conflict, climate change, and the COVID-19 pandemic. In spite of the abundance of food, people are hungry because of inadequate food distribution, inadequate infrastructure that delays or prevents food distribution, food storage waste, waste by consumers, government policies, and poverty.

More production will not solve the hunger problem (Sen 1999).

It is obvious citizens of democratic societies are becoming increasingly reluctant to entrust their water, their diets, and their natural resources blindly into the hands of farmers, agribusiness firms, and agricultural scientists. Ethicists and agricultural practitioners must initiate and participate in a dialog that leads to social consensus about the effects of agriculture's technology, its risks, and reasonable solutions. In the past most risk was borne by users of the technology. Now there is widespread concern the risks and short- and long-term consequences of agricultural technology are borne by others. Agriculturalists must begin to contribute the time and resources needed to listen and explain their positions and understand those of their fellow citizens. All involved in agriculture and those who enjoy abundant societies must recognize they are dealing with how we ought to live.

Agriculture practice, research, and teaching involves scientific and ethical values. Feeding the growing world population is clearly a very good thing, but it does not absolve the agricultural community from critical, ethical examination of the totality of agriculture's effects.

People throughout the world have rational concerns about the ethical dimensions of agriculture and our food system that go beyond the central need to feed humanity. Each of agriculture's multiple responsibilities includes an ethical dimension (achieving sustainability, resolving pollution of water, soil, and humans, harming other species and cruelty to animals, stopping habitat destruction. Assuring availability of surface and ground water, stopping exploitation and inhumane treatment of farm labor, stopping loss of small farms and rural communities, considering the power of corporate farming and its lack of transparency, stopping harmful treatment of animals, addressing public concern about botechnology/GMOs, Stopping loss of crop genetic diversity, and addressing public concern about the nutritional value of foods provided by the food system.

These are not just scientific problems. We should not expect scientists alone to solve them. Leaders of the agricultural enterprise should work together with others to identify, discuss, and address them. Collective action is required to achieve morally good goals. Agriculture will gain little if it wins the production battle and loses the moral battle.

Agricultural education has given too much emphasis to what to think rather than how to think. Universities have traditionally been places where different opinions were welcomed and encouraged. The present trend toward specifying what controversial topics may or may not be welcome is disturbing. It stands in sharp contrast to the role of teaching - to lead out - to educate. Encouraging students and the general public to be aware of and discuss difficult controversial issues is an important role of education and those who teach.

There are 113 universities in the world with agricultural faculties. Forty US universities and only 7% of all other universities that offer agriculture education have departments of weed science (Ahmad *et al.* 2023). Only six US universities have a course on agricultural ethics. The worldwide agricultural curriculum lacks courses that focus on general ethical principles and their application to agricultural issues.

It is my view the lack of university courses on agricultural ethics in the United States is because the faculty who teach, plan the curriculum, and advise undergraduate and graduate students do not regard studying the ethical values of agriculture as important preparation for agricultural professionals. When I was a student, I was never advised to enroll in a class in philosophy, and I assumed that my professors and their mentors were not advised. Present faculty are not interested in or do not care to cooperate with a colleague in the Department of philosophy to create a class on agricultural ethics and encourage students to enroll.

Such classes will be a recognition of the need to acknowledge and discuss agriculture's ethical dimensions. Agriculture has (Zimdahl and Holtzer 2016) problems which have focused attention on production and profit while education and practice have ignored agriculture's human and ethical dilemmas (Damasio 1994).

Professors, Department heads, and Deans of Colleges of Agriculture who have not chosen to address agriculture's ethical dilemmas are contributing to the problems. There is a clash between the environmental and human harm of modern, agricultural production and the values held by the general society and those who practice agriculture. Ignoring value conflicts and societal concerns will lead to a loss of public support and trust in agriculture.

Our technology may outweigh our character. We hold at the level of our training - our education. We risk becoming moral people in an immoral profession (Niebhur 1932). "He who knows only his side of the case knows little of that"Mill 1859). We must begin to interact and listen to people who don't share our beliefs and who confront us with evidence and counter arguments (Haidt 2022).

What we resist pursues us. What we accept transforms us. We are a mass audience consuming the same content while looking in a mirror reflecting the view we have (Haidt 2022). My experience has shown students may be more willing than the faculty to question and explore outside the agricultural curriculum

When the morally good goal of feeding a growing world population bumps up against the morally good goal of protecting the environment one is confronted with value questions that science is not designed to and cannot answer. When the environment's natural objects are valued only in terms of their worth to humans they can be and are legally destroyed or modified.

I offer a few examples of what we have and are doing. We cut down original forests, till the prairies, irrigate deserts, dam and pollute streams, overgraze hillsides, flood the valleys, and prevent forest fires. We have changed the climate and acidified the oceans. Little, if any, attention is paid to the inevitable environmental consequences: ocean hypoxic areas, soil erosion, melting ice, species extinction, invasive species. Our predatory self-interest dominates our environmental concern. Kolbert (2022) correctly noted - It seems normal to send in the bulldozers, chainsaws, and backhoes to cut down the trees, fill the wetlands, and "develop" the land.

Until something or someone receives a right granted by law or public pressure we often see the environment as something for our use. The objection that streams and forests cannot speak has been addressed. Neither corporations, States, estates, infants, incompetents, municipalities nor universities can speak. These entities are amply represented — some might say over represented — in the courts. We make decisions on the behalf of and in the purported interest of others every day. The other creatures (eg. soil microroganisms, pollinating insects) whose wants are far less verifiable may be more important. They are more metaphysical (the fundamental nature of reality) in conception than the wants of rivers, rocks, (Nash 1977), Trees (Stone 1972) and the human benefits from and obligation to them.

Is it possible for human intelligence to increase the range of benevolent impulses and encourage us to consider the needs and rights of other humans in addition to the things to which we are bound by organic and physical relationships? Can we transcend our own interest to grant rights to the interests of our fellow humans and the creatures in the environment? If agriculture's practitioners continue to ignore agriculture's moral dilemmas because we must produce they may lose the right to determine agriculture's future and jeopardize our chances of surviving on this planet (Berry 1977). If we fail to institutionalize study of the ethics of agriculture we will not learn how to ask and discuss moral questions. We should not continue to defend only the interests of agriculture when there are obviously unjust effects on the interests of the planet and our social communites. Human ingenuity has increased the treasures nature provides for the satisfaction of human needs; it will never be sufficient to satisfy all human wants.

Prediction of the future for weed science and agriculture is always tempting, often successful, and usually hazardous. If all parts of the agricultural enterprise including professors, farmer/rancher producers, agribusiness firms, and food processors, and sellers do not begin to recognize and address agriculture's ethical dilemmas three unwelcome outcomes may follow.

First- Agriculture practitioners may find their arguments and justification for their technology and production practices ignored.

Second- Public unease and dissatisfaction with known and perceived effects of agricultural technology (*e.g.* pesticides, cruelty to animals, farm labor, and food quality) will result in increasing societal unrest and pressure for political action. Decisions on how agriculture can be practiced and how land is to be treated will be made by society and government.

Third- The increasing concentration of food production in the hands of agribusiness companies will continue. Small farms, farmers, and rural communities will continue to gradually disappear.

Agriculture is a capital-intensive, high-tech business. Rather than wait to see if appropriate levels of sustainability and resilience can be achieved by the present capital, chemical, and energy intensive system, agricultural people could begin to learn how to impose ethical standards on themselves. Because agriculture is a diverse widespread enterprise reaching agreement will be difficult, but not impossible. Recognizing the possible undesirable outcomes and choosing to act wisely will help maintain the essential industry. I challenge you to consider some hard questions that will affect your future: What does it mean to live well? What matters?

What needs and values do you live by. What needs and values ought you live by.

THE FUTURE OF WEED SCIENCE RESEARCH AND TECHNOLOGY

Prophesy is a difficult thing, especially of the future. I hope my comments make you think. Weed science, although young among the agricultural sciences, has an enviable, rich, productive history and will continue to contribute to agriculture, other disciplines, and food production. Weed control was recognition of necessity by farmers who had been controlling weeds long before herbicides were invented. Herbicides changed the way control was done, but not its fundamental purpose —to improve yield of desirable species. The chemical energy of herbicides replaced human, animal, and mechanical energy. No other method of weed control was as efficient at reducing the need for labor or as selective. People with hoes could distinguish weeds from crops and weed selectively. Mechanical and cultural methods, while effective, were not selective enough. Herbicides enabled prevention, reduced weed populations, and selectively removed weeds from crops. Weed control in the world's developed countries now depends on herbicides. This situation will prevail well into the 21st century.

A. Problems

There are six important problems that have and may continue to hinder progress.

1. Although weeds have been and will continue to be components of agriculture and the environment, they lack the attention, appeal, and urgency of sudden infestations of other pests.
2. Weed science lacks foundational hypotheses "linked to established bodies of ecological and evolutionary theory to provide deeper theoretical justification, a broader vision, and increased collaboration across diverse disciplines (Ward *et al*. 2014). Environmental and production demands will require significant adjustments in weed management and agricultural practice.
3. There is a lack of people and research funds (Davis *et al*. 2009). Research on weed biology, ecology, seed dormancy, and other problems leading to basic understanding rather than immediate control is done by too few scientists.

Publicly funded interdisciplinary agricultural research has lacked adequate funding and, it seems, may remain so (Davis *et al.*).

4. Underlying all agricultural issues there is always an unexamined ethical position (Zimdahl 2022). Thompson (1995) pointed out there is only one imperative: to produce as much as possible, regardless of the environmental/ecological costs and perhaps even if it is not profitable. Agricultural people cannot escape responsibility for societal views of its effect on the environment, other species, and themselves. Agriculture's views on ethical issues have not been and should be examined.
5. All in agriculture know farming is crucial to all economies (Economist 2022) and important to the welfare of all. The public in most societies is certain food is important but is abysmally unaware of the complex processes and people who provide their food.
6. Climate change and lack of appropriate weed control practices will affect farmer's ability to produce. Modern agricultural technology developed country farmers rely on is beyond the reach of poor farmers in the developing world. More than 90% of farmland in Africa has no irrigation, 1/3 of the world's people, and 60% of Africans do not receive warning of impending natural disasters or routine weather forecasts. Agriculture's admirable goal of feeding an expanding world population in warmer, drier places will benefit from expanding its horizons to developed country farmers.

A few conflicting claims (cited herein) illustrate future challenges.

- Moss (2008) charged the overall direction of weed research was wrong. There was too much emphasis on scientific effect at the expense of practical application. Moss argued weed science was weed technology. He suggested his colleagues lacked an awareness of the complexities and resources needed to translate research results into actions for farmers.
- Ward *et al.* (2014) claimed two broad aims have been driving weed science research: improved weed management and improved understanding of weed biology and ecology. Research has developed a high level of repetitiveness, a preponderance of purely descriptive studies, and has failed to clearly articulate novel hypotheses linked to established bodies of ecological and evolutionary theory. Although Ward *et al.* (20214) noted studies of weed management remain important they urged weed scientists to recognize the benefits of deeper theoretical justification, a broader vision, and increased collaboration across diverse disciplines (especially ecology).
- Swanton (2022) accused weed science of being primarily reactive. Scientists responded to current need and worked to solve on-farm problems. He recommended the discipline make long-term thinking automatic and common instead of rare. Long-term thinking is required because weed science, a sub-discipline of agriculture, must begin to answer complex questions regarding cropping systems and environmental challenges.
- The Editor-in-Chief of Weed Research (Marshall 2019) introduced "the post-herbicide era of weed science". He argued this was "increasingly prescient as herbicides continue to face the ever-increasing legislative restrictions and the challenge of evolved resistance. They are key influences of the practice of intensive agriculture whose success is intimately linked to the heart of the planetary crises: climate change, global warming loss of biodiversity, environmental harm, etc.
- Buhler (2017) argued weed scientists must develop integrated cropping systems and weed control strategies in a comprehensive environmental and economically viable system. This approach would "help reduce economic effects and improve weed control practices." Herbicides will continue to be an essential part of integrated cropping systems.
- Westwood *et al.* (2018) claimed weed science was at a "critical juncture" because decades of chemical control have dramatically increased herbicide resistant weed populations. The problems were critical because there were few new herbicides, new modes of action, and no economically acceptable alternative to herbicides in large acreage crops. They suggested new modes of action could be discovered using genetic engineering, computing power, automation, employment of artificial intelligence and machine vision to improve weed management.
- Gould (2002) portrayed the situation by contrasting "immediate and practical" with "distant and deep" issues. Immediate and practical issues are about potent and

unanticipated effects (*e.g.* herbicide resistance). Distant and deep issues include legislative, ethical, aesthetic and practical consequences of altering agriculture's fundamental geometry and permitting scientist's in the developed world to change the way agriculture is and ought to be practiced. He advocated proper development and use while giving adequate, consideration to human and environment health, and sustainability.

This paper deals with thoughts about future weed science research, but not in terms of what will be accomplished. It is conjecture, not prophecy. It might be best conceived as a proposal of what ought to be done. It may not be what will be done because research does not always follow a straight path and other developments may change what is desirable and possible. For example, environmental legislation mandating reduced herbicide use could rapidly change the way agriculture is practiced. A description of research needs is a safer prophetic stance. It describes what could be done rather than describing what the situation will be several years hence. This approach, of course, reduces the possibility the prophet may be wrong.

B. Research needs

Dependence on herbicides for weed control is equivalent to treating the symptoms of a disease without actually curing the disease. Agriculture would be far better served if weed scientists learned how to control weed seed dormancy and seed germination so weeds could be prevented, rather than controlled after they appear. The emphasis should be on the major goals put forth by Ward *et al.* (2014).

1. Discussion and debate of appropriate goals and the pathways necessary to achieve the goals.
2. Rediscovery of the ability to pose critical research questions rooted in and designed to advance the theoretical underpinnings of weed science.

Weed science began when 2,4-D made control possible without studying the weeds. Those who controlled had to know what weeds were to be controlled and where they were growing. That is, control was not blind. There are objects to be controlled and they are known, but, with herbicides, it has not been necessary to know much more.

In general, herbicide development has neither exploited weak points in a plant's life cycle nor used specific physiological knowledge for control purposes. The safest approach has been to aim for complete control of weeds in a crop. As knowledge grows, scientists find some plants may be beneficial and should not be controlled (Chandrasena 2023). Wyse (1992) recommended study of regulation of seed and bud dormancy of perennial weeds and development and life of reproductive propagules. Population genetics and modeling of crop-weed systems will contribute to improved weed management.

C. Weed ecology

Important insights on the future role of weed ecology are found in two papers - Neve *et al.* 2018 (35 authors) and MacLaren *et al.* 2020 (6 authors). Both support the increasingly dominant claim - the present weed management system is unsustainable because of its negative effects and dependence on chemical, capital, and petroleum energy. Both advocate combining multiple known weed management techniques in a new integrated weed management system. Creation of an integrated system based on agro-ecological approaches will require multi-disciplinary participation (Jordan *et al.* 2016). MacLaren *et al.* (2020) argue "new herbicides, gene editing, and seed destructors do not address needed systemic challenges and are unlikely to provide sustainable solutions." Neve *et al.* (2018) advocate better understanding of weed evolution, climate change, weed invasiveness" and, perhaps the greatest challenge, "disciplinary challenges for weed science". They advocate "integration of agro-ecological weed management with socio-economic and technological approaches".

The system that helped create these problems accepts credit but resists accepting blame for negative effects, therein is part of the tragedy. It is an example of the agricultural mind set and justifies Mayer and Mayer's (1974) conclusion - the system is unsustainable. Their second claim - integration and isolation of the system have led to The Island Empire. Agriculture is a vast, wealthy, powerful intellectual and institutional island. The Land-Grant system created Colleges of agriculture and allowed agriculture's isolation within the university and from mainstream American life. Mayer and Mayer accuse agricultural colleges of being separated from the university, mainstream of scientific thought, and rational discussions about social policy. Agriculture does not ask for and only reluctantly receives outside criticism. Those who practice agriculture must move off their island.

Much of the basic information required to develop computer-based models of weed-crop systems and available control techniques has come and will continue to be derived from weed biology and ecology research. What plants compete for and when competition is most severe between crops and weeds is known in sufficient detail to be useful in development of weed-management systems. The still used (Dawson 1965) period threshold concept of weed competition affirms it is nearly always time dependent. Weeds at crop emergence are less detrimental than those emerging later. This principle led to timely use of herbicides and other techniques for weed management. Some crop cultivars are more competitive and this needs to be considered in developing weed-management systems. It is a basis for cooperative work with plant breeders.

Weed populations change with time, and reasons are beginning to be understood. A major challenge presently dominating weed research is the appearance of herbicide resistance often after only a few years use in one field. Research is coupled with development of techniques to combat it. When resistance occurs it has not led to totally unmanageable weed populations because other weed-control techniques (*e.g.*, cultivation, crop rotation) and other herbicides are available. Understanding why populations change and management of population shifts is important to development of successful, sustainable weed management. However, as Harker *et al*. (2012) note, the best way to reduce selection pressure for herbicide resistance is to reduce herbicide use, but dominant weed-management programs advocate herbicide use.

Some of the most difficult weeds in most crops today were not important 10 or 20 years ago. This is evidence weed scientists have developed solutions to some weed problems. It is also true that many common weeds (*e.g.*, cheatgrass, field bindweed. johnsongrass, lambsquarters, nutsedge, pigweeds, Canada thistle) have been targets of control programs for years. Thus, we have simultaneous evidence of success and continuing problems. It is also evidence that nature abhors empty niches. When successful control efforts have reduced the population of a species they inevitably leave space unoccupied and resources unused. Other species move into empty niches created by successful weed control.

Solutions to this dilemma take two forms. The first is to reduce the attractiveness of the niche. Farmers typically over provide for crops. Fertilizer placement and precise rate recommendations have reduced surplus nutrients, but nitrogen runoff due to excessive application is a significant problem with notable externalities. Whole fields are irrigated and light cannot be controlled. If water could be placed (*e.g.*, drip irrigation) as precisely as fertilizer and only as much was provided, the attractiveness of the niche and the success of potential invaders could be reduced = preventive weed management.

The second approach has an element of prevention. Some of the important problem weeds of the next decade are already in fields or lurking on the edges. If they were identified and their weedy potential determined, weed scientists, cooperating with ecologists (see MacLaren *et al.* 2020), could try to predict those most likely to be successful invaders. They could be controlled or managed before invasion. Invasive plant management is now a major area of weed science research as indicated by the 2008 launch of the journal Invasive Plant Science and Management.

Basic biological-ecological knowledge is essential to either approach. Without it weed scientists may be doomed to endure the Red Queen effect (a character in Lewis Carroll's classic book - Through the Looking Glass - 1871). The Red Queen tells Alice, "In this place, it takes all the running you can do to keep in the same place." In trying, and often succeeding, to eliminate weeds from fields, weed scientists have created, in a sense, better, more ecologically successful weeds while accepting herbicide's negative environmental effects.

A difficult and central issue for weed science is understanding the nature of weeds: What makes a weed a weed? How can weeds consistently come out ahead when matched up against the finest commercial varieties? Weeds out-compete crop plants and reduce yields when left uncontrolled. Weeds are not conscious, but they seem to be clever. The nature of the competitive ability weeds possess seems an interesting target for research and an appropriate target for analysis through generation of mutants.

Goethe's "The Sorcerer's Apprentice" and" Mary Shelley's "Frankenstein," and, more recently, Michael Crichton's "Jurassic Park" reinforce the often-inchoate fear of intelligent, rational concern about a powerful form of life manufactured with good intentions, but excessive hubris, which might one day slip out of control (Specter 2016). The 1950s gave us catchy phrases that still resonate—Better Living Through Chemistry and Atoms For Peace. We don't hear similar things now. Chernobyl/Fukushima nuclear reactors, agent orange, space shuttle crashes, thalidomide, ozone destruction, pesticides in food, and climate change dominate the public's thoughts. Scientists clearly solve problems, but in the public's view, untoward problems occur. These well-known problems combined with human drug disasters have made people suspicious of the efficacy and trustworthiness of science and scientists (Lemonick 2006). It is in this context public doubts about genetic modification of anything are raised and must be addressed. Weed scientists and others involved with GM technology often think they could educate/tell people about what they do (William *et al*. 2001). Education is important but careful listening followed by a conversation among equals may be better, especially in a time when science has made mistakes and is regarded with well-founded suspicion. Weed scientists should not regard themselves as the only acceptable arbiters of how developments in their science should be created and used. Because of public perceptions of greed, a bit of arrogance on the part of developers, and misunderstanding of science people view genetic modification as a hazard not a salvation and reject it (Specter 2016).

D. Education

A review of some published articles on the future of weed science reveals few comments on the role of education. Research and appeals for more funding (Davis *et al*. 2009) dominate. There is at least one undergraduate weed science class at all US Land Grant universities and several others required of undergraduate and graduate students. The absence of discussion of what students ought to know among those who teach is disturbing. Surely the education of the next generation of weed scientists with "innovative and diverse teaching practices" advocated by Chauhan *et al*. (2017) are as important to the collective future of weed science as biotechnology, invasive species, and new herbicides. If it is, why isn't education closer to the top of the future agenda? We must integrate weed management and education.

IV, Other challenges

A. Scientific

Several other research areas should be considered when planning weed science's future. They include:

- The value, advantages, and disadvantages of monoculture agriculture.
- The role of companion cropping and regular inclusion of cover crops in weed management? Can weeds be cover crops? (See Young 2020)
- The long-term effects of soil erosion after regular plowing and cultivation? One effect is all too apparent in the brown color of rivers (Logan 1995, Montgomery 2007).
- The future and influence of perennial crops.

Weed scientists were not too concerned with long-term effects when the science was developing. Weeds decreased crop yield — a detrimental long-term effect. The vision didn't extend much farther because solving the weed problem was a sufficient challenge. Any technology, used for enough time, has demonstrable environmental and social effects. A longer-term view will help reveal these effects and compel their consideration before widespread use is achieved.

- Weed scientists must begin to work more closely with economists who ask, what does it cost and what is it worth? What is it worth to do the work to develop a more competitive cultivar, deplete the soil seed bank and achieve assurance of 80% or 100% weed control? What will it be worth to be able to predict weed problems? No one knows, but the answers are important to IWM systems.
- Will nanotechnology affect weed science? Nano integrates biological material with synthetic materials to build new molecular structures. Synthetic biology goes beyond moving existing genes to creating new ones programmed to perform specific tasks. It operates at the nano scale (10"9m) of living and nonliving parts. It has enormous potential for good and harm (Shand and Wetter 2006).

Weed scientists are aware of scientific research opportunities and challenges. There are equally important, though less discussed, social and moral challenges. The primary goal of agricultural scientists has been to develop technologies to achieve maximum yield of a few crops in developed countries. It is a good goal, but one must ask if it is the right goal.

- Is it more important than enabling the poor of the world to feed themselves?
- Can discovering new technologies to maximize yields lead to a sustainable agricultural system to feed 9 billion people?
- Is maintaining rural communities a proper goal for agricultural science?
- Should achieving maximum yield and profit always take precedence over preserving the environment? Should agricultural sustainability to increase crop yields simultaneously decrease environmental effect

Achieving a sustainable agriculture is a goal all agricultural scientists share. In spite of its nearly universal adulation there is little agreement on its nature, what is to be sustained, or on how it is to be accomplished. Production is and always will be important, but it is not possible to create a sustainable agriculture without a sustainable culture. It is impossible to have a serious, comprehensive discussion of sustainable agriculture without including community and culture (Holthaus 2009). Within the agricultural community achieving sustainability is viewed as mainly or wholly technical in nature. It requires different farming methods and adoption of alternative technologies (Morgan and Peters 2006). This ignores the moral, educational, and political tasks and requires a commitment to "philosophical principles that depart from the utilitarian premises of industrial agriculture. It requires new thinking and a change in attitude toward the earth. It requires ceasing attempts to achieve dominion over the earth and achieve humility and reverence before the world (Berry 2002). The dominant agricultural view supports crop intensification as the best route to feed 9 billion people and protect the environment.

Finally, a caution. Weed scientists have an unexamined moral confidence or certainty about the correctness of what they do. The basis of the moral confidence is not obvious to those who have it or to the public. It is potentially harmful. It is necessary to analyze what it is about their science and their society that inhibits or limits their science. All should strive to nourish and strengthen the beneficial aspects and change those that are not. To do this agricultural people must be confident to study themselves, their science, its institutions, and be dedicated to the task of modifying the goals of both (Zimdahl 2022).

V. Agriculture's human dimension

Doohan *et al*. (2010) claim "the human dimension of weed management is most evident when farmers make decisions contrary to science-based recommendations." Agricultural scientists and administrators may be aware their recommendations are often ignored but usually do not ask why because such questions are beyond their area of expertise. Scientists do science leading to science-based recommendations. Reasons for ignoring could be: economic (too expensive), stubbornness, lack of trust, and different perceptions of risk and benefit. Doohan *et al.* argue that farmers exhibit an inverse relationship between perceived risk and benefit. If any technology is regarded as beneficial it is automatically perceived as low risk, which, of course, is not true. Ignoring farmer's reasons is perilous for agriculture's future.

Agricultural scientists have contributed to increasing crop production over several decades. Pesticides have been the primary control technique (Fernandez-Cornejo *et al*. 2014). Because of their efficacy and ease of use there has been over-reliance on them at the expense of other control methods (Blackshaw *et al.* 2008). If the only or primary goal of weed science is to increase production the quest for better herbicides must continue. If the goal is sustainable weed management in a sustainable environment and society other control techniques must be investigated and integrated. Research on non-herbicide weed management must show low or no risk of crop failure and reduced profit. The goal should be development of successful weed-management systems with minimal or no effect on the flora and fauna of soil, water, or air and no adverse effects on people or other creatures.

Scientists and others engaged in agriculture are not, by nature or choice politicians. Failure or inability to consider we live in a political world and are affected by it is a prescription for disappointment or disaster. Political considerations affect our daily life. A major political accomplishment is cheap food, especially in urban areas. It affects the way we practice agriculture and manage weeds. If the government removed itself from agricultural policy making and markets cheap food might disappear.

Given agricultural and environmental history, concern about environmental pollution from agriculture is a fairly recent political development. It wasn't too long ago that pesticide use in agriculture meant prosperity and progress rather than human harm, environmental pollution, and lack of corporate responsibility. For example, a study commissioned by the American Farm Bureau (King 1991) showed 15% of the American public was in favor of abolishing pesticide use in agriculture. Of those surveyed 66% thought pesticide use should be limited in the future and 38% thought farmers were using more pesticides than they had in the past. Such information and concern has political meaning and consequences. About 70% of US agricultural produce harbors some trace of pesticides (Gross 2019). Such challenges are often dismissed by the agricultural community because they are regarded as biased, irrelevant and lack supporting scientific evidence. The findings are ignored or dismissed by those who willfully ignore the effects of criticism on political action (Roberts 2024). Political acts change things and agriculture has to recognize and work in a political milieu or suffer the consequences of regulation by those who do.

VI. Conclusion

The American author Wendell Berry (1981) has written about problems facing American agriculture. He advocates solving for pattern. “To the problems of farming, then, as to other problems of our time, there appear to be three kinds of solutions.” The first solution causes a ramifying series of new problems. This kind of solution shifts the burden away from those who created the problem. The second solution worsens the problem it is intended to solve. These quick-fix solutions ask what herbicide will kill the weed and lead to the need for more quick-fix solutions. The third, most desirable, solution creates a ramifying series of solutions which make, and keep, things whole. For Berry (1981) a good solution is one that acts constructively on the larger pattern of which it is a part. It is not destructive of the immediate pattern or the whole. Good solutions solve for the whole system, not for a single goal or purpose.

Those who create the next generation of integrated, sustainable agricultural production systems for simple and complex problems should remember Berry’s admonition. One must know the whole system and devise solutions that create solutions to maintain the pattern and improve the system. Agriculture’s inevitable problems demand the entire system not just the current problem must be managed.

Contributing to the elimination of hunger in the world is a proper goal for weed science. Two goals of the Millennium goals of the UN (Sachs 2005, pp. 211-212) are relevant. Eradicating extreme poverty and reducing hunger by half and ensuring environmental sustainability.

Although progress has been made, neither goal has been achieved. Berry (1981 p. 98) writes eloquently about a vision of the future shared by those who want to create alternative futures including alternative, improved, sustainable agricultural systems. His words are a good place to end thoughts about the future. Readers may determine if I have reached beyond my knowledge and ability.

We have lived by the assumption that what was good for us would be good for the world. We have been wrong. We must change our lives, so that it will be possible to live by the contrary assumption that what is good for the world will be good for us. And that requires that we make the effort to know the world and to learn what is good for it. We must learn to cooperate in its processes, and to yield to its limits.

But even more important, we must learn to acknowledge that the creation is full of mystery; we will never clearly understand it. We must abandon arrogance and stand in awe. We must recover the sense of the majesty of the creation, and the ability to be worshipful in its presence. For it is only on the condition of humility and reverence before the world that our species will be able to remain in it.

Berry’s challenge is clear - Change requires more than the contemplation of fixed verities. It must move beyond reproducing the qualities of the science to which we have devoted our careers.

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Endnote

The general principle of utilitarian ethics is: actions should be evaluated on the basis of their consequences that maximize happiness and well-being while minimizing harm/suffering for all affected.

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REVIEW ARTICLE

Promoting the utilization of weeds – A way forward

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ABSTRACT

The utilization of 'weedy' colonizing species for direct human benefits and other practical applications is a much-neglected area within 'Weed Science'. It results from an inadequate 'eco-literacy' (*i.e.* ecological understanding of weeds), which author call 'weed-illiteracy'. Most weed scientists have been brought up hearing a flawed myth that '*all weedy species are bad all the time*', and some may even engulf the world. Humans present the greatest threat to biodiversity, of which people and weedy species are constituent parts. However unpalatable this message is, it needs to be given much more publicity to achieve a better balance between human greed, the development aspirations of nations, and global biological diversity. A change in attitude and a focus shift are required to redress the issue. The *Boundary Object* concept provides an opportunity to have meaningful discussions about weedy taxa that have been used as a scapegoat for too long to hide human follies (related to disturbances caused by land-clearing, deforestation, inappropriate forms of agriculture, and excessive population growth). Consensus helps but is not always necessary for cooperation in successfully conducting investigative research. The boundary object approach allows collaborations on investigations of weedy species without always agreeing on divergent viewpoints. These may help ease the tensions and *change our perceptions* of colonizing species. It will also allow weed scientists, trained to think negatively about weeds, to explore the benefits of a positive relationship with a vast array of such taxa and their unique capabilities. Weeds should not be accused as guilty (of harm) until proven innocent! Colonizing species could assist in achieving the *U.N.'s Sustainable Development Goals* (SDGs) and Millenium Development goals, whose visions have been renewed. These globally-accepted frameworks seek to re-align investments and direct research efforts to improve societal benefits. Seeking ways to derive benefits from weedy taxa should be the basis of their fuller integration into societal needs. Instead of waging an unwinnable war against weeds, there is a convincing case for *living with weeds* for societal and environmental benefits.

Weed Science education must be re-aligned to increase 'weed literacy' by providing a much deeper biological and ecological understanding of weeds among agriculturists and environmentalists. Fast-growing and robust weedy taxa are at the forefront of providing *ecosystem services* in all habitats they occupy. Their ecological roles, including pollination and stabilization of degraded landscapes, are much undervalued within Weed Science. There is also compelling evidence that calls for broadening the mandate and the direction of *Weed Science* research to include the utilization of colonizing taxa. A 're-think' on how we perceive weeds and weed research should be a priority for everyone concerned about the Planet's future and preserving its biological integrity and diversity.

Keywords: Colonizing species, Utilization of weeds, Weeds, Weed Science, Weed research

THE COLLIDING 'WORLDVIEWS' ON WEEDS

Most weed scientists are trained from their early careers to 'see' weedy species as 'enemies' and to fight them so that agriculture can be made profitable. This pessimistic 'worldview' on weedy species was purely from an agricultural perspective. The view that we must declare *war* on weeds and 'exterminate' them from our lands was first mooted by William Darlington 1859 in the mid-19th Century. However absurd the thought was, it became entrenched in the early decades of the 20th Century (Evans 2002, Falck 2010, Chandrasena 2014, 2019, 2020, 2021).

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However, not everyone hated weeds, even in the mid-19th Century. Despite the farmers' concern about the *unpredictable* crop losses from pests and weeds, a relatively benign attitude towards weeds also prevailed, at least within some sections of society in North America. For instance, a famous American Poet – James Russell Lowell (1863) wrote:

'One longs for a weed, here and there, for variety, though a weed is no more than a flower in disguise, which is seen through at once if love gives a man eyes...'

Another influential naturalist, Ralph Waldo Emerson (1979, p. 8), praised weeds in a famous lecture delivered in Boston, USA, in 1878:

'What is a weed? A weed is a plant whose virtues have not yet been discovered'.

Such statements show that sections of American society had no qualms about boldly expressing the positive side of weeds. At this time, the USA was emerging from the traumatic Civil War years (1861-65), which had ravaged much of agriculture in the conflicted South-Eastern States of the country. There were other naturalists also in the latter half of the 19th Century, such as George Perkins Marsh (1867), Gerald McCarthy (1892) and Asa Gray (1879), whose sympathetic views on weeds preceded our ecological understanding of the strengths and capabilities of colonizing taxa.

Weed Science, as a discipline in agriculture, first received significant national recognition in the USA and Europe only in the mid-1940s (Burnside 1993). The almost simultaneous discovery of herbicides 2,4-D (2,4-dichloro-phenoxy acetic acid) in the USA and MCPA [(4-chloro-2-methyl-phenoxy) acetic acid] in England during the *World War II* years (1941-42), revolutionized the field of selective weed control.

For the first time in history, around 1944, the selective activity of the auxin-mimic herbicides in controlling broad-leaved weeds in grass turf was demonstrated in the USA and U.K. This led to much excitement and the release of the first commercial herbicides (Duke, 2005). More or less, at the same time, the absurd idea of a '*War With Weeds'* took root (Evans 2002, Falck 2010, Dwyer 2011).

This misguided attitude has been a bane of *Weed Science* and has been around for more than 70 years. From that time, this slogan has been like a *mantra*, repeatedly heard at various weed conferences. The war metaphor, a concocted narrative, believes *humans could win a war against weedy enemies*. The primary 'weapons' of war (herbicides) expanded rapidly as many new molecules were discovered and developed as commercial products in the 1950s and '60s decades. *Weed Science*, as a discipline, flourished in those decades (Duke 2005, Timmons 2005).

Somewhere along the way, we lost track of what we were dealing with. *Weedy species are a small cohort of the Planet's rich biological diversity*. The species we label 'weeds' are ecologically nothing but 'colonizing plants'. They comprise about 9-10% (about 3000 of 375,000 known plants worldwide). The taxa originated under a natural environment and in response to newly opened habitats or imposed habitat constraints to 'colonize' the vacant habitats. The evolutionary driver has been the opportunities created by disturbances and the availability of vacant niches. The genetic makeup of these extraordinary plants was formed more than 100 million years before humans walked on the Earth.

Herbicides initially provided highly effective weed control across agriculture and many other areas where weedy taxa posed problems, such as golf courses, infrastructure, public spaces and rights-of-way. These chemicals were considered 'saviours' and not problems. However, within two decades, the overuse of herbicides for weed control in agriculture and other situations presented a significant difficulty in the USA, U.K. and Western Europe.

More than six decades ago, ecologists and biologists warned that weeds would most likely evolve resistance to the repeated use of herbicides on the same land (Harper 1956). The incredible success of herbicides in killing weeds and the profits that could be made by the chemicals led to these warnings being largely unheeded. It also prompted *Weed Science to be derided as 'Herbicide Science'* (Burnside 1993, Appleby 2005). The excessive focus on weed control and herbicides hampered the discipline from broadening an understanding of how people should integrate colonizing species more effectively and profitably into their lives.

Despite those enlightened views on weedy taxa, the opportunities to utilize their strengths were not realized for another 100 years until the latter part of the 20th Century. Water hyacinth [*Pontederia crassipes* Mart.] and other aquatic weeds were the first taxa to be seriously examined for utilization for societal benefits, mainly in the USA and for promotion elsewhere, especially in developing countries (Wolverton and McDonald 1976, 1979).

The objective in this essay is to explore avenues by which the utilization of colonizing taxa can be promoted, giving their human adversaries a chance to 're-think' and adjust their positions – if that is warranted. Herein, discussions have been made on some ideas, concepts, and a framework that might help shift attitudes on weeds towards a more balanced 'middle path,' a doctrine that humans would do well to embrace.

THE 'BOUNDARY OBJECT'

The *Boundary Object* is an analytic concept of 'scientific' objects or entities inhabiting several intersecting and potentially conflicting social worlds. The idea was first explored by Susan Star and James Griesemer (Star and Griesemer 1989) in a seminal paper published in the *Social Studies on Science* journal. From my viewpoint, the terms '*weeds*' and '*utilization of weeds*' can be both 'boundary objects' because they divide people's opinions by an invisible boundary. Weed Science history knows that disagreements about some weedy taxa can be robust among scientists who deal with them.

Nevertheless, from the original concept, boundary objects can link communities together as they '*allow different groups to collaborate on a common task*' without agreeing on every issue. The 'common task' for which people must 'collaborate' is to understand the beneficial aspects of colonizing species and manage them without causing further damage to fragile ecosystems.

A few definitions and interpretations of a boundary object show this possibility (**Figure 1**).

'A Boundary Object is an entity (**artifact, object, document, vocabulary**) that can help people from different communities build a shared understanding. Various communities will interpret boundary objects differently. Acknowledging these differences enables a shared experience to be formed.

'A boundary object **allows coordination without consensus** as they can allow an actor's local understanding to be reframed in the context of a wider collective activity'.

'Cross-disciplinary collaborations require negotiation across disciplinary work boundaries, rather than working separately at the edges of the shared boundary'.

'Boundary Objects are **learning objects**. This understanding acknowledges their role in 'making meaning' and better communications across diverse social groups'.

'Objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity'.

How could weed scientists apply the boundary object concept as a *learning object* and a *tool* to improve communications between parties with different worldviews? A better ecological and evolutionary understanding of the species in question would reduce the tensions between those who *despise* weeds and others who *admire* them.

What happens when humans excessively disturb and modify their habitations and natural ecosystems is well known. Ecologists expressed six decades ago that w*eeds are not the cause but a symptom of our inability to and failures in managing our living environment* (Bunting 1960, Baker 1965, Baker and Stebbins 1965). Weeds show us how plant succession occurs in new habitats after natural or human-caused disturbances. These taxa also highlight the evolutionary forces in Nature through their adaptations (see Baker 1965). With more than 120 million years of evolution in their genes, weedy taxa are far more successful in every sense as organisms than their human adversaries.

Using the 'boundary object' concept, those who admire weedy taxa could explain their strengths, weaknesses and virtues while asking for sustainable approaches to managing weeds where they may pose

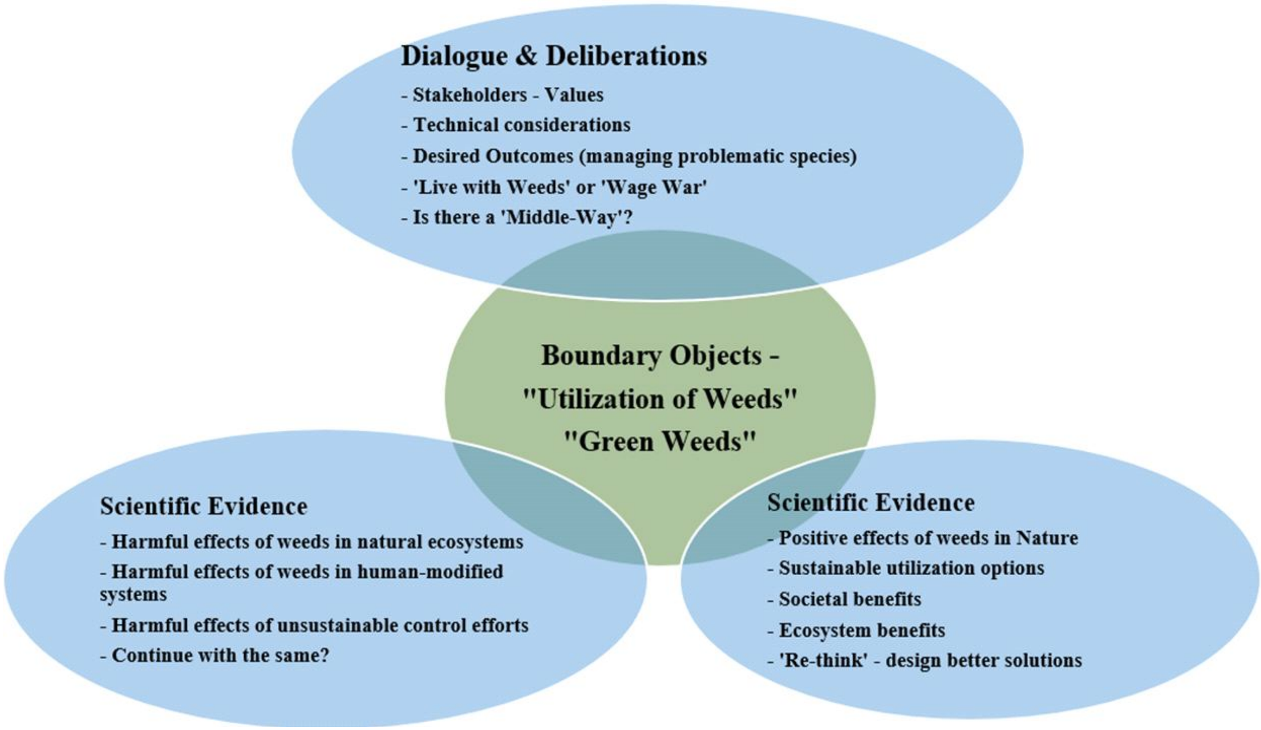

Figure 1. 'Utilization of Weeds' as a Boundary Object in facilitating deliberate discussions without agreeing on every issue but aiming for rational discussions and collaboration between different stakeholders

problems to humans. These may include preventative, cultural and biological weed control, conservation farming, regenerative agriculture and ecological restoration methods. This side of the debate should also present evidence of the failures of overkill and the results of the overuse of herbicides (water and soil pollution, resistance development in weeds, biodiversity losses and public health issues).

Those with a relatively benign but still adversarial relationship with weeds will undoubtedly and justifiably re-iterate the losses of crop yields, farming profits, and other harmful effects of weeds, including potential habitat degradation and biodiversity losses (largely unproven). Those with hard-nosed attitudes towards weeds (i.e. *Invasion Biologists*) and those who follow such a narrative without challenge will continue to defend their robust actions to protect '*natives*' against '*alien invasions'*.

The virulent undertones of this debate hamper the coordination of workable weed management solutions across landscapes. The more balanced position might be a 'middle-way' (Jordan and Davis 2017) to show the progress of *integrated weed management* (IWM) approaches, which are well-developed. All weed scientists and agriculturists know that IWM focuses more on preventative, cultural and biological weed control methods, which minimize the ecological disturbances caused by other methods, such as the excessive use of mechanical weed control or herbicides.

Are Weeds 'Guilty until proven Innocent'? Not So

E O Wilson's book (1992) popularised the notion that '*invasive species*' are the '*second greatest threat in the world'*, following '*habitat loss'*. The contentious idea ignited the emergence of *Invasion Biology* as a subject, expanding the ideas expressed in Charles Elton's book (1958). The simple but fraught ecological process of '*colonization*' by which highly adaptive taxa are established in new areas was misconstrued with a fear-invoking term '*invasion*'. Despite the lack of consensus (Hall 2003, Shackelford *et al.* 2013), many taxa are used as scapegoats for human follies and blamed as '*Invasive Alien Species*' (IAS) that might engulf our Planet (Mooney *et al.* 2005, Rejmánek *et al.* 2005).

Nevertheless, many biologists have challenged the false assumptions in the '*invasions*' and '*native*' versus '*alien*' viewpoints (Davis and Thomson 2000, 2001; Daehler 2001, Theodoropoulos 2003, Davis 2005, Larson 2005, Shackelford *et al.* 2013). These were followed by solid objections by philosophers (Sagoff 2002) and environmental historians (Chew and Laubichler 2003, Chew and Caroll 2011, Dwyer, 2011, Chew 2015, Guiaºu and Tindale 2018). Writing to *Nature*, Davis and 18 others (Davis *et al.* 2011) complained about the nebulous concepts and narratives that blamed introduced species for human follies and objected to using fear-invoking terms in public discourses.

Defence against *invasions* became a primary goal of conservation biologists, who claim that the '*impacts*' of IAS present a dire threat to biodiversity. In this narrative, any form of *colonization* of a new location by plants or animals is viewed as a problem (Chew 2015). Introduced species are accused of driving out the '*natives*' all the time, an unproven claim in many landscapes. The ecological evidence that 'non-native' species seldom compete successfully with 'natives' in relatively undisturbed ecosystems is lost in this debate.

Disagreements about these views hinder the utilization of many species with unique capabilities that can be harnessed to help societies. Regrettably, the ideas were embedded in the *Convention on Biological Diversity* (CBD 1992) without much challenge. This inhibits people from thinking more positively about colonizing species and the advantages they may offer to society. The absurd assertion that all introduced species should be treated as *'guilty' until proven innocent* took the maligning of weedy taxa to unjustified depths.

To say that: '*all weeds must be guilty until proven innocent*' is a form of populism at its worst. The reversal of the universally accepted concept that everyone is '*innocent until proven guilty*', so clearly enunciated for the public good, is intellectually dishonest. The quicker we stop using such divisive language, the better we will be as a society.

A large number of species, including some 'farmer-friendly' weeds, are listed as IAS, deserving lethal killing for merely occupying human spaces. In the confusion created by the IAS branding, one can excuse the public, scientists and policymakers for being misled. Many have been brainwashed to think that all 'weedy' species are plunderers of our resources, moving across geographical barriers to engulf continents. Changes to such irresponsible typecasting will come with time as attitudes change.

Discussions on weed discourses would do well to jettison the politically evocative terms - '*alien*', '*feral*', '*invaders*' and '*invasions*' and revert back to 'introduced species' (Chandrasena 2021). The boundary object concept can provide the framework for such a change, allow rational discussions, and work towards collaborations without necessarily agreeing on every aspect of the entity.

Those concerned with the environment must understand that the *Invasion* narrative was designed to create public awareness of the potential risks of introducing species across continents and countries. Undoubtedly, the powerful terms used influence the public's thinking and prevent positive relationships with weedy taxa. Critics (Theodoropoulos 2003) point out that the *invasion* narrative has nothing to do with a genuine interest in saving the world from *invaders*. The claim appears to be hyperbole to get more funding *for managing such invaders*.

Historical usage of the terms shows that the concept of '*nativeness*' lacks reliable ecological content. It simply means that a species under scrutiny has no *known* history of human-mediated dispersal and may have been a resident of a given bio-geographical area for centuries (Chew and Carroll 2011, Hall 2003). Ecologists are responsible for prong that 'non-native species seldom compete successfully with 'natives' in intact and relatively undisturbed ecosystems. Human influences, *i.e*. deforestation, excessive land clearing for urban developments, nutrient enrichment in waterways, unsustainable levels of pastoralism and altered fire regimes, are some of the most significant causes that facilitate the spread of introduced species.

When moved across geographical barriers and continents, only a mere handful can successfully establish themselves without help from humans. Also, only a few grew so much that they caused problems for humans and natural ecosystems. Moreover, many global examples indicate that not all species' introduction to new areas, regions, or continents is so dramatically detrimental, as conservationists and the media prefer to claim.

Ecology teaches us that given the variety of life cycles, reproductive strategies, and the dispersal means that plants and animals have, species can move about and spread on their own, crossing geographical boundaries. Many are assisted by natural vectors (wind, cyclones, water, landslides) to spread, establish, and colonize new areas. They also benefit from the disturbances that humans and other animals cause. However, *not all species, moved about by humans or other vectors, can succeed in all habitats in their new environments* (Watson 1847, 1870; Dunn 1905, Parker *et al.* 2013).

'GREEN WEEDS' AS A BOUNDARY OBJECT

How valid is the term 'green weeds' when used as a boundary object? The terms 'green economy', 'green technologies' and 'green living' are already well-entrenched boundary objects in the global environmental discourses. As a result, the term 'green' is no longer ambiguous because it has a definite meaning when used in the proper context.

The term 'green' arose from citizen-driven, environmental movements in the 1960s and '70s. For centuries, people arguably lived more or less in balance with their surroundings. But a burgeoning population and economic booms in industrialized and developed countries put unbearable pressure on the Planet's climate as well as its natural environment and resources, including forests, waterways, soil, animals, and plants. The 'green' movement has now captured the attention of a significant population of ecologically-minded people in almost all countries. Climate change uncertainties have renewed the interest in 'green' and sustainable living, in harmony with the environment and 'eco-friendly' technologies. The scientific basis of 'green' living includes less consumption, less demand, fewer ecological perturbations, renewable energy, and recycling all biological and non-biological resources.

The green movement must also be recognized as a diverse scientific, social, conservation, and political movement that broadly addresses the concerns of environmentalism. It encompasses political parties, organizations, and individual advocates operating on international, national, and local levels. These groups are broadly unified 'across their boundaries' by a desire to protect the Planet's environment and Nature's capital (plants, animals, soil, air and water resources). If not for this common goal, many groups are diverse in philosophies, strategies and actions they champion.

Despite obstacles, the 'green movement' has succeeded in heightening public awareness of environmental issues that cause distress to the Planet and its inhabitants. Its growth reflects widespread social and scientific concerns about the degradation of the Earth's bio-physical environment. Everyone needs to realize that 'Going green' implies changing peoples' awareness about how their behaviour and consumption patterns contribute to unsustainable ecological harm to the Planet.

'Green enlightenment' aims to create or increase ecological awareness (*eco-literacy*) in societies. It seeks to cause lifestyle changes and reduce individuals' and collective societies' ecological footprint. These moves must be seen as in the right direction to save a planet in peril. As discussed below, I find 'green weeds' to be an appropriate adjective that can be readily lined up with well-established global concepts and efforts to improve the Planet's well-being.

Ecosystem services and biodiversity

The Millennial Ecosystem Assessment (MEA 2005) defined *ecosystem services* as the direct and indirect contributions of ecosystems to human well-being, survival and quality of life. The concept of an ecosystem provides a valuable framework for analyzing and acting on the links between people and their environment. Ecosystem services can be categorized into ûve main types (MEA 2005):

Provisioning services – these are the products obtained from ecosystems, such as food, fresh water, wood, ûbre, spices and medicines.

Regulating services – those deûned as the beneûts obtained from the regulation of ecosystem processes, such as climate regulation, natural hazard regulation, water puriûcation and waste management, pollination or pest control.

Habitat services highlight the importance of ecosystems in providing habitat for migratory species and in maintaining the viability of gene pools.

Cultural services include non-material beneûts that people obtain from ecosystems, such as spiritual enrichment, intellectual development, recreation and aesthetic values.

Evolutionary services including beneûts, such as genetic resources that evolve due to selection pressure exerted by humans and nature.

Biodiversity is the source of many ecosystem goods, such as food and genetic resources, and changes in biodiversity can inûuence the supply of ecosystem services. *Colonizing species are crucial members of global biodiversity and contribute to all of the five types of ecosystem services*.

Sustainable development goals

Within the 'greening' ethos, I propose using the term 'green weeds' deliberately as a *semiotic* (a sign) to create an impression of opportunities. Can 'green weeds' be a part of human efforts to save the Planet? The evidence is compelling to say yes. However, weed scientists need to be convinced and encouraged to change their deeply-held views about the harm to human endeavours caused by weedy taxa. As discussed in this essay, 'green weeds' could help in many ways that would reduce the ecological impacts of humans and redress some damage that has already occurred on the Earth.

Historical facts and existing global knowledge illustrate that our weedy colonizers undisputedly contribute heavily to societal development in several critical areas, such as (1) Food and nutritional security and sustainable diets; (2) Sustainable livelihoods; (3) Poverty alleviation, (4) Women's empowerment, and (5) Gender equity.

Nevertheless, given the need to break down barriers and get people to 're-think' their entrenched beliefs and lead them to have a balanced and rational discussion on the contribution weedy species can make to society, frameworks are needed. One important tool on which to base a balanced discussion is the United Nation's *Sustainable Development Goals* (SDGs), which have been updated for 2030 (U.N. 2024). The latest update encourages signatory countries to pursue with vigour 17 goals (**Table 1**). Based on widely published information, data, and results over at least seven decades, a vast array of colonizing taxa can contribute significantly to achieving these goals.

At a UN summit in September 2015, 193 countries agreed to work towards the 17 Goals with the aim of improving the lives of all people and the Planet we inhabit. I propose using these Goals as a driver to promote the utilization of weedy taxa and thinking prompts, as shown in **Table 1**. To illustrate, I used an arbitrary scoring system from 0-5 to comment on the potential of weedy species to deliver benefits in achieving the UN-declared SDG goals. In this scoring, numerous, palatable edible weeds, which form a part of the diet in most countries, will score high in their potential to end hunger and achieve improved nutrition for societies (SDG Goal 2). *Sustainable diets* are diets with low environmental impacts that contribute to food and nutrition security and a healthy life for current and future generations.

Medicinal weeds that can be commercially extracted for pharmaceutical benefits need no further elaboration. Most societies also appreciate the dual benefits (nutritional and medicinal) that some taxa provide. Knowledge about such weeds dates back many millennia, well before the Christian Era, and must be an integral part of human society's future development (see **Appendix 1** for examples).

The SDG Goal 1 – Ending poverty relies on all forms of employment that can increase peoples' income and living standards. A great many weedy taxa, particularly multi-purpose, fast-growing shrubs and trees, already form the basis of cottage industries. These range from cellulose, fibre, dyes and essential oil extractions to paper and pulp industries. The production of innumerable saleable items by craftspeople and artisans using weed species as raw material is well established.

The products based on weedy species extend from baskets and mats to the globally-popular water hyacinth furniture. In addition to contributing

Table 1. Potential Contribution of Colonising Species to Sustainable Development Goals (U.N., 2024) [Score 0-1 = Low; 2-3 = Medium; 3-5= High]

Goal No.	Goal purpose contribution	Score	Comments
1	End poverty in all its forms	3-4	Cottage industries, medicinal and edible weeds, food and fodder for livestock
2	End hunger, achieve food security and improve nutrition via sustainable agriculture	4-5	Edible weeds, market gardens, diversified crops, multi-purpose trees
3	Ensure healthy lives and promote well-being for all at all ages	3-4	Those mentioned above, plus Nature-based solutions (NSBs) and education
4	Ensure inclusive and equitable quality education and promote lifelong learning for all	1-2	Nature-based solutions and education
5	Achieve gender equality and empower all women and girls	3-4	Cottage industries, especially crafts
6	Ensure availability and sustainable management of water and sanitation for all	0-1	Water treatment wetlands for water quality improvement
7	Ensure access to affordable, reliable, sustainable, and modern energy for all	3-4	Many biofuel crops and potential taxa are weedy (i.e. high biomass grasses and those that yield oils (such as jatropha and castor-oil).
8	Promote inclusive and sustainable economic growth, productive employment and decent work for everyone	4-5	Small-scale and/or cottage industries, especially handicrafts, based on a large number of weedy raw materials with women's participation.
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	3-4	Industries such as essential oils, perfumes, dyes and a wide variety of value-added products from weedy species
10	Reduce inequality within and among countries	0-1	No direct effect
11	Make cities and human settlements inclusive, safe, resilient, and sustainable	1-2	Urban greening with fast-growing and resilient species, water-sensitive urban designs and stormwater treatment wetlands
12	Ensure sustainable consumption and production patterns in societies	3-4	Backyard market gardens with edible weeds provide food supplements and raw materials for sustainable consumption and production
13	Urgent action to combat climate change and its impacts (U.N. Convention on Climate Change)	4-5	Resilient landscapes, diversified farming
14	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development	0-1	It may include fish farming and food from Azolla, Lemna, etc.
15	Protect, restore and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	4-5	All fast-growing species, including grasses, legume trees and others, restore vegetation via succession processes.
16	Promote peaceful, inclusive societies for sustainable development, with access to justice for all and build effective, accountable institutions.	0-1	No direct effect
17	Strengthen the means of revitalizing the Global Partnership for Sustainable Development.	0-1	No direct effect

U.N. (2024). Take Action on Sustainable Development Goals (https://www.un.org/sustainabledevelopment/sustainable-development-goals/).

significantly to poverty alleviation, cottage industries empower women (gender equity) and provide life-long learning to children and youth of the future while supporting families, livelihoods and the well-being of societies (SDG Goals 3, 4, 5, 8 and 9).

SDG 6 relates to sustainable management of water resources and sanitation. Colonizers, such as water hyacinth, cattails (*Typha* L. spp.), common reed [*Phragmites australis* (Cav.) Trin. ex Steud.] and many others are crucial components of wastewater treatment systems and constructed wetlands used to extract nutrients from stormwater draining large areas. Without such resilient species with robust growth and wide ecological amplitudes, pollution reduction in waterways is not achievable. The phytoremediation potential of colonizing aquatic taxa, which is well demonstrated by a large variety of heavy metal accumulators, also falls under this goal. Some of the best examples are given in Appendix 1.

SDG 7 aims to promote affordable, reliable, sustainable and 'green' energy for all. This means renewable energy sources, including biofuel crops. Many fast-growing grasses, such as arundo (*Arundo donax* L.) and oil-yielding weeds, such as jatropha (*Jatropha curcas* L.), are at the forefront of contributing to this global goal.

Colonizing species are crucial contributors to SDG 8 (Promoting inclusive and sustainable economic growth and, productive employment and fair work for all) and SDG 9 (Building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation). Similarly, pioneer species are indispensable components of urban greening, water-sensitive urban designs, urban stormwater treatment wetlands and other Nature-Based-Solutions (NSBs). Resilient, liveable and sustainable cities (SDG 11) cannot be constructed with only slow-growing natives without fast-growing and resilient 'weedy' species.

SDG 12 sets goals to ensure sustainable consumption and production patterns. Cultivating beneficial weed species in backyard market gardens will provide supplementary food, balanced diets, and sustainable raw materials, contributing to lifestyle changes, sustainable consumption and production.

SDG 15 seeks to protect and restore damaged terrestrial ecosystems. Attaining the goal requires action towards sustainable forest management while expanding revegetation of large landscapes to combat desertiûcation. The goal also encourages action to halt and reverse land degradation and prevent biodiversity losses. These objectives are unlikely ever to be attained without selecting and promoting resilient, fast-growing species, including multi-purpose trees from which societies could benefit greatly in the longer term [5].

Can the two colliding worldviews be reconciled?

The essential question we need to answer is how the conflicting worldviews of weedy species can coexist without adversely affecting each other. The boundary object concept allows scientific collaborations without consensus on any aspect. Ultimately, all parties need a way forward to manage the adverse effects of weeds while balancing control efforts with their practical and bioresource values.

A vast knowledge base in *Weed Science* confirms weeds' actual and potential adverse effects on agricultural crops and non-agricultural situations. The adverse effects depend on many factors, including the levels and nature of the disturbances, the specific species and/or the weed community.

Whether the weedy species grow unchecked also determines their success in modifying ecosystems by their sheer abundance and pertinacity. However, not all such species are harmful in all situations. Regrettably, ecological knowledge about plants, animals, microbes and how complex biological systems work on this fragile Earth is not a high priority for most people. As a result, making people understand the virtues of weeds is a considerable challenge. The uses and opportunities of the species remain under-explored (Jordan and Vatovec 2004, Chandrasena 2008, 2014). For some weed scientists, the utilization of weedy taxa seems like an *idealistic position* rather than a realistic and attainable goal. A few, surprisingly, have gone even further, believing that the *utilization of colonizing taxa is the future!*

With some species, such as water hyacinth that can be exploited for innumerable practical uses, as well as arundo and jatropha that can potentially be expanded as biofuel crops, utilization may present modest but manageable risks. Herein, I invoke Colorado State University's Emeritus Professor Robert Zimdahl's thoughts on what a 'good observer' would be (*pers. comm.* Nov 2020):

"What we need are good observers. A good observer sees what they are looking for when it is there, does not see what they are looking for when it is not there and sees what they are not looking for when it is there".

'*Good observers*' and good researchers in Weed Science should not miss possibilities of utilization of weedy taxa. I would also add that all good observers need to *observe as objectively as possible* and have an open mind in acquiring new knowledge. We owe that to Science and our training.

'Responsibility' – a Virtue

Responsibility is counted as an environmental virtue in ethics and is often expressed as a good character trait. With compassion and benevolence, a 'good human being' will take responsibility for behaving appropriately towards the environment, including all other species (Thompson 2011).

Extending from such ideas, individuals and a collective society *must* take *responsibility* to obtain an enhanced ecological understanding of the interactions between humans, other species and the environment. This awareness is critical in dealing with colonizing taxa. When and where the excessive growth of a weedy species or a community becomes a problem, whether in agricultural or non-agricultural settings, we must manage them using well-developed tools, tactics, and strategic approaches. We must also do so without harming the environment or other organisms that rely on the colonizing taxa. This is being good environmental stewards.

The echo of the misinformation – that humans can win a war against weeds - reverberated through the discipline in the 1960s, '70s and '80s decades. The message was heard loud and clear by public officials, land managers and volunteers, who enthusiastically joined the 'forces' against weeds. More ecological understanding and common sense should have alerted ecologists, weed scientists and environmental scientists that it is foolish to believe in such a myth just because we have an arsenal of herbicides in our possession. As a result of accepting the pervasive myth, most weed scientists have become wary of evaluating the ecological roles that weedy taxa play in Nature and exploring the opportunities to integrate them into our lives.

These days, most media stories blare out the sensational message: *All weeds are bad news*. Disappointingly, thousands of weed research articles, even in recognized weed science journals, also give the same negative message. Many weed scientists are still too busy '*battling*' the evolving weedy taxa to think about concepts and practical applications of utilization that weedy taxa offer. A major obstacle is the shallowness of the discourse and prevailing '*weed-illiteracy*'. Ideas regarding '*beneficial*' or '*tolerable*' weeds run contrary to killing weeds. Any ideas about utilization are thwarted by the '*fear*' in people's minds regarding weedy species, presented as '*aliens*' ready to engulf the world.

Hiding the positive attributes of the accused is part of this story of misinformation. The ease with which proponents spread falsehoods about colonizing taxa inhibits a better relationship with them. *Our societies are poorer for this mistake*.

The frameworks and concepts for managing a potential risk posed by a specific species are well-developed within Weed Science and related scientific disciplines. Given this, we have a moral responsibility to change our attitude towards colonizing taxa so that suitably targeted action to manage them can be taken on a *case-by-case* basis, *where, when and if required*. The experience of ecological restoration projects is that taking drastic and lethal action against any widespread species in most habitats is often unnecessary and futile.

Devine-Wright *et al*. (2022) recently argued: '*The learnings from Social Sciences prove that placing people at the centre of solving the problems they have created is essential*'. Additionally, actions by individuals and society are crucial, as humans face a precarious future under a changing climate.

The resolution of most environmental conflicts lies in people's power over issues that concern them. The vexed issue of *colonizing taxa*, which are accused of being a constant problem in agricultural land, home gardens, public spaces or nature reserves, falls into this category. There can be no doubt that sustainable solutions need to be found for problems that weedy taxa may create by their sheer abundance in specific situations. However, people can only find lasting solutions with a sympathetic attitude and enlightened ecological understanding. Developing practical solutions will require balancing the harmful effects of colonizing taxa with their positive effects, previously discussed.

Zimdahl and Holtzer (2021) have argued that in all our activities, we should worry about the *ethics* of what we do. Humanity has a moral responsibility to '*do no harm*' to the environment, biodiversity and the Planet. In their view, profits alone must not be the critical driver in agriculture or all other productive endeavours. The *environmentally responsible* person will be disposed to acquire the knowledge to achieve and execute that know-how.

It is also important to note that, as climate change adaptations show, *science and technology alone cannot solve complex societal problems*. All our actions should be undertaken with an eye on protecting the Earth and sharing resources with billions of other animals and plants. A priority must be to conserve what *Mother Earth* has endowed us with. However, we must allay our fears of the so-called '*Aliens*' or '*Invasive Alien Species*'.

Regardless of our capacity to kill weeds in most situations, by their sheer tenacity and abundance, pioneering species give us several messages. The paramount message they give is their capacity to adapt rapidly to climate change and to any other selection pressures humans may apply on them. *Despite our undoubted ingenuity, do humans have that adaptive capacity? The answer is no.*

Notwithstanding the inconveniences weeds may cause humans, they will always be there, now and in the future, as part of the Earth's rich biodiversity. *We should be thankful that these pioneer species exist and are unlikely to go extinct.* The time is upon us to enter into a peaceful co-existence with colonizing taxa and learn how to live with them.

Contrary to the alarmists' view, colonizing taxa *will not take over the world*. It should hardly be necessary to point out that *the Earth has no feral future!* The distortions of what science has taught us are driven by the feeding frenzy of the twenty-four-hour news cycles. Sensational messages consume us day-in-day-out. Science writers, looking for attention-grabbing stories, put their own spin and often get the message wrong.

The echo chambers of negative messages on weeds are primarily designed to obtain more funding to manage the *invasion* threats. But they skew our thinking, make people feel powerless, and often debilitate our rational thought processes concerning the true Nature and virtues of colonizing species. Public servants who deal with policies on weeds and natural resources, feeling the need to protect their jobs, prefer not to be too vocal in support of weedy taxa and their uses. Some convince themselves that what they do is correct, and the alternate view - promoting the utilization of weeds for any ecological or societal benefit - will *go against the grain*.

Since the mid-1990s, substantial weed research funding has been spent in Australia, unimaginatively, to 'manage', more or less, the same list of species, with limited success. The absence of funding for exploring potential uses of colonizing taxa in such calls for research reflects how the discourses have been hijacked by the more powerful (negative) voices. *Use-inspired, utilization research funding, whether basic (pure) science or applied science, will only come with determined campaigning by concerned citizens, researchers, scholars and academics, who seek better solutions.*

In dealing with weedy taxa, governments often take a '*we-know-it-all*' attitude, which leads to '*top-down*' enforced approaches. Such approaches fail because it does not adequately foster collaborations and community-based weed management. The availability of funding for on-ground weed management is also influenced by privileged stakeholder groups whose voices are more powerful than those of environmental groups and advocates of conservationist agendas.

Compared to countries with diverse and mature cultures, the European mindset on weeds is an impediment to exploring the utilization of colonizing taxa as bio-resources in Australia. The fear of weeds, stealing resources from crops and drawing energy out of human endeavours is deeply ingrained in the population. Unfortunately, the knowledge of the extensive use of weeds as biological resources within Australia or by other traditional cultures extending to nearby Oceania has not penetrated deeply into the society's worldview.

The low population density in the large Australian continent does not help. Generally, low-density regional communities are too small to economically utilize the large biomasses of colonizing taxa, spread across vast and mostly arid landscapes. Another powerful reason is the relative affluence of the population, given Australia's mining-based economy. Most people are wealthy, deriving income from manufactured goods and services rather than from biological resources. The affluence creates little incentive for people to utilize natural resources for their livelihoods. This is especially true for plant resources unless that use is directly related to profitable pastoralism (*i.e.* fast-growing grasses as fodder, and N-fixing ground-covers or shade trees). A large portion of wealthy Australians also have no reason to develop sympathetic attitudes toward Nature, which they believe is there to be exploited. *In this social milieu, weedy taxa are cast aside as unimportant, or worse still, to be killed off at every opportunity*. The disconnect between sectors in the community and the environment is also a contributory factor that creates conflicts with species.

In Australia, pastoralists derived enormous benefits from N_2-fixing legume trees and leguminous cover crops, introduced over a Century ago to improve grazing lands and animal fodder. But it did not take long for the same farmers to despise these species as they spread across vast, arid rangelands. Although the judgements of wealthy landowners and pastoralists with vested interests are flawed, they form solid political constituencies, and their voices drown opposite views on specific species.

Science is not enough to answer whether we can ever coexist with weeds. Value judgements, societal considerations and democratic decisions are involved. These should be underpinned by scientific and non-scientific knowledge and a commitment to Nature. Non-scientific knowledge comes from traditional knowledge, as well as the personal experiences, intuition, logic, and authority of individuals in a society. Scientific knowledge, on the other hand, relies on hypothesis-testing and research findings obtained by following the scientific method. Weed scientists are responsible for engaging more with people working on 'weed policies' or focusing on the *social ecology* of weeds. Weed scientists across the globe must also take responsibility for a better understanding of colonizing taxa before embarking on developing unsustainable and lethal solutions. We must learn lessons from how weedy taxa rapidly evolved resistance to the continuous use of herbicides (Heap 2022).

If our genuine desire is to protect the Planet's environment from the ravages allegedly caused by 'colonizing taxa, blamed as the '*second greatest threat to biodiversity*', we must find more funding to prove this claim more convincingly. We also need better measures and ecological data to inform our understanding of the effects of colonizing species across varied landscapes and time scales. In the long term, most weedy species will *coexist* with the so-called 'natives' without completely displacing the latter or causing irreparable harm.

By writing many articles on weeds, one should not expect the public to understand weeds or weed-related issues of concern. Suppose researchers care about how their findings influence public opinion and government policies. In that case, they must redress this ‘*communication gap*’ and ‘*translational deficit*’. This deficit, evident in many *Weed Science* articles, is possibly due to inadequate *ecological literacy* and, often, poorly selected research topics with only an academic interest but little practical value to society.

The *translational deficit* regarding the practical applications of specific research findings and insights can only be remedied by balancing scientific evidence with societies’ priorities. Perhaps weed researchers should better understand weedy taxa and moderate their views regarding the objects they are dealing with. This will help many researchers not start every article saying that all weeds should be controlled at all costs and that weeds are among the greatest threats to the Planet’s biological diversity.

Only cross-disciplinary research, integrating weed research with other disciplines, including *Social Science* and *Ethnobotany*, will allow weed scientists to better appreciate the values of weedy taxa. Weed scientists must realize that they are also responsible for forming hypotheses regarding the potential uses of colonizing taxa that can be carefully tested. Presenting a convincing research agenda is the only way to attract funding from governments or civil societies and change the discourses to favour these resourceful taxa.

The prevailing *minority view* that weeds are not the enemy of humans, not liabilities, but are valuable resources – for now and for the future, is not a radical idea. Nor is it a misleading notion. Although the message is somewhat muted in the discourses, most people, farmers, biologists, and even politicians who care for the environment will have to agree.

Colonizing taxa have clearly staked claims on disturbed habitats over large landscapes, which are increasing around human habitations. This is inevitable as the vast human population disturbs the Planet’s natural ecosystems. Hardly any areas on the Planet now exist untouched by human hands.

The sheer abundance and persistence of many weedy taxa get our attention. They meet our wrath because they will not yield to control easily. These experiences often cloud our judgements, and in this confusion, it is easy to overlook the redeeming values of colonizing species. They provide vegetative cover over barren areas, stabilizing soil, anchoring nutrient cycles, producing food for animals and humans, and pollen and nectar for bees. They enrich Nature by adding variety, richness, abundance and biological diversity to any landscape.

Let’s listen carefully and also observe carefully. We will hear the silent story that weedy, pioneering species tell us – *of their resilience in the face of adversity and capacity to adapt* – profound lessons humans can and should learn. The species also spotlight a spectrum of human follies in damaging the environments we should preserve.

Learning from nature

Instead of demonizing species, we must learn from each other, Nature, and pioneering plants and animals. Our ancestors, *pioneers themselves*, did so admirably. Our existence today is a testament to our pioneer ancestors’ adaptability and survival skills. Unfortunately, survival is now precarious for many human cultures and societies across the globe. As climate change poses the greatest threat to humankind’s survival, our future existence as a species depends on how well we integrate with Nature’s wonders and the challenges the natural world throws at us. Humility, combined with a fundamental understanding that we are merely a species passing through a specific period in the Planet’s life, would be a definite advantage as we continue our struggles to survive on Earth.

We must also do our best to mitigate human impacts on the environment. Some of the most destructive human activities include the excessive use of fossil fuels (related to global warming), over-exploitation of natural resources (such as caused by mining for oil, gas and minerals), habitat destruction, large-scale deforestation, expanding animal farming, monocultures and other forms of unsustainable agriculture. One must add soil, air, and water pollution, damages caused by the globally rampant wildlife trade and poaching, and pollution caused by human waste created by a burgeoning population.

An emerging idea – of *Nature’s Contributions to People* (NCP) – was recently highlighted by Pascual and co-workers (2017). It is a conceptual framework that fits the world of colonizing taxa and how we may strive to create a sustainable future for the present and future generations. As the authors explain:

“…Nature’s contributions to a good quality of life are often perceived and valued by people in starkly different and often conûicting ways. People perceive and judge reality, truth, and knowledge in ways that may differ from the mainstream scientiûc lens…”

“…Hence, it is critical to acknowledge that the diversity of values of nature and its contributions to people’s good quality of life are associated with different cultural and institutional contexts and are hard to compare on the same yardstick…".

The NCP concept is a pluralistic approach, applicable to knowledge-based policy initiatives. The NCP platform recognizes the benefits of embracing diversity and power relationships across stakeholder groups with different values regarding human-nature relationships. Resonating with the term *Ecosystem Services*, the NCP concept includes all of the positive beneûts and occasionally negative contributions, losses, or detriments that people obtain from Nature (*anthropocentric values*). It also captures a *non-anthropocentric* value centred on something other than human beings. These values can be *non-instrumental* (*e.g.* a value ascribed to the existence of a speciûc species for their own sake) or *instrumental* to non-human ends (for example, the instrumental value a particular habitat type may have for a species that is well-adapted to it).

Other knowledge systems, such as '*Nature's Gifts*', prevalent in many indigenous and traditional cultures, are recognized within the NCP concept. In a sympathetic worldview, colonizing taxa, which are accused of causing adverse effects on biodiversity and people, fall within the milieu of NCP and are most certainly '*Nature's Gifts*'. *A flexible mind will allow us to seek clarification on this viewpoint.*

Conservation of biodiversity

I sometimes wonder how many people actually appreciate that the most unique feature of the Earth is its biological life, and the most amazing feature of life on Earth is its biological diversity. Innovative messaging and a greater emphasis on '*ecological literacy*' are required in discourses to hammer this message to some sections of society.

Approximately nine million types of plants, animals, protists and fungi inhabit the Earth. So, too, do more than eight billion people. Human actions have been continually dismantling the Earth's ecosystems, eliminating genes and biological traits of these species at an alarming rate (Hooper *et al.* 2012, Cardinale *et al.* 2012). Most people push global biodiversity losses and their link to human activities to the margins of their consciousness because they cannot comprehend the complexities of understanding 'causes and effects'. Some people (such as climate change denialists) refute the linkages altogether, mainly for their own benefit.

There is still a great deal of money to be made by continuing destructive activities, such as large-scale logging of the tropical forests in Borneo or the Amazon and relentless extraction of oil and gas in the fossil fuel industry. Despite the overwhelming evidence (IPCC 2022), it is too risky for many parties to accept that climate change is occurring. *And the poor will suffer most from inaction by the rich.*

Nevertheless, a clear message emerging from ecological studies is that increased biodiversity often leads to more significant and less variable levels of ecosystem functioning. That means that the richer the biodiversity, the lesser the threat of the extinction of plant and animal species.

Cardinale *et al.* (2012) and Hooper *et al.* (2012) argued that diversity-driven increases in function can boost rates at which nutrients, energy and organic matter flow through an ecosystem and increase their overall multi-functionality and stability. Therefore, in the conservation efforts of global species and ecosystems, maintaining high levels of overall biodiversity across landscapes is necessary to even reduce the extinction risks of specific species.

As critical components of biodiversity in any bio-geographical area, assemblages of pioneer taxa would collectively exploit the resources of particular environments to maximize the cycling of energy and nutrients through those ecosystems. Along with all other life forms of plants, pioneer species will fill various ecosystem roles. Of their very unique Nature, they will withstand disturbances and bounce back, responding to environmental changes. Although frugal in how they consume resources, these highly adaptive species will share them.

Concluding comments

It has been argued in this paper that *Weed Science* will continue to under-perform if our discipline does not consider that weeds may, in many situations, provide positive ecosystem services for the Planet and societal benefits, not just disservices (Marshall *et al.* 2003, Jordan and Vatovec 2004, Altieri *et al.* 2015, Chandrasena 2019). Therefore, weeds are not plants that should *necessarily* be killed all the time with herbicides or any other method. This point has emerged strongly in recent discourses on ecosystem services and disservices (Vaz *et al.* 2018; Tebboth *et al.* 2020, Guo *et al.* 2022).

Therefore, we should encourage weed scientists in India and elsewhere to look beyond the paddock in researching weedy taxa for their values and usefulness in future societies. Those who are in cropping systems research and agriculture must look for opportunities to live with weedy species and focus on *nature-friendly farming, conservation farming* and *regenerative agriculture* systems. As Altieri *et al.* (2015) showed, the pollination benefits alone of maintaining weedy taxa in agricultural landscapes is enormous. Besides, weedy taxa and their genes enrich the biological diversity of landscapes which they occupy. Can people ever imagine a world without colonizing species?

At all times, we must use IWM approaches to tackle and manage those problematic species in the field and be aware that this might take more than a few seasons. None of the above ideas is new. Many countries have adopted ways by which they could use weedy taxa and the bioresources they provide to the maximum. However, in our Asian-Pacific region, weed biodiversity and utilization are topics that are yet to become front and centre of weed discourses.

Hill and Hadly (2017) recently wrote: '*As the world stumbles deeper into the Anthropocene, the novel biogeographic dynamics (globalization, mass disturbance, and climate change) will progressively warp habitats*'. Under such disturbances, colonizing taxa will thrive and change their habitats. However, I must emphasize that *weedy species are no more alien or villainous than we humans have been*. With or without humans on the Planet, colonizing species will play vital roles in stabilizing the Earth's ecosystems. *They will also survive future catastrophes on Earth. We may not.*

Countering mis-information about weedy taxa requires the following: (1) recognition of the seriousness of the problem and (2) refuting the claims that weeds are bad news all the news with evidence-based scientific findings. Science helps us approach the '*world of weeds*' with wonder and humility. Scientific ethics call for us to have an honest dialogue with Nature. Science will also help us fight fake news and mis-information, navigate the troubled waters, and find a more resilient and reasonable position concerning weedy taxa. We must all strive to '*re-think Nature*' (Hill and Hadly 2018) and attempt to find the '*middle ground*' in the discourses (Shackelford *et al*. 2013) instead of blaming colonizing taxa for human follies.

Sometimes, science, as a human enterprise, moves too slowly, as Thomas Kuhn (1962) said. Science is also largely conservative in the sense that changes in ideas and directions occur only after the cumulative accumulation of sufficiently robust evidence, which might take a long period. Science also suffers from prejudices, sentiments and conventions, as it is a human endeavour.

Concerning the broad aspect of *utilization of the powers and strengths of weedy taxa*, I believe that we have reached a point that the evidence cannot be ignored any more. We are all aware that scientists spend too much time taking long periods and small steps towards working out solutions to a problem. Weed researchers are no exception to this. Introspection and profound reflections on the subject matter are critical to formulate new hypotheses and test their validity. However, when there is a large volume of evidence to support changing a paradigm, scientists should not hesitate for too long.

We believe colonizing taxa, labelled intruders in human-modified landscapes, have suffered enough. This "fixed" pessimistic worldview of colonizing species has led us to a crisis point of relentless warfare against them. This unsustainable, negative attitude must change to a new paradigm of 'living with weeds', which is not radical. Positive appreciation of weeds has also existed around human-plant interactions for millennia.

With their remarkable botanical and ecological attributes (Baker 1965), weedy taxa generate 'threshold' situations for us – moments when the factors that cause environmental degradation are, for a time, reversed. We can take advantage of these moments. Weeds can turn the plant world and enhance the biodiversity of landscapes around them and make a genuine dialogue with all that is 'still wild' possible. This suggestion (claim) can be scientifically investigated, which will help understand their critical ecological roles better. We encourage weed researchers all over the world to urgently re-focus attention on understanding the ecology and biology of weeds a great deal more. Weed scientists should also redouble their efforts to combat misinformation about weeds and seek a collaborative co-existence.

Egocentric humans might argue that humans can devise ways to survive without the natural world and that we need not depend on it for our existence. But is that world we want to live in? People will find no joy in a world without the rich diversity of flora and fauna, including colonizing species that share the Planet with us. Weed Science, in my view, should also be taught at various levels, to foster a deeper appreciation of our natural world and the critical role weedy species play in it. A change in attitude towards misunderstood weedy taxa can be expedited by focusing on their utilization and economic values and *what they can offer to our Planet mother, who is presently in distress*. In that sense, what I have sought to highlight in this essay is not necessarily a need for a 'paradigm shift' in Weed Science (in the sense of Thomas Kuhn 1962) but simply an objective re-appraisal of weedy taxa that can assist both human societies and the distressed Planet.

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REVIEW ARTICLE

Impact of climate change on invasive weeds affecting biodiversity and natural ecosystems

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ABSTRACT

Invasive weeds pose a growing threat to biodiversity and natural ecosystems, a challenge that is escalating with climate change. These resilient plants, marked by rapid growth and adaptability, outcompete native species, disrupt ecological balances, and alter critical ecosystem functions. As climate change progresses, rising temperatures along with CO_2 and shifting precipitation patterns create favorable conditions for invasive weeds to proliferate, often at the expense of native flora. The ecological consequences of these invasions are profound, leading to the displacement of native species, altered species composition, and a significant reduction in biodiversity. Herbivores, pollinators, and other wildlife are increasingly affected as their habitats and food sources are transformed by the spread of invasive plants. Additionally, the disruption caused by these weeds extends to essential ecosystem functions, including nutrient cycling, soil health, and water regulation. The management of invasive species is becoming increasingly complex due to the unpredictability of climate change. In response, adaptation strategies, such as integrated pest management (IPM), are being developed to address these evolving challenges. Predictive models and scenario analyses are providing valuable insights into potential future risks, while effective management increasingly relies on robust policies and public engagement. Despite these efforts, significant research gaps persist, particularly in understanding the long-term impacts of invasive weeds and in developing effective restoration strategies for ecosystems already compromised by their spread.

Keywords: Climate change, Biodiversity, Invasive weeds, Natural ecosystem

INTRODUCTION

Plant invasions are often facilitated by human activities such as global trade, horticulture, and agriculture, sets the stage for a dynamic and often destructive competition with native flora (Charles and Dukes 2007, Pysek *et al.* 2020, Aguin-Pombo 2012, Mashhadi and Radosevich 2004). In their native habitats, plants co-evolve with local species, maintaining ecological balance. However, in new environments, invasive weeds often escape their natural predators and diseases, giving them a competitive edge (Wang *et al.* 2009). Their rapid growth, high reproductive rates, and adaptability enable them to quickly establish, spread, and outcompete native plants for essential resources like light, water, and nutrients (Daehler 2003) which results in significant ecological consequences like reduced biodiversity and disrupted food webs (Ehrenfeld 2003, Ngondya 2017, Narango *et al.* 2018). Major invasive weeds and their ecosystem impacts have been depicted in **Table 1**.

Invasive species may fail to stabilize soil as effectively as native plants, leading to increased erosion and altered hydrological cycles due to changes in water infiltration and runoff. Furthermore, invasive weeds can alter soil chemistry, rendering it less suitable for native species (Weidenhamer and Callaway 2010). These weeds also significantly impact fire regimes and habitat structures, contributing to widespread ecological and infrastructural challenges. *Bromus tectorum*, for instance, increases the frequency and intensity of wildfires by creating a continuous layer of fine, easily ignitable fuel, leading to the destruction of native plant communities and a cycle that favors further invasion (Bradley *et al.* 2018). Dense stands of invasive plants block sunlight, inhibiting understory growth and

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Table 1. Global overview of major invasive weeds and their ecosystem impacts

Country	Invasive weed	Species	Family	Ecological impact	Reference
India	Lantana	*Lantana camara*	Verbenaceae	Forms dense thickets, outcompetes native vegetation, releases allelopathic chemicals, reduces habitat quality for native wildlife, and invades pastures and croplands.	Dar *et al*. 2019
India	Chromolaena	*Chromolaena odorata*	Asteraceae	Rapid growth smothers native vegetation, reduces biodiversity, alters fire regimes, and impacts forest regeneration.	Dar *et al*. 2019
India	Congress Grass	*Parthenium hysterophorus*	Asteraceae	Outcompetes native vegetation, reduces agricultural productivity, and causes health problems in humans and animals.	Dar *et al*. 2019
India	Water Hyacinth	*Eichhornia crassipes*	Pontederiaceae	Forms dense mats on water surfaces, blocks sunlight, depletes oxygen levels, kills aquatic organisms, impedes water flow, and provides breeding grounds for mosquitoes.	Dar *et al*. 2019
India	Mikania	*Mikania micrantha*	Asteraceae	Rapid growth overwhelms native vegetation, decreases biodiversity, and interferes with ecosystem functions.	Dar *et al*. 2019
India	Goat weed	*Ageratum conyzoides*	Asteraceae	Rapid growth chokes out native vegetation, diminishes biodiversity, and changes habitat structures.	Dar *et al*. 2019
India	Mesquite	*Prosopis juliflora*	Fabaceae	Outcompetes native vegetation, forms thick mats, diminishes grazing areas for livestock, modifies soil chemistry, and escalates water consumption.	Dar *et al*. 2019
India	Mimosa	*Mimosa pudica*	Fabaceae	Surpasses native vegetation, dense mats are formed, diminishes biodiversity, and affects agricultural lands. 4o mini	Dar *et al*. 2019
India	Morning Glory	*Ipomoea* spp.	Convolvulaceae	Smothers native vegetation by rapid spread, reduces biodiversity, and alters habitat structures.	Dar *et al*. 2019
United States	Kudzu	*Pueraria montana*	Fabaceae	Diminishes biodiversity, overwhelms native plants depletes soil nutrients and water, and disrupts habitat structures.	Marler 2000
United States	Cheatgrass	*Bromus tectorum*	Poaceae	Alters fire regimes by increasing frequency and intensity of wildfires, Forms dense monocultures, surpasses native grasses and reduces native plant populations.	Marler 2000
United States	Purple Loosestrife	*Lythrum salicaria*	Lythraceae	Invades wetlands, outcompetes native vegetation, reduces habitat quality for wildlife, and disrupts water flow and sedimentation patterns.	Marler 2000
United Kingdom	Japanese Knotweed	*Fallopia japonica*	Polygonaceae	Damages infrastructure with robust root systems Forms dense thickets that crowd out native plants, destabilizes riverbanks, and increases erosion.	Shaw *et al.* 2011
Australia	Lantana	*Lantana camara*	Verbenaceae	Releases allelopathic chemicals, Forms dense thickets, outcompetes native vegetation, reduces habitat quality for native wildlife, and invades pastures and croplands.	Shaik *et al.* 2022
Australia	Prickly Pear	*Opuntia* spp.	Cactaceae	Forms impenetrable thickets, outcompetes native vegetation, alters habitat structure, and reduces grazing land for livestock.	Shaik *et al.* 2022
South Africa	Water Hyacinth	*Eichhornia crassipes*	Pontederiaceae	Forms dense mats on water surfaces, blocks sunlight, depletes oxygen levels, kills aquatic organisms, impedes water flow, and provides breeding grounds for mosquitoes.	Zimmermann *et al.* 2004
South Africa	Black Wattle	*Acacia mearnsii*	Fabaceae	Outcompetes native vegetation, Forms dense stands, reduces water availability, and alters fire regimes.	Zimmermann *et al.* 2004
New Zealand	Old Man's Beard	*Clematis vitalba*	Ranunculaceae	Smothers native trees and shrubs, reduces biodiversity, and alters habitat structure.	Ogle *et al.* 2000
Brazil	African Tulip Tree	*Spathodea campanulata*	Bignoniaceae	Outcompetes native vegetation, reduces biodiversity, and alters habitat structure.	Pimenta *et al.* 2020
China	Mile-a-Minute Weed	*Mikania micrantha*	Asteraceae	Rapid growth smothers native vegetation, reduces biodiversity, and disrupts ecosystem functions.	Zhang *et al.* 2004
Canada	Common Reed	*Phragmites australis*	Poaceae	Establishes dense stands in wetlands, outcompetes native plants, diminishes habitat quality for wildlife, and disrupts hydrology and sedimentation patterns.	Catling, and Mitrow 2011
Mexico	Yellow Star-Thistle	*Centaurea solstitialis*	Asteraceae	Invades pastures and rangelands, outcompetes native plants, reduces forage availability for livestock, and increases management costs.	Grimsrud *et al.* 2008
Kenya	Prosopis	*Prosopis juliflora*	Fabaceae	Forms dense thickets, outcompetes native vegetation, reduces grazing land for livestock, alters soil chemistry, and increases water use.	Gichua 2014
Russia	Sosnowsky's Hogweed	*Heracleum sosnowskyi*	Apiaceae	Creates dense stands, outcompetes native vegetation, lowers biodiversity, and its toxic sap can cause severe skin burns and blindness in humans.	Chadin *et al.* 2017
Indonesia	Siam Weed	*Chromolaena odorata*	Asteraceae	Rapid growth smothers native vegetation, reduces biodiversity, and alters habitat structure.	Tjitrosoedirdjo *et al.* 1991
Philippines	Cogon Grass	*Imperata cylindrica*	Poaceae	Forms thick mats, outcompetes native vegetation, decreases biodiversity, and increases fire risk.	Walpole 2005
Sri Lanka	Salvinia	*Salvinia molesta*	Salviniaceae	Forms dense floating mats, reduces light penetration, depletes oxygen in water bodies, and harms aquatic ecosystems.	Kariyawasam *et al.* 2021
Zimbabwe	Water Lettuce	*Pistia stratiotes*	Araceae	Creates dense mats on water surfaces, obstructs sunlight, depletes oxygen, and disrupts aquatic ecosystems.	Mujaju *et al.* 2021
Thailand	Mimosa Pigra	*Mimosa pigra*	Fabaceae	Outcompetes native vegetation, establishes dense stands, decreases biodiversity, and disrupts wetland ecosystems.	Pramual *et al.* 2011
Egypt	Giant Reed	*Arundo donax*	Poaceae	Increases fire risk, alters riverbank habitats, forms dense stands, and outcompetes native vegetation.	Galal and Shehata 2016
Fiji	Koster's Curse	*Clidemia hirta*	Melasto-mataceae	Forms dense thickets, displaces native vegetation, reduces biodiversity, and disrupts forest regeneration.	Conant 2009
Nigeria	Tithonia	*Tithonia diversifolia*	Asteraceae	Displaces native vegetation, changes soil chemistry, and affects agricultural productivity.	Ayeni *et al.* 1997

reducing plant diversity, which in turn affects animals dependent on the understory for food and shelter. In aquatic environments, invasive species like *Eichhornia crassipes* clog waterways, disrupting water flow and quality, reducing oxygen levels, and harming aquatic life (Yigermal and Assefa 2019). Additionally, *Fallopia japonica* can cause severe infrastructure damage by penetrating foundations and pavement with its roots, leading to costly repairs. Invasive aquatic weeds also clog pipes and irrigation systems, resulting in significant maintenance and repair expenses (Docking 2024).

Invasive weeds spread and establish themselves through various natural and human-induced mechanisms. They use wind, as seen with *Taraxacum* spp. and *Cirsium* spp., which have lightweight seeds with plumes or wings for easy dispersal (Abbas *et al.* 2023). Water-dispersed species like *E. crassipes* spread through currents in rivers and lakes, while animals contribute by transporting seeds on their fur or in their digestive tracts, with birds, mammals, and insects playing key roles (da Cunha *et al.* 2022). Human activities further exacerbate their spread: contaminated agricultural products, transportation methods such as vehicles, ships, and planes, and global trade facilitate the movement of seeds and plant fragments (Perrault *et al.* 2003). Horticulture and landscaping practices, exemplified by *F. japonica* and *Lythrum salicaria*, can lead to the escape of ornamental plants into the wild (Donahue 2017). Vegetative reproduction through rhizomes, stolons, or tubers allows species like *F. japonica* to quickly form dense stands, while aquatic weeds such as *Hydrilla verticillata* can grow from small fragments. Invasive weeds also exhibit high phenotypic plasticity, adapting to diverse environmental conditions and rapidly outcompeting native species (Stahlman 2016). Some use allelopathy, releasing chemicals that inhibit the growth of surrounding plants, as seen with *Juglans nigra* and *Alliaria petiolate* (Srivasava *et al.* 2017). They often colonize disturbed habitats such as roadsides and construction sites, establish quickly before native species can recover, and thrive in post-fire environments by rapidly germinating in nutrient-rich ash. Additionally, escaping natural predators and diseases from their native ranges, combined with traits that confer resistance to local pests, and hybridization with local or introduced species further enhance their invasiveness (Daly *et al.* 2023). This amalgamation of dispersal methods, reproductive strategies, adaptability, and lack of natural enemies facilitates their successful colonization and dominance in new environments.

Climate change and its effects on invasive weeds

Global climate change has profound implications for ecosystems, particularly through its effects on invasive weeds. (Ramesh *et al.* 2017, Finch *et al.* 2021). Warmer temperatures hasten the growth rates of invasive weeds due to extended growing seasons and increased physiological processes like photosynthesis and respiration. For instance, *Pueraria montana var. lobata* in the southeastern United States grows more rapidly with rising temperatures, smothering native vegetation and lessening biodiversity (Kato-Noguchi 2021). Similarly, *Lepidium latifolium* and *Arundo donax* display enhanced growth and competitiveness in warmer conditions. These temperature-driven changes enable invasive weeds to outpace native species and rapidly dominate new areas (Jimenez-Ruiz *et al.* 2016). Increased rainfall benefits species like *Heracleum mantegazzianum* and *F. japonica*, which thrive in moist conditions and expand their range by monopolizing water resources (Seeney 2018, Marigo and Pautou 1998). In contrast, drought-tolerant species such as *Cenchrus ciliaris* and *B. tectorum* gain a benefit in arid regions, where they outcompete native plants, alter fire regimes, increase soil erosion, and degrade ecosystem services (Walther 2019). Water hyacinth also showed increased flowering and seed production rates under higher temperatures, contributing to their spread in freshwater systems (Yan *et al.* 2017). The shift in climatic conditions transforms previously unsuitable regions into promising environments for these invasive species. For example, *Lythrum salicaria,* a native of Europe has moved northward in North America, threatening wetlands, while *C. ciliaris* has migrated to higher elevations, altering fire regimes and diminishing native plant diversity (Harper-Lore *et al.* 2007).

Storms, floods, and droughts can spread aquatic weeds such as *Eichornia. crassipes* and *Hydrilla. verticillata*, leading to the formation of dense mats that block sunlight, deplete oxygen, and disrupt water flow, thereby collapsing native aquatic ecosystems (Ta *et al.* 2017). In terrestrial situations, shifting wind patterns and animal behavior further facilitate the spread of invasive seeds. For instance, seeds of *Arundo donax* and *Tamarix* spp. are dispersed more widely by wind and water as temperatures rise (Gonzalez *et al.* 2017). Increased atmospheric CO_2 increases photosynthesis, resulting in higher biomass production for invasive species like *Pueraria montana var. lobate* and *Cirsium arvense*, which outcompete native plants for resources and form dense stands that alter habitats (Ziska 2011). Higher

CO_2 favors water-use efficiency by reducing stomatal conductance, benefiting arid-adapted species such as *B. tectorum* and *C. ciliaris*, allowing them to flourish during dry periods and outperform water-sensitive natives (Dukes and Mooney 1999), which leads to changed hydrological cycles and more intense fire regimes, impacting water availability and soil properties, eventually compromising ecosystem health (Ryan *et al.* 2012).

Severe storms, hurricanes, and floods significantly enable the spread of invasive weeds like seeds of *A. donax* and *Tamarix* spp. over long distances, aiding their colonization in new areas and *Triadica sebifera* colonized in the Gulf Coast after Hurricane Katrina (Felger *et al.* 2013, Henkel *et al.* 2016). Floods aggravate this issue by dispersing seeds and vegetative fragments like *E. crassipes* and *Salvinia molesta* to form dense mats that choke native plants and disrupt water quality favor species like *F. japonica*, which rapidly colonizes riparian zones and alters riverbank stability (Akpabey 2012, Rapp 2006). Drought's stress makes native vegetation vulnerable to drought-tolerant invasives like *B. tectorum C. ciliaris C. solstitialis* and *Salsola tragus* (Schmitz and Jacobs 2007) (**Figure 1**). To mitigate these effects and preserve ecosystem health, it is crucial to develop and implement adaptive management strategies that address the complex dynamics of invasive weeds in a rapidly evolving climate.

Interactions between climate change and invasive weed management

In recent years, climate change has significantly impacted both natural and human ecosystems, with agriculture (Ainsworth and Long 2005, Chauhan *et al.* 2014, Kang and Banga 2013). Shifts in weather patterns affect all components of agricultural systems, especially weeds, and their management (Ramesh *et al.* 2017). However, in agricultural ecosystem, weeds and crops coexist, requiring a more integrated method to understanding their interactions under changing climate conditions (Chauhan *et al.* 2014, Kang and Banga 2013). Prevention is better than cure, and weed management should be supported by comprehensive prevention measures. To manage this, countries must conduct risk assessments for national planning to address new threats from invasive weeds (Chandrasena 2009). Gathering data through local and regional surveys, sharing data on the distribution and abundance of potential invasive weeds, and enhancing border protection via quarantine are crucial preventive steps.

Cultural control strategies, such as adjusting sowing times to create a less weedy environment, have proven effective in reducing weeds like *Phalaris minor* and *Avena fatua* in North India. Incorporating climate-smart, weed-suppressing crops into cropping systems can further help manage invasive weeds (Jinger *et al.* 2016). Furthermore, developing new crop varieties with higher yield potential and resilience

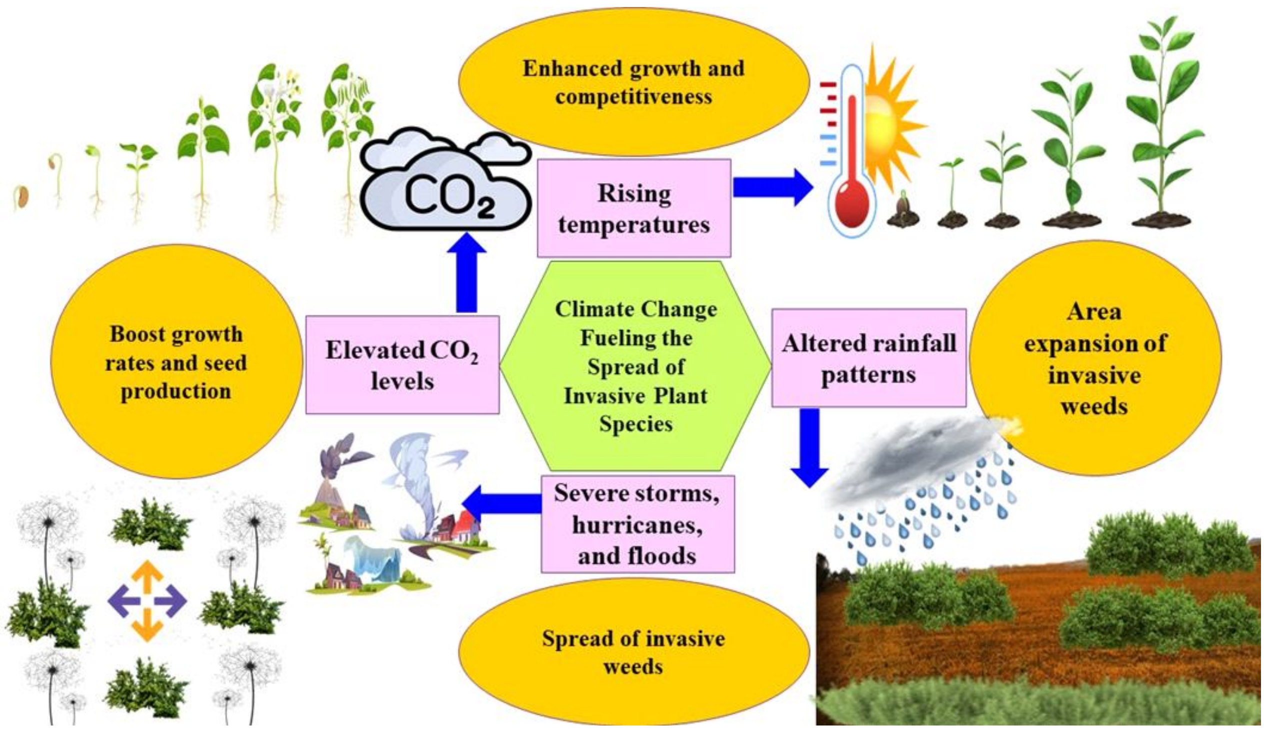

Figure 1. Visual representation of climate change impacts on invasive weed dynamics

to changing climatic factors, such as drought and elevated CO_2 levels, will enhance weed management.

Mechanical control is widely used for managing invasive weeds in developing countries. However, climate change can complicate this method by altering the root-to-shoot ratio in plants. For example, elevated CO_2 can lead to increase below-ground carbon storage and growth in perennial invasive weeds like *Lantana* spp., making its mechanical control more challenging (Rogers *et al.* 1994) and such as *Chondrilla juncea* and *Solanum elaeagnifolium* (Ziska *et al.* 2004, Kriticos *et al.* 2010).

Biological control success of bioagents relies on their ability to feed exclusively on the target weed (Kriticos *et al.* 2010). However, climate change can impact the efficacy of these biological control agents by altering their biology or the ability of the host weed to tolerate or resist herbivores or pathogens (Singh *et al.* 2016). Elevated CO_2 can also change the profile of secondary compounds in weeds, affecting weed-herbivore interactions (Ziska *et al.* 2005), and changes in the carbon-to-nitrogen (C: N) ratio in weeds (Malarkodi *et al.* 2017). Drought conditions may increase the levels of insect-resistant allelochemicals in some weed species (Gerard *et al.* 2010), and can alter the distribution of both invasive weeds and their biological control agents. For example, with elevated temperatures potentially causing bioagents to move from subtropical to temperate regions, affecting their efficacy (Reeves 2017). Thus, as invasive weeds and their biological control agents respond differently to various climate change factors (Holt and Hochberg 1997). Kumar *et al.* (2021) when offered leaves of Parthenium grown in open top under elevated CO_2 and temperature *Zygogramma bicolorata* recorded increase in consumption, slower food conversion rates, increase in developmental period with reduced reproduction efficiency. They interpreted that the reproduction efficiency of *Z. bicolorata* is likely to be reduced as the climate changes, despite increased feeding rates exhibited by grubs and adult beetles on parthenium weed foliage.

The use of novel herbicide molecules to control invasive weeds is considered one of the most cost-effective methods and are now widely used in managing invasive weeds (Clout and Williams 2009; Radosevich *et al.* 2007). However, the success of herbicide-based weed management profoundly depends on climatic situations, particularly for foliage-applied post-emergence herbicides (Kudsk and Kristensen 1992, Ziska 2020). Climate factors like temperature, CO_2 levels, soil moisture, and wind speed can significantly influence herbicide coverage, persistence, mode of action, efficacy, selectivity, herbicide volatility, altering selectivity for both pre- and post-emergence herbicides (Madafiglio *et al.* 2000, Medd *et al.* 2001, Bailey 2004). Higher temperatures may hasten plant growth, narrowing the window for effective herbicide application before the critical crop-weed competition period begins (Howden *et al.* 2007).

Predictive modeling of invasive weed dynamics

An ecological model is any form of simplification of the relationship between a species and its environment (Kriticos 1996). Ecological niche models (ENMs) are used to predict suitable ecological niches for a species across a landscape and niche concept is central to ENMs and is based on Hutchinson's (1957) concept of fundamental and realized niches (Araujo and Guisan 2006). There is a risk of invasion in the unoccupied part of the fundamental niche of introduced range (Soberon and Nakamura 2009). Ecologists have used ecological niche models (ENMs) to map suitable areas for potential invaders to guide conservation and management strategies (Gama *et al.* 2017). These models found correlations among environmental conditions and species occurrence records to identify suitable climatic conditions (Broennimann *et al.* 2012). It has been highlighted that invasive species often show a wider range of climatic conditions during the invasion process, than those described in their areas of origin (Rodrigues *et al.* 2016). Thus, in order to capture a major part of suitable conditions for the invader, ENMs must be calibrated bearing in mind both the native and invasive geographic ranges of the species (Sales *et al.* 2017). To effectively study the impact of climate change on invasive weeds, several decision support tools have been successfully utilized.

Policy and legislation

Nearly 50 international legal instruments or guidelines deal with some aspects of invasive alien species including invasive weeds (IAS),) prevention or management. They provide a baseline for national legal frameworks. The longest-established agreements focus on controlling the introduction and spread of pests and diseases to protect animal and plant health by means of quarantine systems. The International Plant Protection Convention and policy guidelines by IUCN. Biodiversity-related tools focus on IAS threats to native species and ecosystems. e.g. CBD, CITES and particularly Biodiversity Act 2002 in India. Technical guidelines and codes of conduct are also there to minimize risks of unwanted introductions through specific transport or trade pathways. It includes WTO's SPS agreement. Of these, the important ones are discussed briefly below.

- The International Plant Protection Convention offers a framework for international cooperation to prevent the spread of pests of plants and plant products between countries and to help appropriate measures for their control within countries. Hence, IAS of weeds are covered by the IPPC as they qualify as pests of plants or plant products (Shine 2024)
- United Nations Convention on the Law of the Sea (1982) works for the marine environment, introductions of non-native species are covered in a general way (Article 196).
- Ramsar Convention on Wetlands sees after coastal and inland wetlands, parties to the Ramsar Convention on Wetlands are urged to address issues relating to invasive alien species in a decisive and holistic manner, making use of tools and guidance developed by various institutions and under other conventions (resolution VIII.18, November 2002).
- United Nations Environment Programme (UNEP) under Regional Seas Programme in Annex V of the Convention for the Protection of the Marine Environment of the North-East Atlantic (1992) provides for listing and management of human activities capable of causing adverse impacts on the marine environment, including introductions of alien or genetically modified species.
- UN Sustainable Development Goal 15, concerned with life on land states its target 15.8 to "reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species." The measure for the accomplishment of this target is the "proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of IAS (Shine *et al.* 2000)
- Legislation relating to IAS in India works on the Prevention and Control of Infectious and Contagious Disease in Animals Act 2009; The Plant Quarantine (Regulation of Import into India) Order, 2003; The Destructive Insects and Pests Act, 1914 and amendments; The Plants, Fruits & Seeds (Regulation of Import into India) Order 1989 (PFS Order 1989); Livestock Importation Act, 1898 and the Livestock Importation (Amendment) Ordinance, 2001; Environment Protection Act, 1986; The Biological Diversity Act, 2002; Indian Forest Act, 1927; Wildlife (Protection) Act, 1972 ; Forest (Conservation) Act, 1980

Regional focus: Climate change has significantly impacted weed spreading and behavior in various ways. The expansion of thermophile weeds, such as *Amaranthus retroflexus*, *Abutilon theophrasti*, *Panicum dichotomiflorum*, and *Datura stramonium*, has been observed in more northern regions of Europe (Guillerm *et al.* 1990, Breitsameter *et al.* 2014). Additionally, late-emerging weeds like *Chenopodium* spp., and millet weeds including *Echinochloa* spp., *Setaria* spp., *Digitaria* spp., and *Sorghum halepense*, have also extended their distribution ranges (Mehrtens *et al.* 2005, Otte *et al.* 2006). In the past two decades, Greenland and Antarctic ice sheets have been losing mass, and global glaciers are shrinking [IPCC 2013]. Climate change could shift climatic zones significantly, for example Mediterranean climates will move northward, and deserts could advance 400-800 km north into subtropical regions.

Research and knowledge gaps

Although, it is well-established that climate change can aggravate the spread and impact of invasive species, the specific mechanisms by which these factors interact, mainly in different types of ecosystems, are not fully understood. There is a need for more research on how unstable climate patterns influence the phenology of invasive species relative to native species, which could provide insights into the timing and effectiveness of management interventions (Panda *et al.* 2018). Another less-researched area is the role of invasive weeds in altering ecosystem services under changing climatic conditions (Mainka and Howard 2010). For instance, research is needed to determine how invasive plants like *P. hysterophorus* in India might affect soil carbon storage in agricultural and forested landscapes under varying climatic scenarios. (Ahmad *et al.* 2019). One capable area of research is the development of predictive models that integrate climate change projections with the potential spread and impact of invasive species (Smith *et al.* 2012). Another important research direction involves exploring the genetic and physiological adaptations of invasive species to changing climates. For example, studying the genetic diversity and adaptive traits of *L. camara* in various regions of India could reveal insights into how this invasive species might respond to future climate conditions, enabling more precise and effective management strategies (Bhagwat *et al.* 2012).

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REVIEW ARTICLE

Climate change and crop-weed interactions: Unraveling the complex interactions between crops and weeds

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ABSTRACT

As the global climate continues to shift, the impacts of rising temperatures and elevated atmospheric CO_2 on agricultural systems have become increasingly significant, particularly in relation to crop-weed interactions. Several crops are especially vulnerable to climate-adaptable weeds, which possess higher fecundity, aggressiveness, and ecological resilience. Elevated CO_2 levels typically enhance the growth and competitive advantage of C_3 crops over C_4 weeds, due to the greater photosynthetic efficiency of C_3 plants under higher CO_2 concentrations. However, this advantage may diminish with rising temperatures, as C_4 weeds are more resilient to heat stress and can outcompete C_3 crops. The interaction between elevated CO_2 and temperature creates complex scenarios where the benefits of CO_2 enrichment for C_3 crops can be offset by the competitive edge gained by C_4 weeds under higher temperatures. Additionally, drought conditions further complicate these interactions, with C_4 weeds generally exhibiting greater resilience and competitive ability under moisture stress compared to C_3 weeds. Key outcomes of this review include the enhanced competitiveness of weeds under climate change, the altered physiological responses of both crops and weeds, and insights into the molecular and biochemical mechanisms driving weed adaptability to elevated CO_2 and temperature. These shifts in crop-weed dynamics present serious implications for crop yields. The review emphasizes the urgent need for adaptive, climate-resilient weed management strategies to mitigate these effects and sustain agricultural productivity in the future.

Keywords: Climate Change, Crop-weed interaction, Drought stress, C_3 weeds, C_4 weeds, elevated CO_2 and elevated temperature

INTRODUCTION

The world is currently off track in achieving the second Sustainable Development Goal (SDG2) to "end hunger, achieve food security and improved nutrition, and promote sustainable agriculture" by 2030 (UNICEF *et al.* 2019). Food security is vital for global sustainability, yet the increasing sensitivity of food production to climate change poses significant challenges (Porter *et al.* 2014). In recent decades, extreme weather events such as heatwaves, droughts, and prolonged precipitation have become more frequent, with devastating effects on agricultural productivity (Yan *et al.* 2022, Lobell *et al.* 2013, Vermeulen *et al.* 2013).

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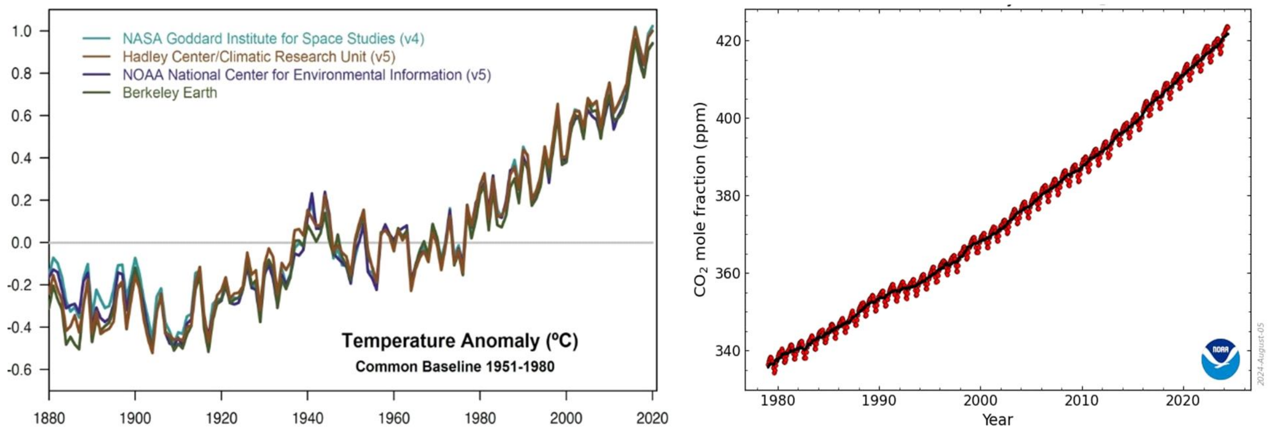
The impact of climate change on agricultural production is profound. Many regions worldwide have experienced reduced yields in essential crops such as wheat, maize, rice, and oilseed rape (Lachaud *et al.* 2022, Chandio *et al.* 2023). In India, for example, the annual average crop losses due to extreme weather events are estimated to account for around 0.25% of the nation's GDP (Singh *et al.* 2019). Without effective adaptation measures, global yields of critical food crops could decline by 12–20% by the end of the century (Aggarwal *et al.* 2019). This decline is expected to worsen as the current warming trend predicts average global temperature increases of 1.5–4.8 °C by 2100 (Malhi *et al.* 2021). The long-term warming patterns since pre-industrial times indicate a rise in temperatures by 0.1 to 0.3 °C per decade (IPCC, 2018). The Intergovernmental Panel on Climate Change (IPCC) forecasts that the average world temperature could increase by 2 °C by 2100 and 4.2 °C by 2400 (IPCC, 2021, NASA) (**Figure 1**). Simultaneously, the concentration of CO_2 in the atmosphere has been rising at an unprecedented rate, reaching 426 parts per million (ppm) in 2024 (https://www.co2.earth/daily-co2). Projections



Source: NASA **Source:** NOAA

Figure 1. Global atmospheric temperature and CO_2 levels trend

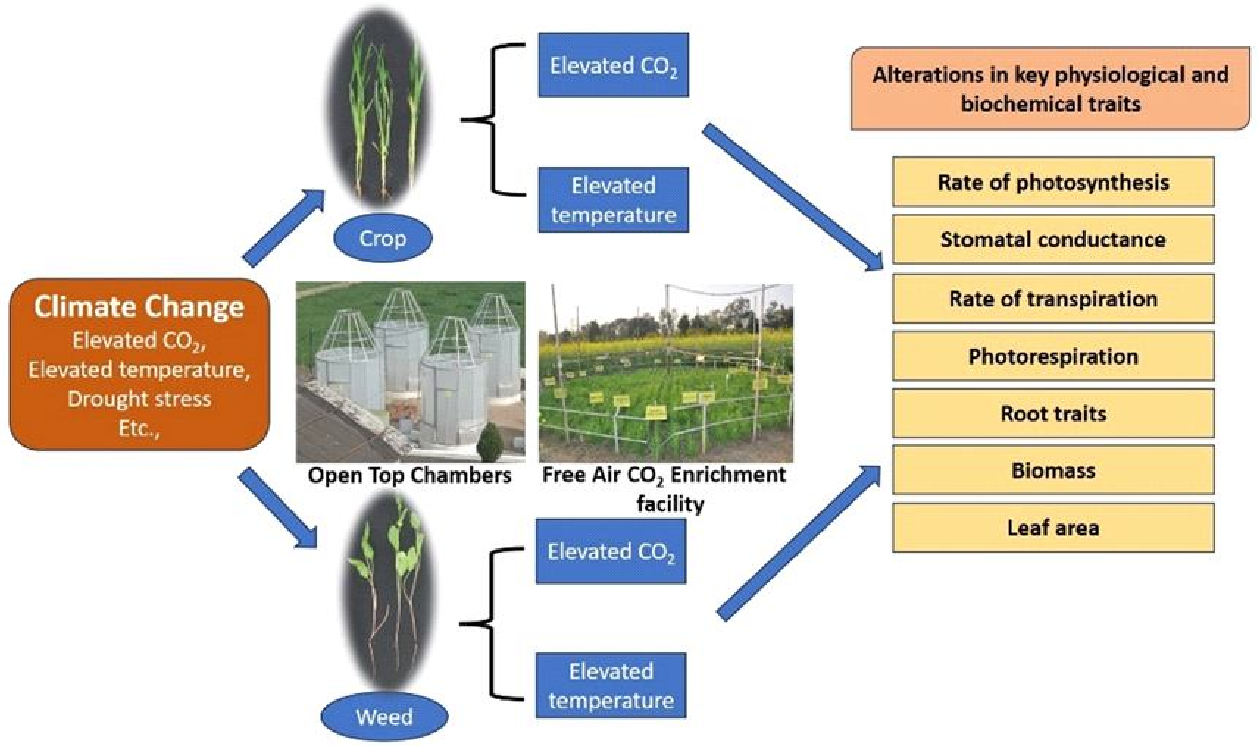


Figure 2. Impact of elevated CO_2 and temperature on crop-weed physiology and biochemistry

suggest that CO_2 levels may exceed 600 ppm in the near future (**Figure 1**), with a conservative estimate of 700 ppm by the end of the century (Ramanathan and Feng 2008, IPCC 2007, NOAA). Both elevated CO_2 and high temperatures are known to alter metabolic pathways in crop plants, generally leading to reduced yields and total biomass. However, elevated CO_2 can also have beneficial effects, such as increasing carbon uptake and improving water use efficiency through transcriptional reprogramming of metabolism (Leakey *et al.* 2009).

As the planet grapples with the effects of climate change, it becomes increasingly vital to understand how rising temperatures and atmospheric CO_2 levels influence various aspects of the natural world. Among these considerations, the impact of elevated CO_2 and temperature on weed growth and physiology emerges as a critical area of research (Upasani *et al.* 2018) (**Figure 2**). Weeds, often seen as nuisances in agriculture, play a complex and multifaceted role in ecosystem dynamics. Globally, weeds are responsible for approximately 34% of crop yield losses (Oerke 2006), and they pose additional challenges under changing climate conditions (Sreekanth *et al.* 2023; Mahawar *et al.* 2023, Roy *et al.* 2023). These weeds can severely impact crop productivity and agricultural systems, affecting major crops like rice (Sreekanth *et al.* 2024, Pawar *et al.* 2022), wheat (Sondhia *et al.* 2023), soybean (Chander *et al.* 2023), and potato (Chethan *et al.* 2023) *etc*. These opportunistic plant species exhibit remarkable adaptability, aggressiveness, competitiveness, and high fecundity, enabling them to thrive in diverse and challenging environmental conditions (Nguyen *et al.* 2015).

Given their adaptability and resilience, weeds are particularly responsive to changes in atmospheric composition and temperature regimes, making them formidable competitors to crops under climate change (Rodenburg *et al.* 2011, Blumenthal *et al.* 2013). Studying the effects of climate change on weed growth and physiology is essential not only for understanding the broader implications for ecosystems but also for devising effective strategies for sustainable agriculture (Mahajan *et al.* 2012, Grossman *et al.* 2014). While the influence of climate change on crops can be extrapolated to weeds, the dynamics often favor weeds, which, due to their plasticity, superior adaptability, and broader ecological tolerances, are more likely t outcompete crops.

Weeds' ability to compete with crops for scarce resources such as water and nutrients leads to significant reductions in crop yields (Ramesh *et al.* 2017). Furthermore, some weeds offer positive ecological benefits, such as absorbing heavy metals from contaminated soils (Roy *et al.* 2021). The genetic diversity and physiological flexibility of weeds often surpass that of crops, allowing weeds to survive and thrive under fluctuating environmental conditions and resource availability. As climate change is projected to enhance weed competitiveness, ineffective weed management practices could lead to substantial yield losses (Miri *et al.* 2012, Valerio *et al.* 2013). Therefore, efficient weed management and control are critical to maintaining crop productivity.

This review explores the intricate relationship between rising atmospheric CO_2 levels, increasing temperatures, and their combined effects on crop-weed interactions and associated physiological responses. As global climate change continues to reshape environmental conditions, understanding how weeds respond to these changes is imperative for ensuring sustainable agriculture and effective ecosystem management. It provides an in-depth analysis of the underlying molecular and biochemical mechanisms governing weed responses to elevated CO_2 and temperature, offering a foundation for understanding the observed physiological changes and informing strategies for sustainable agriculture and ecosystem management.

CLIMATE CHANGE FACTORS INFLUENCING WEED GROWTH AND BIOMASS

Photosynthetic mechanism of C_3 and C_4 plants

The varying responses of C_3 and C_4 plants to altered climatic conditions require a more thorough understanding of the C_3 and C_4 photosynthetic cycles in weeds (**Table 1**).

Table 1. Differences in photosynthetic mechanism of C_3 and C_4 plants

Aspect	C_3 Plants	C_4 Plants	References
Photosynthetic Pathway	C_3 pathway (Calvin Cycle)	C_4 pathway (Hatch-Slack pathway)	Taiz & Zeiger, 2010, Sage *et al*. 2012
Initial CO_2 Fixation	RuBisCO enzyme	PEP carboxylase enzyme	Raven *et al*. 2009
Initial CO2 acceptor	3-carbon compound (3-PGA)	4-carbon compound (oxaloacetate)	Long *et al*. 2006, Smith & Stitt, 2007
Carbon Fixation Location	Stroma of chloroplasts	Mesophyll cells and bundle sheath cells	Long *et al*. 2006
Photorespiration	High, significant loss of CO_2 during photorespiration	Low, efficient CO_2 use due to CO_2 concentration mechanism	Walker *et al.* 2013, Tazoe *et al*. 2008
Oxygen Sensitivity	High sensitivity to photorespiration	Low sensitivity to photorespiration	Feng & Hu, 2013
Photosynthesis Efficiency	Lower efficiency in hot and dry conditions	Higher efficiency in hot and dry conditions	Sage & Monson, 1999
Leaf Anatomy	Simple anatomy; no specialized structures	Kranz anatomy (distinct bundle sheath cells)	Ehleringer *et al.* 1997
Energy Requirements	Lower energy cost for carbon fixation	Higher energy cost due to additional ATP and NADPH requirements	Lange *et al.* 2001
Water Use Efficiency (WUE)	Lower WUE compared to C_4 plants due to higher photorespiration	Higher WUE due to reduced photorespiration and enhanced CO_2 fixation	Condon *et al*. 2004
Optimal Temperature Range	Cooler temperatures (10–25 °C)	Warmer temperatures(30–45 °C)	Sage *et al.* 2012
CO_2 compensation point	50–150 ppm	0–10 ppm	Taiz & Zeiger, 2010
Environmental Adaptations	Adapted to temperate and cooler climates	Adapted to hot and arid tropical and sub-tropical areas	Lichtenthaler & Buschmann, 2001
Examples	Wheat, Rice, Soybean	Maize, Sugarcane, Sorghum	Ehleringer *et al.* 1997

Elevated CO_2 levels

Increased carbon dioxide (eCO_2) levels are known to significantly enhance the growth and maturation of many plant species, with the response varying based on the photosynthetic pathway employed by the plant (C_3 or C_4) (Kimball and Idso, 1983). For C_3 crops like rice and wheat, eCO_2 levels can potentially improve their competitive advantage against C_4 weeds, as observed by Yin and Struik (2008). This advantage is attributed to the greater efficiency of C_3 plants in utilizing the increased CO_2 for photosynthesis. However, when both CO_2 and temperature rise simultaneously, the competitive edge shifts back to C_4 species, which are better adapted to higher temperatures. Patterson and Flint (1980) also support this, indicating that C_3 plants generally benefit more from CO_2 enrichment compared to C_4 plants.

For instance, Ziska (2000) demonstrated that under monoculture conditions, soybean (C_3) exhibited increases in yield (23%) and biomass (32%) under high CO_2 levels (ambient + 250 ppm). However, when grown in competition with the C_3 weed *Chenopodium album*, soybean's yield and biomass reductions were more pronounced under elevated CO_2, decreasing from 28% and 23% at ambient CO_2 to 39% and 34% at eCO_2, respectively, due to a 65% increase in the dry weight of *C. album*. Conversely, when competing with the C_4 weed *Amaranthus retroflexus*, the soybean yield decreased from 45% to 30% at higher CO_2 levels, suggesting that *C. album* might dominate under eCO_2, while *A. retroflexus* would be less competitive, potentially giving soybean an advantage over *A. retroflexus*.

Bunce and Ziska (2000) further argue that with rising atmospheric CO_2 levels, competition from weeds in C_3 plants might diminish. However, this benefit can be offset by simultaneous increases in temperature, which tend to intensify weed competition. Thus, while elevated CO_2 may favor C_3 crops over C_4 weeds, the combination of elevated CO_2 and temperature is likely to increase the overall competitive pressure from weeds, potentially reducing the crop's advantage. In summary, when CO_2 levels rise, C_3 crops may benefit if they compete with C_4 weeds, but under conditions of both elevated CO_2 and temperature, weeds may generally gain a competitive edge over crops. eCO_2 had a positive effect on overall growth and biomass of the following weeds (**Table 2**).

Table 2. Effect of elevated CO_2 on major C_3 and C_4 weeds

Weed species	Reference
C_3 weeds	
Abutilon theophrasti Medic	Miri *et al.* 2012
Alternanthera paronychioides A. St.-Hil.	DWR 2020
Avena fatua L.	DWR 2008-09
Bromus tectorum L.	Zelikova *et al.* 2013
Chenopodium album L.	DWR 2010-11
Cirsium arvensis L.	O'Donnell and Adkins 2001
Commelina diffusa Burm. f.	DWR 2009-10
Convolvulus arvensis L.	Valerio *et al.* 2013
Elymus repens L.	Jia *et al.* 2011
Euphorbia geniculata Ortega.	DWR, 2008-09
Lathyrus sativa L.	DWR 2010-11, 2013-14
Lolium multiflorum Lam.	Davis and Ainsworth 2012
Medicago denticulata Willd.	DWR 2010-11, 2013-14
Oryza spp.	DWR 2013-14
Parthenium hysterophorus L.	DWR 2016-17
Phalaris minor	DWR 2010-11, 2013-14
Polygonum convolvulus L.	Ziska *et al.* 2004
Xanthium strumarium L.	Ziska 2013
Parthenium hysterophorus L.	Chandrasena 2009
Chromolaena odorata L.	Chandrasena 2009
C_4 weeds	
Amaranthus viridis L.	DWR 2016-17
Amaranthus retroflexus	Ziska and Bunce 1997
Echinochloa crus-galli	DWR 2014-15
Sorghum halepense	DWR 2008-09

Increased temperatures

Under elevated temperatures, weeds utilizing the C_4 photosynthetic pathway often gain a competitive edge over crops that rely on the more prevalent C_3 pathway (Yin and Struik 2008). High-temperature stress can impact growth rates during various developmental stages due to shifts in temperature thresholds. C_4 plant species are more resilient to heat stress and can stimulate meristematic regions, leading to rapid canopy growth and enhanced root proliferation, whereas such temperatures typically hinder growth in C_3 species (Morgan *et al.* 2001) (**Table 3**).

Table 3. Effect of elevated temperature on major C_3 and C_4 weeds

Weed species	Reference
C_3 weeds	
Avena fatua	O'Donnell and Adkins, 2001
Chenopodium album	Miri *et al.* 2012
Cirsium arvensis	Davis and Ainsworth, 2012
Abutilon theophrasti	Ainsworth, 2012
Lolium multiflorum	Ziska *et al.* 2004
Polygonum convolvulus	Valerio *et al.* 2013
Convolvulus arvensis	Ziska, 2013
Xanthium strumarium	Jia *et al.* 2011
C_4 weeds	
K. scoparia, S. halepense	McDonald *et al.* 2009
E. indica	Mahajan *et al.* 2012
E. crus-galli	Valerio *et al.* 2011;
D. sanguinalis	Satrapova *et al.* 2013
A. retroflexus	Zheng *et al.* 2011
C. dactylon	Rodenburg *et al.* 2011
Sida spinosa	Blumenthal *et al.* 2008

Interactive effects of elevated CO_2 and temperature on C_3 and C_4 weeds

Elevated CO_2 levels mitigate the effects of sub-optimal temperatures and other stressors on plant growth (Bazzaz 1990). As plants mature more rapidly under these conditions, they contribute a greater number of seeds to the soil seed bank. This increase in seed accumulation can lead to a higher density of *A. ludoviciana* populations. Specifically, at 480 ppm CO_2, *A. ludoviciana* produced 44% more seeds compared to plants exposed to 357 ppm CO_2 (**Table 4**).

Impact of drought on C_3 and C_4 weeds

Rice crops are vulnerable to both biotic (weeds) and abiotic (drought) stresses early in the season when they are most susceptible to weed competition, leading to oxidative stress in the plants (**Table 5**). Research indicates that the C_4 weed *E. colona* has a more pronounced negative impact on yield compared to the C_3-C_4 intermediate weed *A. paronychioides*, due to the greater physiological plasticity and mechanisms of C_4 weeds (Sreekanth *et al.* 2024). Low soil moisture significantly reduces the rate of photosynthesis, transpiration, and stomatal conductance (Kondo *et al.* 2004, Xu *et al.* 2007). The spread of weeds and crop productivity are highly influenced by fluctuations in rainfall patterns and aridity. With projected temperature increases of 1–5 °C for each doubling of atmospheric CO_2, aridity is expected to rise in many agriculturally significant regions. Increased evaporation and rainfall variability will likely lead to drier monsoon regions (Giannini *et al.* 2008), with a 5–8% increase in drought-prone areas (Rodenburg *et al.* 2011). Under these conditions, weed spread and prevalence will become significant issues in agricultural ecosystems, with summer droughts impacting weed control in spring-sown crops (Peters and Gerowitt 2014). C_4 and parasitic weeds, such as *Striga hermonthica*, are likely to survive better under extreme drought conditions (Rodenburg *et al.* 2010). Despite these challenges, there is limited information on how drought affects crop-weed interactions, highlighting the need for further research in this area.

Table 4. Interactive effect of elevated CO_2 and temperature on weed growth

Weed species	Reference
Leptochloa chinensis (L.) Nees	DWR 2020
A. paronychioides	DWR 2020
E. geniculata	DWR 2016-17
C. album and *P. minor*	DWR 2017-18
E. colona	DWR 2018-19
Elytrigia repens	Tremmel and Patterson, (1993)
Echinochloa glabrescens	Alberto *et al.* (1996), Carter and Patterson (1983)

PHYSIOLOGICAL AND BIOCHEMICAL RESPONSES

Photosynthesis and respiration

Increased atmospheric CO_2 levels induce various physiological changes in plants, including larger leaf areas, higher mass per unit area, enhanced photosynthesis, improved water use efficiency, increased tillering, accelerated flowering, greater grain weight, more grains per spikelet, elevated grain yields, and a higher harvest index (Jagadish *et al.* 2011). The rising CO_2 levels are expected to boost leaf photosynthesis in C_3 plants by increasing CO_2 concentrations within the leaf and reducing CO_2 loss through photorespiration. In contrast, C_4 plants, which utilize an internal biochemical pump to concentrate CO_2 at the carboxylation site, effectively minimize carbon loss through photorespiration and reduce the oxygenase activity of Rubisco (Naidu 2013). The specialized mesophyll cell arrangements in C_4 plants enhance CO_2 transfer and minimize photorespiration, giving them a photosynthetic advantage over C_3 plants (Drake *et al.* 1997). As a result, C_3 plants are anticipated to benefit more from CO_2 enrichment than C_4 plants, leading to lesser responses to elevated CO_2 in many C_4 weed species compared to C_3 crops. Under elevated temperatures, C_4 plants, which are commonly found among weeds, gain a competitive edge over C_3 crops (Yin and Struik 2008). For example, a 3°C increase in temperature significantly boosts the growth of itch grass (*Rottboellia cochinchinensis*), a C_4 weed that affects crops such as sugarcane, corn, cotton, soybean, grain sorghum, and rice (Patterson *et al.* 1999).

Relative water content (RWC) dynamics are influenced by root water absorption and transpiration-related water loss. Climate change generally reduces RWC across plant species, with non-stressed plants usually maintaining RWC levels between 85% and 90%, while those exposed to higher temperatures may see RWC drop to as low as 30% (Lee *et al.* 2017). Elevated temperatures and moisture stress can lead to more significant reductions in leaf elongation rates compared to net photosynthesis (Lyons *et al.* 1979).

Table 5. Effect of drought stress on weed growth (C_4 weeds)

Weed species	Reference
Echinochloa crus-galli	Patterson 1986
Eleusine indica	Patterson 1986
Digitaria ciliaris	Patterson 1986
Bromus tectorum	Patterson 1995
Centaurea solstitialis	Patterson 1995
Striga hermonthica (Del) Benth.	Rodenburg *et al.* 2010

Changes in photosynthesis and C assimilation

Increased CO_2 concentrations and rising temperatures significantly affect plant carbon metabolism and contribute to a feedback loop that influences future climate change. Elevated CO_2 enhances net photosynthesis by supplying more CO_2 to Rubisco and reducing photorespiration. However, this effect is nonlinear; at low internal CO_2 concentrations (Ci), photosynthesis is limited by Rubisco carboxylation rates, and as Ci increases, net CO_2 assimilation rates (Anet) rise sharply. Limitations on photosynthesis at higher Ci levels are influenced by the capacity to replenish RuBP and utilize triosephosphates for starch and sucrose production, which are less sensitive to CO_2 than Rubisco carboxylation (Sharkey *et al.* 2007). Although future CO_2 increases may have diminishing effects on carbon uptake, the rise in CO_2 since the Industrial Revolution has substantially stimulated photosynthesis (Gerhart and Ward 2010). For instance, elevated CO_2 has been shown to enhance rice yield due to the positive response of C_3 species, increasing carbon assimilation rates (Yang *et al.* 2006, Kim *et al.* 2003, Ma *et al.* 2007). There is limited research on how elevated CO_2 or temperature affects the distribution of photosynthetic carbon (C) and nitrogen (N) uptake across different rice organs (Yang *et al.* 2007).

Water use efficiency and transpiration rates

The concept of water use efficiency (WUE) was introduced by Briggs and Shantz (1913) to illustrate the relationship between plant productivity and water usage. They defined WUE as the amount of biomass produced per unit of water used by plants. To evaluate the impact of climate change on WUE, it is useful to start at the leaf level. This is because changes in CO_2 levels, water availability, and temperature are most apparent at this level, with fewer confounding factors such as canopy structure and soil interactions. WUE at the leaf level varies depending on the carboxylation pathway, including C_3 and C_4 photosynthesis as well as Crassulacean acid metabolism. Generally, C_4 plants exhibit higher inherent WUE compared to C_3 plants (Taylor *et al.* 2010).

Impact on nutrient uptake and metabolism

Climate change significantly impacts crop growth and production, primarily through changes in photosynthetic carbon assimilation (Reddy *et al.* 2010). Elevated CO_2 levels act as a carbon fertilizer, enhancing crop growth and development (Van der Kooi *et al.* 2016). The primary effect of increased atmospheric CO_2 is an enhanced rate of carbon fixation in photosynthetic leaves (Taub 2010). Free-air carbon dioxide enrichment (FACE) trials have shown that many plant species can increase their photosynthetic rate by nearly 40% under higher CO_2 levels (475–600 ppm), leading to greater photosynthate production and dry matter accumulation (Ainsworth and Rogers 2007). Elevated CO_2 levels also impact plant development by increasing leaf area, leaf area index (LAI), leaf area duration (LAD), leaf thickness, and dry biomass production, as observed in crops like tomatoes (Pan *et al.* 2019).

This increase in dry matter under elevated CO_2 conditions enhances radiation interception by plants. Studies in rice and chickpeas have shown a linear relationship between solar radiation interception and total dry matter accumulation (Weerakoon *et al.* 2000). Elevated CO_2 often leads to higher LAI and LAD, which significantly affect radiation interception (Hikosaka 2005). However, the combination of elevated CO_2 and increased ambient temperatures can alter phenological phases and crop duration, leading to shorter crop cycles and faster initiation of phenological stages in crops like rice, wheat, maize, and mungbean (Cai *et al.* 2016). Elevated temperatures can negatively impact net photosynthesis, influencing processes such as photorespiration and ribulose-1,5-bisphosphate carboxylase activity, resulting in heat-induced physiological disorders and reduced crop yields (Cai *et al.* 2018).

The effects of elevated CO_2 on plants are influenced by additional meteorological conditions, including air temperature and moisture stress, which impact plant metabolism through photosynthesis, especially in high-altitude environments (Dusenge *et al.* 2019). While higher CO_2 levels are expected to increase photosynthetic rates, this effect depends on factors such as soil nutrition, leaf air temperature, and moisture availability (Leakey *et al.* 2009). Elevatesd CO_2 increases plants' access to carbon but also requires additional soil resources like mineral fertilizers. Essential nutrients such as nitrogen, phosphorus, and potassium play a crucial role in moderating crop responses to rising CO_2 levels, affecting soil nutrient dynamics (Raj *et al.* 2019).

CROP-WEED INTERACTION

Effect of enhanced atmospheric CO_2 concentration on crop-weed interaction

CO_2 enrichment has been shown to significantly stimulate the growth and development of many plant species (Kimball 1983, Kimball *et al.* 1993, Poorter

1993, Sage 1995). The variation in response to elevated CO_2 levels is largely influenced by the type of photosynthetic pathway (C_3 or C_4) in plants (**Table 6**). However, predicting the effects of increased atmospheric CO_2 on crop-weed interactions in isolated environments often leads to inadequate assessments of competition, as fields rarely host a single weed species (Ziska and Goins 2006). Although some studies have quantified the growth of crops and weeds under elevated CO_2 in competitive environments (Ziska 2004, Ziska and Goins 2006), more research combining various weed and crop species is urgently needed.

Under elevated CO_2, C_3 plants such as soybeans and *Chenopodium album* show significantly higher yields compared to C_4 plants like millet and pigweeds (Miri *et al.* 2012). The increase in biomass and yield of weedy rice, compared to cultivated rice at elevated CO_2 levels, suggests that future CO_2 concentrations may lead to a larger decline in the yield of cultivated rice in competition with C_3 weeds (Ziska *et al.* 2010). This could be due to the greater physiological flexibility and higher genetic variation found in wild species compared to cultivated lines (Treharne 1989).

Impact of elevated temperature on crop-weed interaction

Temperature alterations are poised to significantly impact the growth, development, and distribution patterns of weed plants. Generally, increased temperatures favor C_4 weeds over C_3 weeds due to the higher rates of photorespiration in C_3 plants under such conditions (Varanasi *et al.* 2016). Elevated temperatures enhance canopy growth and root proliferation in C_4 plants, giving them a competitive edge over C_3 crops (Morgan *et al.* 2001, Yin and Struik 2008). For instance, a 3°C rise in temperature has been shown to significantly boost the growth of itch grass (*Rottboellia cochinchinensis*), a major C_4 weed that threatens crops like sugarcane, corn, cotton, soybean, sorghum, and rice, with potential expansion towards the central Midwest and California (Patterson *et al.* 1999).

Moreover, C_4 weeds like red root pigweed (*Amaranthus retroflexus*) and Johnson grass (*Sorghum halepense*) are predicted to fix CO_2 more efficiently than C_3 crops like soybean and cotton, particularly around noon when temperatures and light intensity peak. The enhanced water use efficiency and CO_2 compensation point of C_4 photosynthesis make these weeds better adapted to high evaporative demand (Bunce 1983). Under elevated CO_2 conditions, C_4 weedy species have demonstrated greater stimulation in photosynthesis and biomass production compared to C_4 crops (Ziska and Bunce 1997). Interestingly, during early growth stages before the differentiation of their 'Kranz anatomy,' C_4 plants initially rely on the C_3 pathway for carbon fixation, allowing them to benefit from elevated CO_2 (Nelson and Langdale 1989).Warmer conditions have also been observed to delay the germination of green foxtail (*Setaria viridis*), a C_4 weed that could become a more serious problem in maize crops globally due to its synchronization with maize germination, driven by increased temperature sensitivity (Peters and Gerowitt 2014).

Interactive effect of elevated CO_2 and temperature on crop-weed interaction

Several studies from ICAR-DWR have highlighted that *P. minor* gains a competitive edge over wheat when exposed to higher temperatures, either alone or in combination with elevated CO_2 (**Table 7**). Additionally, research indicates that a combination of high CO_2 and temperature delays

Table 6. Impact of elevated CO_2 on crop-weed interaction

Crops	Weeds	Response	Reference
C_3 Rice, wheat, soybean, *etc*.	*Amaranthus palmeri* L., *Amaranthus rudis*, (C_4 weeds)	Elevated CO_2 favoured crops	Elmore and Paul, 1983, Yin and Struik 2008
Wheat	*Phalaris minor* (C_3)	Elevated CO_2 favoured weed	Naidu and Varshney, 2011
C_4 crops (maize, sorghum, sugarcane, *etc*.)	C_3 weeds *C. album*, *Ambrosia theophrasti*, *Ambrosia artemisiifolia* L., *Ambrosia trifida* L.	Elevated CO_2 favoured weeds	Ziska *et al.* 2000
Chickpea	*Lathyrus sativa,Medicago denticulata*	Elevated CO_2 favoured crop and weeds	DWR, 2013-14
Cultivated rice	weedy rice	Elevated CO_2 favoured crop and weed	DWR, 2013-14
Maize	*Euphorbia geniculata*	Elevated CO_2 favoured weed	DWR, 2008-09
Greengram	*Commelina diffusa, Euphorbia geniculata*	Elevated CO_2 favoured weed	DWR, 2009-10
Greengram	*Brachiaria reptans* L., *Eragrostis diarrhena* (Schult.) Steud.	Elevated CO_2 favoured crop and weed	DWR, 2012-13

Table 7. Combined effect of elevated CO_2 and temperature on crop-weed interaction

Crop	Weed	Response	Reference
Greengram	*E. geniculata* (C_3), *A. viridis* (C_4)	EC+ET favoured weed	DWR 2016-17
Wheat	*P. minor* (C_3)	EC+ET favoured weed	DWR 2015-16
Maize	*C. album* and *P. minor*	EC+ET favoured crop and weed	DWR 2017-18
Soybean	*E. colona* and *I. rugosum*	EC+ET favoured crop and weed	DWR 2018-19
Rice	*A. paronychioides* (C_3-C_4) and *L. chinensis* (C_4)	EC+ET favoured weed	DWR 2020

panicle maturity in cultivated, weedy, and wild rice (DWR, 2014-15, DWR, 2015-16).

Impact of drought on crop-weed interaction

Water is a critical factor influencing plant growth, with each species requiring specific moisture conditions for optimal development. Climate change is expected to increase the frequency of droughts, floods, and erratic rainfall, leading to moisture stress in both arable and non-arable ecosystems. This stress affects crops and weeds alike, though weeds often exhibit greater physiological plasticity and genetic variation, making them somewhat less vulnerable to such conditions. Nonetheless, weeds will still respond to moisture stress, with their responses varying by species and environmental conditions. For example, some weeds release allelochemicals during drought to outcompete crops (Patterson 1995). C_3 weeds thrive under submergence, while C_4 weeds are better suited to dry conditions, explaining the dominance of C_3 weeds in flooded areas and C_4 weeds in arid soils (Matsunaka 1983).

A study highlighted that C_4 weed (*E. colona*) showed considerable negative impact on rice yield than C_3-C_4 intermediate weed (*A. paronychioides*) under drought stress due to C_4 weed physiological plasticity and mechanism (Sreekanth *et al.* 2024). The highest accumulation of MDA was observed under drought due to *A. paronychioides* (38.66 µg/g FW) and *E. colona* (66.21 µg/g FW) interference (Sreekanth *et al.* 2024). Drought and arid conditions favor the growth of C_4 weeds because of their strong internal physiological mechanisms. Competition of cotton with *A. theophrasti* and spurred anoda (*Anoda cristata* Schlecht.) is more under drought conditions (Patterson and Highsmith 1989). A decline in yield is due to *X. strumarium* was prominent in well-watered soybeans compared with water-stressed soybeans (Mortensen and Coble 1989). A raise in rainfall results in greater competition to wheat growth and yield against *C. arvense* (Donald and Khan 1992). Weed competition had little effect on crops under water deficit conditions, as the potential crop yield was already reduced by water stress Patterson (1995); Chauhan and Abugho (2013). By contrast, spiny amaranth (*Amaranthus spinosus* L.) and *L. chinensis* survived under water stress conditions and produced a significant number of tillers/branches and leaves even at the lowest soil water content Chauhan and Abugho (2013). Only few studies have been conducted on this area, therefore, there is an urgent need to explore this aspect to cope up the upcoming climate change challenges.

EFFECT OF CLIMATE CHANGE ON CROP-WEED DYNAMICS AND WEED FLORA SHIFT

Changes in weed species composition and distribution

Climate change is expected to reshape the composition, distribution, and dominance of weed species in arable ecosystems, which are already influenced by human activities (Pautasso *et al.* 2010). Weeds, highly adapted to varying farming practices, will be affected by changes in land use, management practices, and climate conditions (Gunton *et al.* 2011). As climatic factors alter crop management, they will likely shift crop-weed interactions, potentially allowing some weeds to dominate (Fleming and Vanclay 2010). Key factors such as soil moisture, temperature, and CO_2 levels will drive these changes (Chauhan *et al.* 2014).

While most troublesome weeds are currently confined to tropical and subtropical regions, climate change may enable their expansion into cooler areas due to increased tolerance of low temperatures under elevated CO_2 (McDonald *et al.* 2009). Elevated temperatures and CO_2 are likely to enhance the growth of some weed species and shift the range of tropical and subtropical species northward (Chandrasena, 2009). C_4 weeds, benefiting from higher temperatures and drought, may outcompete C_3 crops, while C_3 weeds could dominate in high CO_2 conditions (Singh *et al.* 2016).

High temperatures and elevated CO_2 levels have been shown to affect weed growth and seed production, enhancing both for invasive and cropland weeds (Dukes *et al.* 2009). Increased CO_2, for example, has been linked to greater plant height in weedy rice, which aids in seed dispersal (Thomson *et al.* 2011). Similarly, temperature changes impact weed growth, seed production, and germination

(Benech-Arnold *et al.* 2000). These climatic shifts influence evolutionary pressures within plant communities, affecting species distribution and interactions (Grossman 2014).

Climate change significantly impacts weed populations, altering their distribution, abundance, and management in agroecosystems. As temperatures rise, weeds may either adapt locally, migrate to more suitable areas, or evolve to survive new conditions (Pautasso *et al.* 2010). Shifts in weed populations are expected as species respond to changes in climate, such as increased CO_2 and temperatures. For instance, many tropical weeds are expanding northward due to warming (Patterson 1995), with species like kudzu and itchgrass already moving into new regions (Patterson 1995).

Increased CO_2 levels and temperature may also enhance the growth and spread of invasive weeds, with species such as *Lonicera sempervirens* and *Pueraria lobata* becoming more common in cropland areas (Patterson 1995). In Australia, frost-intolerant species like rubber vine may shift to higher latitudes (Kriticos *et al.* 2003). The expansion of non-native weeds and the alteration of local weed dynamics due to climate change highlight the need for adaptive management strategies. Research should focus on the interactions between climate variables and weed traits to predict future shifts accurately (Hulme and Barrett 2013, Mack *et al.* 2000). Additionally, understanding how temperature and moisture stress interact is crucial for predicting weed behavior under global warming conditions.

Weed invasion

Weed species often spread beyond their native ranges, sometimes becoming invasive and negatively impacting native species (Mack *et al.* 2000). Approximately 10% of introduced species become invasive, threatening ecosystems and biodiversity (Kathiresan and Gualbert 2016). Climate change may further facilitate weed invasions by enhancing the adaptability of introduced species to new environments and increasing their competitive edge, especially with higher CO_2 levels (Hellmann *et al.* 2008). Invasive potential is influenced by genetic factors (*e.g.*, photosynthetic pathways, seed dormancy) and climatic factors (*e.g.*, temperature, CO_2 concentration) (Kathiresan and Gualbert 2016). Climate change interactions with land use practices may also convert benign species into invasive ones, affecting agricultural productivity (Irmaileh *et al.* 2010). Increased CO_2 may promote invasiveness, as observed with *Parthenium hysterophorus*, which shows higher coverage under warmer conditions (Singh *et al.* 2011). While climate change impacts on invasiveness can be variable, increased CO_2 alone has been linked to higher risk. Understanding the mechanisms behind weed success in new areas is crucial. For example, C_4 weeds like *Panicum dichotomiflorum* and *Datura stramonium* are expected to spread northward or southward with climate changes (Clements and Ditommaso 2011, Weber and Gut, 2005). Winter annuals may thrive under milder winters, while thermophilic summer annuals may extend their range into cooler regions (Hanzlik and Gerowitt 2012).

Conclusion

The review highlights the multifaceted nature of crop-weed interactions in the context of changing climate conditions. Elevated CO_2 tends to benefit C_3 crops by improving their growth and competitive ability against C_4 weeds. However, this advantage is challenged by increased temperatures, which favor C_4 weeds due to their superior heat tolerance and growth characteristics. The combined effects of elevated CO_2 and temperature can exacerbate weed competition, potentially undermining the benefits of CO_2 enrichment for crops. Drought conditions further intensify these interactions, with C_4 weeds often outperforming C_3 weeds under water stress. As climate change continues to impact agricultural systems, it is crucial to develop adaptive management strategies that account for these complex interactions. Future research should focus on understanding the combined effects of CO_2, temperature, and drought on crop-weed dynamics to inform effective weed management practices and safeguard crop yields in a changing climate. Future strategies must focus on developing climate-resilient crops, optimizing weed control methods, and adjusting agricultural practices to mitigate the adverse effects of these environmental changes. Continued research and adaptation will be essential to ensure sustainable crop production in an evolving climate.

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REVIEW ARTICLE

Prediction on distributional patterns of weeds under future climatic scenarios

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ABSTRACT

Biological invasion pose serious threat on the natural ecosystem, human health and the economy. It has become important part of today's global ecological change and major threat to native biodiversity, ecosystem stability and its services and give rise to numerous management and control issues. Furthermore, climate change has the potential to enhance the detrimental effect of these species on the natural ecosystem and agriculture globally. Climate change is expected to affect the distribution and occurrence of the weeds in future. It will have a profound effect on crop protection, including the effects on pests, diseases and weeds. Therefore, assessing the impact of climate change on the geographical distribution of the species under future climatic scenarios is of great importance. This information helps in understanding the impact of the species and in making informed decisions on the matter related to biodiversity, public health, agriculture and the economy. Apart from this, it also helps in early detection of the hot spots of the species enabling prompt actions in order to reduce management cost after its introduction in new places. Hence, in the present article, we reviewed the work studying the distributional patterns of different weeds under future climate scenarios. It is concluded that species distribution modelling is a powerful tool to evaluate the expansion risk of invasive alien weeds into non-native regions based on the information on their climatic niche. However, it is essential to consider limitations of the models and uncertainties behind the use of future climate change scenarios.

Keywords: Climate change, Distribution modelling, Geographical distribution, Prediction, Weed distribution

Weeds may be considered as undesirable plants interfering with agriculture and natural ecosystem and are one of the biggest problems in achieving the potential yield of the crops. If left uncontrolled, weeds can cause extreme yield losses in crops. Crop yield losses depend upon the types of weed species present in the field along with the farming practices being followed (Varanasi *et al*. 2016). Weeds put negative impacts on crop yields by competing for essential resources such as light, water, space and nutrients and they are responsible for deteriorating quality of produce by contaminating the seed and lowering the value of harvested crops (Boydston *et al*. 2008). Hence, weed management is the key component of successful crop production. Alien weeds are exotic, introduced, foreign and non-native those have been intentionally or accidently introduced by humans from one region to another. These plant species adversely influence the natural biodiversity, ecosystem and human well-being. These species pose a great challenge because of their capability of spreading fast, great competitiveness and ability to establish in new areas within a short period.

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Globally, there is a great concern about the negative effects caused by invasive alien species to the natural ecosystems and rates of their establishment increased with globalization and global warming (Huston 2004, Williams *et al*. 2015, Adhikari *et al*. 2020). Biological invasion pose serious threat on the economy, human health and the natural ecosystem. It has become important part of today's global ecological change and major threat to native biodiversity, ecosystem stability and its services (McGeoch *et al*. 2010) and also give rise to numerous management and control issues (Lodge *et al*. 2006, Hulme 2009). Many previous studies reported that the climatic factors are important driving factors behind the biological invasion into the non-native ranges. This is happened because invasive alien species normally spread into those areas who possess the similar climatic conditions to their native habitat (Petitpierre *et al*. 2012, Wang *et al*. 2017). Furthermore, climate change has the potential to enhance the detrimental effect of these species on agriculture globally (Wang and Wan 2020, Neve *et al*. 2009, Ziska 2016). In the past, climate change has occurred over hundreds or thousands of years, but recent changes in the climate have occurred just in few decades (Varanasi *et al*. 2016). It is observed that extreme weather phenomenon such as floods and droughts may occur due to the effects of climate change and cause massive impacts on the global ecosystem, changes in the habitat of species and their spread (Kwak *et al*. 2008, Pearson and Dawson 2003, Gharde *et al*. 2023a).

Climate change and distribution of weeds

Climate change, mostly known by the term "Global Warming", is now a well-accepted phenomenon which may be due to both natural and human intervention. According to Inter-governmental Panel on Climate Change (IPCC), "climate change refers to any change in the state of climate identified by fluctuations in the mean and/or the variability of its properties due to natural event or human activities, and that persists for a longer period like decades or more" (Anwar *et al*. 2021). Global climate model projects that in the 21st century, mean global surface temperature will increase by 1.5–4.5°C due to rise in CO_2 concentrations and also due to greenhouse effect (IPCC, 2001). Furthermore, IPCC (2007) has claimed that, since the nineteenth century, global mean annual surface temperature has already increased by 0.76°C. It is also stated that about 50% of the anthropogenic CO_2 emissions between 1750 and 2011 have already occurred in the last 40 years (IPCC 2014) of which, around 40% of the CO_2 emissions remain in the atmosphere and the rest on land and in oceans, which is an alarming situation. Climate change is also expected to affect the distribution and occurrence of the weeds in future. It will have a profound effect on crop protection, including the effects on pests, diseases and weeds. Furthermore, the physiology and biological cycle of the weeds and their competitive relationship with crops will also be affected significantly (Gonzalez 1995). Climate change may also affect the geographic distribution of a native species or invasion of crops by a new weed species (López-Tirado and Gonzalez-Andújar 2023). Sometimes future climate change can lead to shifts in the geographical distribution and richness of the species (Wang *et al*. 2018); their extinction (Bestion *et al*. 2015), and shift in their ranges (Bellard *et al*. 2012). Climatic change has already brought significant changes in the behaviour of the species, biodiversity, its spatial distribution and habitat (Weiskopf *et al*. 2020). Many previous studies focused on assessing the impact of climate change on the geographical distribution of the species under future climatic scenarios at global level as well as at regional level. This information helps in understanding the impact of the species and in making informed decisions on the matter related to biodiversity, public health, agriculture and the economy. Apart from this, it also helps in early detection of the hot spots of the species enabling prompt actions in order to reduce management cost after its introduction in new places (Dorji *et al*. 2022).

Species distribution modelling

To assess the impact of climate change on the distribution of weed species, species distribution modelling approach is widely used for prediction purposes. Predictive models used for the species distribution modelling are powerful tools that can assist in making the decision on the management of these invasive species under different climate scenarios. For studying the impact of future climatic scenarios on the species habitat and their distribution, various species distribution models are used. These models mainly includes MaxEnt, BIOCLIM, DOMAIN, Random forest, *etc*. which are known for their simplicity and the data accessibility (Katz and Zellmer 2018, Srivastava *et al*. 2019, Gharde *et al*. 2023a). Among these, MaxEnt is popular and widely adopted method, which can generate much more robust results even in the case of small sample sizes (Phillips *et al*. 2006). This modelling approach is a well-established approach to model and project the habitat suitability of a species based on their current distribution relative to climatic factors (Elith *et al*. 2006, Gharde *et al*. 2023b). This technique has gained importance in ecology, biogeography, biodiversity conservation and management of natural resources (Adhikari *et al*. 2019). Numerous studies have been conducted in the past to assess the impact of climate change on the potential distribution of the species and found the difference in the result (Merow *et al*. 2017) which is typically depend upon the climatic requirement of the species. In India, widespread obnoxious invasive alien weeds such as *Parthenium hysterophorus*, *Lantana camara*, *Chromolaena odorata*, *Cassia tora*, *Tridax procumbens*, *Ethulia gracilis*, *Calyptocarpus vialis*, *Phalaris minor* etc. have been studied for their probable geographical distribution in future climatic scenarios. Steps followed in the modelling process are depicted in the flow chart given as **Figure 1**.

Studies on species distribution modelling for invasive alien weeds in India

Species distribution modelling may aid in understanding the current and future invasion potential of the invasive alien weeds under climate change scenarios. Numerous studies have been

Data collection and pre-processing

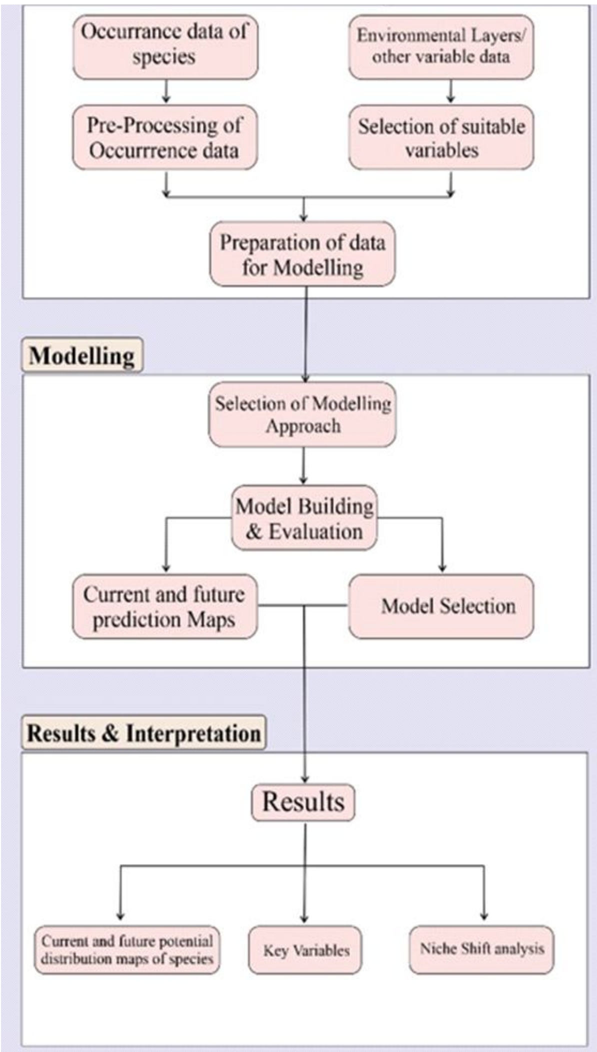

Figure 1. Steps followed in the species distribution modelling for projecting the distributional patterns of species

conducted in the past to show the invasion potential of the species in the world as well as in India. for instance, potential distribution of three obnoxious weeds in north-western Ghats of India, *viz*. *Chromolaena odorata*, *Lantana camara* and *Parthenium hysterophorus* have been studied by Patil and Janarthanam (2013) using 32 environmental variables and MaxEnt modeler. They observed that the weeds might have adapted to different sets of environmental conditions throughout their distributional range. In case of Parthenium, most of its potential distribution was shown on the eastern side of Western Ghats. Whereas, the distribution of *L. camara* and *P. hysterophorus* was not predicted along the western coastal regions. In case of *C. odorata*, its potential distribution starts from coastal areas and extends up to the hilly regions of Western Ghats in Goa and in border areas of Karnataka and Maharashtra states; the potential distribution is predicted only to the hilly areas towards north and south. Distribution of *L. camara* was also studied by Tiwari *et al*. (2022) in Jharkhand, eastern India for its climatic niche under future scenarios. Study predicted the area expansion by 20-26% by 2050 in all RCPs as compared to the current invasion (~13%). In another study, Panda *et al*. (2017) revealed that the distributions of annual *Senna tora* (*Cassia tora*) and *Lantana camara* (perennial) would depend on the precipitation of the warmest quarter and moisture availability. According to this study, in future climate, *C. tora* may invade central India, while *L. camara* is expected to invade the Western Himalaya, parts of the Eastern Himalaya and the Western Ghats. Analysis revealed that the distribution ranges of both species could shift in the northern and north-eastern directions in India, due to the changes in moisture availability in these regions. Similarly, Kishore *et al*. (2024) revealed the large invasion and spread of species, *viz*. *Chromolaena odorata* (33.01%) and *L. camara* (30.33%) in the Western Ghats, especially the Nilgiri Biosphere Reserve (NBR) under the current scenario. The future projections confirmed a significant reduction in the invasion of *C. odorata*, while expansion in the invasion of *L. camara* excluding a few exceptions in the study area. *C. odorata* was also studied by Panda and Behera (2019) and found that it could invade the biodiversity-rich regions of India *viz*. the Eastern Ghats, the Western Ghats, the Eastern Himalaya and the north-eastern regions. They also studied the distribution of *Tridax procumbens* and revealed that it will be more prevalent in Central India due to its dependencies on precipitation seasonality and radiation rather on temperature. It is expected that these species will spread in those regions not utilized by others.

Gharde *et al*. (2023a) used MaxEnt model to predict the invasion potential of *Phalaris minor* in India under current and future climatic scenarios in RCPs 4.5 and 8.5 for the years 2050 and 2070. They found that currently, 21% area of the country is either highly (9%) or moderately (12%) suitable as habitat for the species. Model predicts approximately 90% contraction in the area considered highly or moderately suitable climatically under both moderate and high emissions scenarios. Aravind *et al*. (2022) worked on identifying potential habitats of *Ethulia gracilis* which was recently found for the first time in India growing along the roadside as well as in fallow lands. They found that the regions with risk are warmer and thus, temperature is the factor affecting the species more compared to precipitation. They concluded through their study that this species has potential to be the invasive or at least attain the status of pest in Peninsular India. In the similar study, Thapa *et al.* (2018) projected the potential distribution of eleven invasive alien plant species (*Ageratina adenophora*, *Ageratum conyzoides*, *Ageratum houstonianum*, *Amaranthus spinosus*, *Bidens pilosa*, *Erigeron karvinskianus*, *Lantana camara*, *Parthenium hysterophorus*, *Senna occidentalis*, *Senna tora* and *Xanthium strumarium*) in the part of Kailash sacred landscape region in Western Himalaya under future climatic conditions. They projected that distribution of most of these invasive plants is going to expand under future climatic scenarios. They might pose a serious threat to the native ecosystems through competition for resources in the infested area. Native scrublands and subtropical needle-leaved forests will be the extremely affected ecosystems by the expansion of these species in the future. A detailed study on probable distribution of *Parthenium hysterophorus* in current and future climatic scenarios was conducted by Ahmad *et al.* (2019). The study revealed that 65% of the total area of the country is suitable for species potential invasion under current climate. They found three invasion areas *viz.* Western Himalaya, North-East and parts of Peninsular India as hotspots for the species. However, they predicted overall decrease in habitat suitability for *P. hysterophorus* under future climate but some of the region currently invaded will remain equally (North-east) or will be at high risk (Western Himalaya) to its invasion under future climate. Similarly, *Calyptocarpus vialis*, an emerging invasive weed in the north-western Indian Himalayan Region (IHR), was studied by Lal *et al.* (2024) for its possible habitats under current climatic scenarios and potential range expansion under future climatic scenarios. Study revealed that unlike the current condition, areas with "high" and "very high" suitability status would rise while less-favourable areas would contract. All RCPs (2.6, 4.5, 6.0, and 8.5) indicate the expansion of *C. vialis* in "high" suitability areas, but RCP 4.5 predicts contraction, and RCPs 2.6, 6.0, and 8.5 predict expansion in "very high" probability areas. The current distribution of *C. vialis* is 21.59% of the total area of the state, with "medium" to "high" invasion suitability, but under the RCP 8.5 scenario, it might grow by 10% by 2070. The study also reveals that *C. vialis* may expand its niche at both lower and higher elevations. Some of such studies based on species distribution modelling for revealing the probable geographical distribution of the weeds in future climatic scenarios are compiled and listed in **Table 1**. Similarly, distribution and abundance of aquatic plants are greatly affected by the variations in the environmental factors; however, these plants assimilate the temporal, spatial, physical, chemical and biological characteristics of the ecosystem. In the previous studies, it was demonstrated that environmental interaction play an important role in deciding the distribution and abundance of the aquatic plant species (Berendregt and Bio 2003, Bernez *et al.* 2004) in addition to other factors such as competition, predation and disease. Some of the distributional studies of aquatic plants are listed in **Table 2**.

Thus, species distribution modelling is a powerful tool to evaluate the expansion risk of invasive alien weeds into non-native regions based on the information on their climatic niche. It has become an essential method in biogeography, ecology and natural resource management. This modelling is based on the information about the species occurrence data along with their climatic requirement. Most of the studies include invaded range data as the species occurrence data, however, it is suggested that the modelling potential distribution of invaded species should preferably be based on occurrence data of the native range along with invaded range data since the species might not reach its full potential of habitable space on invaded region. Additionally, each modelling work should include the selection of parameter value carefully and critical assessment of model results if they are biologically sound and easy to interpret. Furthermore, it should always keep in mind that species do not necessarily distribute across the suitable environment as predicted by models. There are multiple reasons responsible for limiting the species to cover all the suitable habitats, which includes geographical barriers, competition with native species, variable dispersal ability of the species *etc*. Hence, species distribution modelling should be used keeping all these facts in mind for forecasting invasion hotspots to enable the implementation of early detection and fast response systems, and development of successful scientific policies to avoid the future invasions of the species.

Table 1. Studies on Species distribution modelling and prediction of weeds' invasion under future climate scenarios

Weed(s)	Region	Prediction about Contraction/expansion in areas	Reference	Prediction for future scenarios	Model used
Ageratina adenophora (Spreng.) R. M. King & H. Rob.	China	Expansion in new areas	Tu *et al*. 2021	SSP 245 and 585 for 2050, 2070 and 2090	MaxEnt
	China	Expansion of the dispersal zone towards the northeast and coastal areas, and a slight contraction in the Yunnan–Guizhou plateau	Zhang *et al.* 2022	SSP126, 245, 370, and 585 for the year 2050 and 2090	MaxEnt
	Global	Contraction globally but increase in six biodiversity hotspot regions	Changjun *et al*. 2021	RCP 2.6, 4.5, 6.0, and RCP 8.5 in 2050 and 2070	MaxEnt
	Chitwan–Annapurna Landscape (CHAL), Nepal	Expansion in the suitable areas	Poudel *et al.* 2020	RCPs 2.6, 4.5, and 8.5 in 2050 and 2070	MaxEnt
Alternanthera philoxeroides (Mart.) Griseb.	China	Expansion	Tu *et al*. 2021	SSP 245 and 585 for 2050, 2070 and 2090	MaxEnt
Ambrosia artemisiifolia L.	China	Expansion	Tu *et al*. 2021	SSP 245 and 585 for 2050, 2070 and 2090	MaxEnt
	South Korea	Expansion	Adhikari *et al*. 2022	RCP 4.5 and 8.5 for the year 2070	ANN, GLM, MARS, MaxEnt, and RF
Mikania micrantha Kunth	China	Expansion	Tu *et al*. 2021	SSP 245 and 585 for 2050, 2070 and 2090	MaxEnt
	South and Southeast Asia, Australia, Oceania and parts of the USA	Expansion toward cold and dry areas of the invasive range	Banerjee *et al*. 2019	RCPs 2.6 and 8.5 for the years 2050 and 2070	MaxEnt
	India	Expansion	Banerjee *et al*. 2017	-	MaxEnt
Parthenium hysterophorus L.	World and Oman	Contraction in areas in 2081–2100 at global level. Expansion for 2021-40 and a contraction for 2081–2100	Ruheili *et al*. 2022	SSP6–8.5 for the years 2030 and 2090	MaxEnt
	Bangladesh	Expansion	Masum *et al.* 2022	RCPs 2.6 and 8.5 for the year 2070	MaxEnt
	Bhutan	Expansion	Dorji *et al*. 2022	RCPs 4.5 and 8.5 for the years 2050 and 2070	MaxEnt
	Chitwan Annapurna Landscape, Nepal	Expansion in the suitable habitat under RCP 4.5 for 2050 and 2070, and decrease in suitable areas under RCP 8.5 in 2050 and 2070	Maharjan *et al.* 2019	RCPs 2.6, 4.5 and 8.5 for the years 2050 and 2070	MaxEnt
	Sri Lanka	Contraction in the areas under very low class and expansion for moderate class of suitability.	Kariyawasam *et al.* 2019	RCPs 4.5 and 8.5 for the years 2050	MaxEnt
	China	Expansion towards northward	Guan *et al.* 2020	RCPs 2.6 and 8.5 for the years 2050	Ensemble approach
	India	Overall decrease in habitat suitability with some highly vulnerable (Western Himalaya) region to its invasion	Ahmad *et al*. 2019	RCP 2.6 and RCP 8.5 for the years 2050 and 2070	Ensemble approach
Cynodon dactylon, Cyperus rotundus, Echinochloa colona, Echinochloa crus-galli, Eichhornia crassipes, Eleusine indica, Imperata cylindrica, Panicum maximum, and *Sorghum halepense*	World	Expansion in new areas	Wang and Wan 2020	RCPs 4.5 and 8.5 for the years 2050 and 2080	MaxEnt
Ambrosia trifida, Symphyotrichum pilosum, Ageratina altissima, Hypochaeris radicata, Lactuca serriola, Paspalum dilatatum, Paspalum distichum, Rumex acetosella, Sicyos angulatus, Solanum carolinense, Solidago altissima	South Korea	Expansion in new areas	Adhikari *et al*. 2022	RCP 4.5 and 8.5 for the year 2070	ANN, GLM, MARS, MaxEnt, and RF
Spartina alterniflora Loisel	China	Expansion in new areas	Yuan *et al*. 2021	RCPs 2.6 and 8.5 for the years 2050 and 2070	MaxEnt
Verbesina encelioides (Cav.) Benth. & Hook. Fil ex Gray	South Africa	Expansion in new areas	Moshobane *et al.* 2022	SSP 585 for the years 2030, 2050, 2070 and 2090	Ensemble approach
Apium leptophyllum, Astragalus sinicus, Bromus unioloides, Chenopodium ambrosioides, Coronopus didymus, Gnaphalium calviceps, Lolium multiflorum, Modiola caroliniana, Oenothera laciniata, Paspalum dilatatum, Sida rhombifolia, Silene gallica, Sisymbrium officinale, Sisyrinchium angustifolium, Spergularia rubra, Malva parviflora	South Korea	Expansion in new areas	Hong *et al*. 2021	RCPs 4.5 and 8.5 for the years 2050 and 2080	MaxEnt
Urochloa panicoides P. Beauv.	World	Area contraction in Brazil, Australia, India, and Africa, and an expansion in Mexico, the United States, European countries, and China	Duque *et al*. 2022	-	CLIMEX

MaxEnt- Maximum entropy

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Weed(s)	Region	Prediction about Contraction/expansion in areas	Reference	Prediction for future scenarios	Model used
Amaranthus palmeri	USA	Northward range expansion and significant increase in suitability across large portions of the U.S. overall	Briscoe Runquist *et al.* 2019	CliMond and PRISM	Maxent and Boosted Regression Trees
Lantana camara L.	World	Contraction in the global suitable areas. Some areas in North Africa, Europe and Australia may become climatically suitable. In South Africa and China, its potential distribution could expand further inland.	Taylor *et al.* (2012)	-	CLIMEX
	World	Expansion in new areas	Wang and Wan 2020	RCPs 4.5 and 8.5 for the years 2050 and 2080	MaxEnt
	Sri Lanka	Contraction in the areas of very low class and expansion in the moderate class of suitability	Kariyawasam *et al.* 2019	RCPs 4.5 and 8.5 for the years 2050	MaxEnt
	China	Species expansion northward	Guan *et al.* 2020	RCPs 2.6 and 8.5 for the years 2050	Ensemble approach
	Queensland, Australia	Reduction in climatic suitability	Taylor and Kumar 2013	A1B and A2 scenarios for the years 2030, 2070 and 2100	CLIMEX
	Jharkhand, eastern India	Expansion up to 20–26% by 2050	Tiwari *et al.* 2022	RCP 2.6, 4.5, 6, and 8.5 for the year 2050	MaxEnt
Butomus umbellatus	North America	Decrease in suitable areas, though two of three global circulation models predict range expansion across gas emission scenarios	Banerjee *et al.* 2020	-	Ensemble approach
Ageratum conyzoides, Praxelis clematidea, Solidago canadensis, Anredera cordifolia, Conyza sumatrensis, Chenopodium ambrosioides, Avena fatua, Pharbitis purpurea, Aster subulatus	China	Species expansion northward	Guan *et al.* 2020	RCPs 2.6 and 8.5 for the year 2050	Ensemble approach
Lonicera japonica	Forests of the Cumberland Plateau and Mountain Region in the southeast of USA	Expansion in new areas	Lemke *et al.* 2011	-	Ensemble approach
Chromolaena odorata	World	Expansion in new areas	Kriticos *et al.* 2004	-	CLIMEX
	India	Higher suitability for species in northeastern states, the central Himalayan provinces and the Western Ghats and Eastern Ghats	Barik and Adhikari 2012	2020 A2 & B2 and 2080 A2 & B2	MaxEnt
Amaranthus retroflexus, Amaranthus spinosus, Amaranthus viridis, Bidens pilosa, Conyza bonariensis, Conyza Canadensis, Galinsoga parviflora, Physalis angulata	China	Expansion	Wan *et al.* 2017	RCP 4.5 and 8.5	MaxEnt
Chromolaena odorata and Tridax procumbens	India	Both are likely to reduce their potential distribution areas	Panda and Behera 2019	A1B and A2 scenarios for the years 2050 and 2100	MaxEnt
Ageratina adenophora L., *Ageratum conyzoides* L., *Ageratum houstonianum* Mill., *Amaranthus spinosus* L., *Bidens pilosa* L., *Erigeron karvinskianus* DC., *Lantana camara* L., *Parthenium hysterophorus* L., *Senna occidentalis* (L.) Link., *Senna tora* (L.) Roxb., *Xanthium strumarium* L.	Western Himalaya, India	Most of these invasive plants are expected to expand under future climatic scenarios	Thapa *et al.* 2018	RCP 2.6 and RCP 8.5 for the year 2050 and 2070	MaxEnt
Cassia tora and *Lantana camara*	India	Distribution ranges of both species could shift in the northern and north-eastern directions in India	Panda *et al.* 2018	A1B and A2 scenarios for the years 2050 and 2100	MaxEnt, GLM and GAM

MaxEnt- Maximum entropy

Table 2. Studies on species distribution modelling and prediction of aquatic weed invasion under future climate scenarios

Weeds	Region	Prediction about Contraction/expansion in areas	Reference	Future scenario(s) used	Model used
Alternanthera philoxeroides, Ceratophyllum demersum, Crassula helmsii, Elodea canadensis, Hydrilla verticillata, Ludwigia peruviana, Najas minor, Pistia stratiotes, Potamogeton crispus, Sagittaria platyphylla	World	Climatic suitability was significantly higher for temperate coastal rivers and temperate floodplain rivers	Wanga *et al*. 2017	-	MaxEnt
Myriophyllum aquaticum, Pistia stratiotes, Azolla filiculoides, Eichhornia crassipes, Salvinia molesta	South Africa	*Myriophyllum aquaticum* and Pistia will contract and rest three will increase their areas	Hoveka *et al*. 2016	2080	MaxEnt
Nitellopsis obtusa	United States	Decrease in the species' suitable range	Romero-Alvarez *et al.* 2017	RCP 2.6, 4.5, 6, and 8.5	MaxEnt

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REVIEW ARTICLE

Effect of increasing atmospheric CO_2 and temperature on weeds and their management - Mitigation strategies

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ABSTRACT

Agriculture is highly vulnerable to climate change, which influences key factors like land, water, and environmental conditions critical for crop production. Rising atmospheric CO_2 and global temperatures exacerbate these challenges, particularly by enhancing the growth and competitive advantage of certain weed species. Elevated CO_2 levels stimulate photosynthesis and biomass accumulation in C_3 weeds, allowing them to outcompete crops, while higher temperatures shift weed growth cycles and distributions. Together, these changes complicate weed management, reduce herbicide efficacy, and contribute to resistance development. The combination of environmental stressors, such as heat and water scarcity, further strains agricultural systems, threatening food security and economic stability. This review critically examines the impacts of ever-increasing CO_2 and temperature on weed biology, physiology, and population dynamics. It highlights the consequences of weed shifts, invasions, and altered life cycles, emphasizing the challenges these pose to agricultural systems. Drawing on recent findings, including experimental data from Open Top Chambers (OTCs) and Free Air CO_2 Enrichment (FACE), the review discusses how elevated CO_2 and elevated temperature can impact weed management practices. It also proposes mitigation strategies aimed at addressing these challenges, including the development of climate-resilient weed management practices and integrated weed management approaches. Understanding the impacts of climate change on weed dynamics is crucial for designing sustainable agricultural systems capable of adapting to future environmental conditions.

Keywords: Climate change, Crop-weed interaction, Elevated CO_2 and Elevated temperature, Weed physiology, C_3 plants and C_4 plants

INTRODUCTION

Agriculture is particularly vulnerable to climate variations, as it heavily depends on land, water, and other natural resources that are directly influenced by changing environmental conditions (Walsh *et al.* 2020, Gowda *et al.* 2018). In addition to nutrient and field management, crop production is strongly influenced by the cumulative effects of soil, water, and weather conditions throughout the growing season (Nolte *et al.* 2018). Frequent and severe droughts, in particular, negatively affect plant growth, physiology, and reproduction, leading to significant reductions in crop yields (Barnabas *et al.* 2008, Satoh *et al.* 2020, Yordanov *et al.* 2020, Pokhrel *et al.* 2021). These yield reductions not only threaten global food security but also exacerbate economic volatility in agriculture, with fluctuations in crop prices and trade restrictions impacting farmers' livelihoods.

Global average temperatures have been consistently reaching new records, accompanied by increasingly unreliable rainfall patterns and extreme weather events such as droughts, floods, and storms, all of which are intensifying the stress on agricultural systems (Global Climate Report, 2022). The risks of heat and water stress are expected to escalate, posing further challenges to crop production (USGCRP 2017). Furthermore, climate change is contributing to the wider spread of pests, weeds, and diseases, which are causing severe crop failures across various regions (Ziska *et al.* 2016, EPA 2022). As these climatic shifts continue, agricultural productivity is expected to become more variable, with some regions experiencing improvements while others suffer devastating losses (Wu *et al.* 2015, Liang *et al.* 2017, Ortiz-Bobea *et al.* 2021, Liang 2022).

Among the numerous threats posed by climate change, the proliferation of weeds under elevated CO_2 and temperature conditions presents a critical

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challenge for sustainable agriculture. Rising atmospheric CO_2 levels enhance photosynthesis in certain weed species, particularly C_3 weeds, leading to greater biomass and competitive ability against crops. Simultaneously, higher temperatures may shift weed growth cycles, phenology, and geographical distributions, complicating management efforts. Consequently, the effectiveness of herbicides, which are already under pressure due to resistance development, is further compromised under these altered environmental conditions. This review explores the impact of ever-increasing atmospheric CO_2 and temperature on weeds and their management, while highlighting potential mitigation strategies aimed at maintaining agricultural productivity in the face of a changing climate.

Climate change: Rising atmospheric CO_2 and temperature

The 2023 IPCC Synthesis Report underscores the mounting challenges of climate change, warning of a high likelihood that global temperatures could exceed 1.5°C between 2021 and 2040, particularly under high-emission scenarios (Bacchin *et al.* 2023). By 2023, human-induced warming had already reached 1.31°C, driven by record levels of greenhouse gas emissions (Forster *et al.* 2024). The report highlights the disproportionate effects of climate change on vulnerable populations and stresses the urgency of taking substantial, immediate action to reduce emissions. If these efforts are not undertaken, the consequences could be dire, with current climate commitments falling short and potentially leading to a 3.2°C rise in global temperatures if current trends continue (Bongaarts 2024). While adaptation strategies, particularly in urban systems, are viewed as critical, many argue that adaptation alone will not suffice and that broader systemic changes are required to build resilience (Bacchin *et al.* 2023).

One of the key contributors to rising global temperatures is the increase in atmospheric CO_2, which has surged by approximately 40% since the late 19th century, contributing to a 1.07°C increase in global temperatures (Adak *et al.* 2023). Projections suggest that, without significant mitigation efforts, CO_2 levels could rise to two to four times higher than those seen in the past 800,000 years, leading to unprecedented climatic changes (Raviraja 2023). The IPCC warns that if emissions remain unchecked, global temperatures could rise by 3.6 to 4.4°C by the end of the century (Adak *et al.* 2023), with severe implications for biodiversity and food security. Agricultural systems, in particular, are at risk, as rising temperatures and CO_2 levels are expected to exacerbate the severity of diseases such as rice sheath blight, further threatening food production (Shen *et al.* 2023). Continued reliance on fossil fuels could significantly increase CO_2 emissions, further destabilizing global climate systems (Raviraja 2023). While natural climate variability is also debated as a factor influencing temperature trends, the overwhelming consensus emphasizes the need for robust mitigation strategies to prevent the most severe consequences of climate change (Edmonds 2023). Without decisive action, the future of ecosystems and human societies faces unparalleled risks.

Effect of rising levels of CO_2 and temperature on plants in general

The rising concentrations of atmospheric greenhouse gases, particularly CO_2, have accelerated global warming and increased the frequency of climate extremes in recent decades (Sage 2020, Zandalinas *et al.* 2021). These extreme climate events, including temperature extremes and erratic patterns of precipitation, have had profound impacts on global agricultural systems, leading to reductions in crop growth and yield (Fahad *et al.* 2017). Concurrently, the ongoing decline in arable land and increasing population pressures have raised concerns about global food insecurity (Borrelli *et al.* 2020, Sage, 2020; Zandalinas *et al.* 2021). With global food demand expected to rise significantly in the coming decades (Conijn *et al.* 2018), the sustainability of crop production under changing environmental conditions has become a central challenge for agriculture.

Cereals, which are essential for human food and livestock feed (McKenzie and Williams 2015, Bruinsma 2017), are particularly vulnerable to these environmental changes. The ability of different cereal species and varieties to withstand such stress is strongly influenced by their genetic makeup, as well as by physiological and molecular mechanisms that contribute to stress tolerance (Raza *et al.* 2019). To adapt to the rapidly shifting climate, one promising strategy is the alteration of cropping systems to favor species with specific traits, such as adjusting the proportion of C_3 and C_4 plants based on their differing responses to environmental conditions (Rezaei *et al.* 2023). Additionally, crop management practices and the development of crops with enhanced resistance to environmental stresses are critical for ensuring resilient food systems. While the mechanisms governing crop responses to individual stressors are relatively well understood, the effects of multiple, simultaneous environmental factors on crop performance—particularly under conditions where stress responses interact synergistically or antagonistically—remain poorly understood (Zandalinas and Mittler 2022). Crop modeling has emerged as a valuable tool for predicting the future impacts of climate change on cereal production and for evaluating the differential responses of C_3 and C_4 crops to environmental stress (Wang *et al.* 2023).

Drought stress, for instance, can significantly reduce photosynthesis, nutrient uptake, and overall biomass production, leading to lower grain yields. In response, plants activate a range of physiological and molecular mechanisms, such as stomatal closure, osmolyte and antioxidant accumulation, and modifications in root architecture (Farooq *et al.* 2009, Anjum *et al.* 2011, Zhao *et al.* 2020). Elevated CO_2 concentrations, on the other hand, can improve photosynthesis and water use efficiency, potentially boosting biomass and yield under favorable conditions (Leakey *et al.* 2019, Souza *et al.* 2019). Moreover, CO_2 enrichment has been shown to mitigate the adverse effects of water scarcity to some extent (Abdelhakim *et al.* 2022). However, increased leaf area under elevated CO_2 could counterbalance these benefits by amplifying transpiration, thereby exacerbating the effects of drought (Burkart *et al.* 2011). Studies have also reported a reduction in herbicide efficacy under drought stress conditions (Sreekanth *et al.* 2024b)

High temperatures also pose a significant threat to cereal crops, particularly during reproductive stages, by disrupting key physiological processes like photosynthesis, respiration, and stress signaling pathways (Tiwari and Yadav 2019). While plants employ protective mechanisms such as heat shock proteins, antioxidant production, and alterations in membrane fluidity to combat heat stress (Jat *et al.* 2016), prolonged exposure to extreme heat can cause irreversible tissue damage and, in some cases, plant death. Addressing the combined challenges of drought and heat stress, especially in the context of rising atmospheric CO_2, will require a deeper understanding of how these factors interact to influence crop productivity.

Effect of rising levels of CO_2 and temperature on weeds in particular

Rising atmospheric carbon dioxide and temperature can alter the growth and physiology of weedy plants. A few of the weed species may become inactive, while the rest may become aggressive invaders. Certain weed species possess the ability to survive and establish under changed climate by means of different dispersal and adaptive mechanisms (Bergmann *et al.* 2010) and try to persist after they have become established (Smith *et al.* 2011).

Weed shift and invasion

Weeds which are not adapted to the changing climate tend to shift to more favorable conditions. Native weeds that are favored by changes in carbon dioxide, temperatures and rainfall will tend to become invasive by intensifying its population and range. *Lantana camara*, for example, could expand its range if rainfall increased in some areas. Alien invasive weeds, which have strong reproductive potential, are reportedly get benefited from climate change. Introduced weeds can contribute to significant economic losses in agriculture and impose a substantial financial burden on resources allocated for the management of natural areas (Sreekanth *et al.* 2022). Therefore, it is predicted that alien weeds, such as parthenium (*Parthenium hysterophorus* L.) and chromolaena (*Chromolaena odorata* (L.), will be more aggressive under raised CO_2 level (Chandrasena 2009, Naidu 2013). Overall, increasing CO_2 and temperature may alter dominant weed species and increase weed problems (Ziska and Dukes 2011).

Weed growth and biology: Increasing atmospheric CO_2 has been shown to stimulate growth and development in several weed species. CO_2 can affect plant and leaf size, seed size and production, the nutritive value of leaves to herbivores, plant toxicity and pollen production. Due to changing climate, changes in timing of life-cycles are expected that will affect flowering, fruiting and reproduction as the flowering is the most thermal sensitive stage of plant growth (Boote *et al.* 2005). From the experiments conducted in Open Top Chambers (OTCs) at ICAR-Directorate of Weed Research, Jabalpur, India, it was observed that CO_2 enrichment (550 ppm) hastened the seed maturity in *Avena fatua* (Wild oat), a common weed in wheat and the seeds matured two weeks in advance compared to that of seeds from the plants grown under ambient CO_2 (380 ppm) conditions (Naidu 2011).

Crop-weed Interactions: Coexisting crop and weed plants primarily have competitive interactions. Changes in climatic factors such as increasing CO_2, temperature and precipitation can potentially influence crop-weed competition. Weeds pose significant challenges under changing climate conditions, severely impacting crop productivity and agricultural systems, particularly in major crops such as rice (Sreekanth *et al.* 2023a, Mahawar *et al.* 2023, Roy *et al.* 2023, Sreekanth *et al.* 2024a, Pawar *et al.* 2022), wheat (Sondhia *et al.* 2023), soybean

(Chander *et al.* 2023), and potato (Chethan *et al.* 2023). The rising CO_2 and temperature will affect the crop-wed competition (Ziska 2022), which varies with the nature of weeds and crops (Chongtham *et al.* 2019, Ziska *et al.* 2019). It is likely that rising CO_2, coupled with high temperature conditions will benefit weeds more than crops (Holt *et al.* 2013)

a. Effect of elevated CO_2 on crop-weed interaction: Increasing atmospheric CO_2 concentrations have been shown to significantly enhance the growth and development of numerous plant species (Poorter 1993, Sage 1995). The plant response to elevated CO_2 varies based on their photosynthetic pathways (C_3 or C_4). However, predicting the effects of elevated CO_2 on crop-weed interactions in controlled environments often leads to insufficient quantification of competition, as field conditions rarely involve single-weed infestations (Ziska & Goins 2006). Limited studies have explored the response of crops and weeds in competitive settings under elevated CO_2 (Ziska 2004, Ziska & Goins 2006), highlighting the need for more research involving weed-crop mixtures. In general, C_3 crops (e.g., rice, wheat, soybean) tend to benefit more from elevated CO_2 due to higher photosynthetic rates compared to C_4 weeds like Palmer amaranth (*A. palmeri*), waterhemp (*Amaranthus rudis*), and kochia (*K. scoparia*) (Elmore & Paul, 1983). For C_3 crops such as rice and wheat, elevated CO_2 can improve competitiveness against C_4 weeds (Yin & Struik 2008, Fuhrer 2003). However, studies have shown that under drought conditions and elevated CO_2, *Phalaris minor*, a C_3 weed, was more competitive than wheat (Naidu & Varshney 2011). The impact of elevated CO_2 on weedy and cultivated rice was also studied in open-top chambers, revealing positive effects on leaf area, tiller number, photosynthetic rate, and transpiration in both rice types (DWR 2013-14, Sreekanth *et al.* 2023b).

b. Impact of elevated temperature on crop-weed interaction: At elevated temperatures, plants with the C_4 photosynthesis pathway, primarily weeds, tend to have a competitive edge over crops that use the more common C_3 pathway (Yin and Struik 2008). A temperature increase of 3°C, for instance, significantly boosts the growth of itch grass (*Rottboellia cochinchinensis*), a highly competitive C_4 weed in key cropping systems like sugarcane, corn, cotton, soybean, grain sorghum, and rice. This weed is predicted to spread further into regions like the central Midwest and California (Patterson *et al.* 1999). C_4 species, such as *Amaranthus retroflexus* and *Sorghum halepense*, are expected to fix CO_2 more efficiently than C_3 crops like soybean and cotton, especially during midday when both light intensity and temperature peak. Due to their high water use efficiency and CO_2 compensation point, C_4 plants are better suited to cope with increased evaporative demand in high temperatures (Bunce 1983).

c. Interactive effect of elevated CO_2 and temperature on crop-weed interaction: Several studies conducted at ICAR-DWR have shown that *Phalaris minor* gains a competitive advantage over wheat under elevated temperature alone, or when combined with elevated CO_2. Similarly, other research revealed that the combination of elevated temperature and CO_2 delays panicle maturity in cultivated rice, weedy rice, and wild rice (DWR 2014-15, DWR 2015-16). In competitive interactions, elevated CO_2, elevated temperature, and their combination favored *Euphorbia geniculata* (C_3) over greengram and C_4 weeds like *Amaranthus viridis* (DWR 2016-17). Elevated temperature, whether alone or combined with CO_2, had a negative impact on wheat, while *Phalaris minor* was unaffected (DWR 2015-16). These findings suggest that under future climate change scenarios (elevated CO_2 and temperature), *Euphorbia geniculata* may outcompete both greengram and *Amaranthus viridis* (DWR 2016-17).

Climate change and weed management

Climate change poses several challenges for managing weeds. Climate change may have more implications on weed management in different crops and cropping systems owing to differential growth response of crops and weeds.

Manual and mechanical weed management: Elevated CO_2 commonly stimulates below ground growth and this may make manual weeding a difficult task as CO_2 rises. High temperatures create drier conditions which makes manual or even mechanical removal of weeds harder. Efficiency of farm labor vis-a-vis manual weeding would get negatively affected due to temperature rise and also harder surface soil.

Chemical weed management: It is imperative to manage the weeds to reduce the crop losses and it is generally done through a number of control strategies including manual, mechanical, biological and chemical methods depending on various factors such as cropping systems, environment, resources *etc*. However, chemical methods are favored because of uniformity and ease of application, high efficacy, cost effectiveness and time saving (McErlich and Boydston 2013). Over the past two decades, the use of herbicides for weed control has increased in India because of its effectiveness in improving e crop yields and saving labour and energy. However, the effectiveness of a given herbicide relies not only on its chemical properties but also on its interaction with the plant and the environment. Besides morphological and anatomical characters of the target plant, environmental conditions play a crucial role in determining the efficacy of herbicides at the time of application. Several environmental factors such as temperature, solar radiation, humidity etc., and interaction among them influence physiological processes of a plant and its susceptibility to herbicide. Changes in the global climate due to a rise in atmospheric CO_2 and associated increase in temperature can have significant impacts on plant growth and herbicide performance. Therefore, understanding the effects of rising CO_2, temperature and other environmental factors on weed growth and herbicide efficacy is important to optimize the herbicide application for effective weed control. Climate change factors, besides positive effect on weed growth, could affect the efficacy of many herbicides, making weed management a difficult task for sustainable crop production. A number of studies indicate that rising atmospheric CO_2 is likely to alter or negatively influence the performance of herbicides (Manea *et al.* 2011, Sreekanth *et al.* 2023). Higher temperatures could increase both absorption and translocation of foliar applied herbicides adding to efficacy, but also increase volatility and microbial breakdown (Atienza *et al.* 2001).

Research findings evidently show that rising CO_2 can significantly reduce protein levels in plant tissues (Taub *et al.*, 2008). Less protein would result in less demand for aromatic and branched chain amino acids, with a potential decline in the efficacy of herbicides (e.g. Glufosinate, Glyphosate) that act as enzyme inhibitors (Varanasi *et al.* 2016). Absorption and translocation of foliar applied herbicides varies with orientation and surface area of the leaf. If leaf number or area is stimulated due to rising CO_2 or temperature, then such changes would increase herbicide interception and absorption during spraying. Temperature alters relative humidity and the main effect of relative humidity is in controlling the speed at which a spray drop dries on the leaf surface. There is good evidence that penetration slows down and may cease when the drop dries out. Low relative humidity causes the drop to dry out faster thus herbicide activity is usually lesser. High relative humidity favors opening of the plant stomata, low relative humidity may lead to stomatal closure. Allometric changes (variable growth in different plant parts) can affect herbicide interactions. For example, altered root shoot ratio in Parthenium exposed to elevated CO_2 (Naidu 2013).

It is increasingly evident from the research findings that changing climate conditions may reduce the sensitivity (increase the tolerance) of weeds to some herbicides. Matzrafi *et al.* (2019) reported that glyphosate-treated plants (*Conyza Canadensis* and *Chenopodium album*) grown under increased temperature and elevated CO_2 level exhibit reduced glyphosate sensitivity. Thus, the continued overreliance on glyphosate for weed control under changing climatic conditions may result in more weed control failures. High CO_2 and high temperature increased the resistance level of Multiple Resistant *Ehinochloa colona* to cyhalofop-butyl (Refatti *et al.* 2019).

Bio-control of weeds: Climate change may indirectly affect bio-control of weeds by the way of its direct influence on the reproduction, survival, distribution and behavior of bio-agents especially insects (Sujayan and and Karuppaiah 2016). Feeding habits of insects may get affected due to changes in nutritional properties of weeds under high CO_2 (Casteel *et al.* 2012). Successfully adapted and established bio-agents may also get affected due to climate change. For example, feeding efficiency of *Zygogramma bicolorata* on Parthenium is reportedly decreased at the optimal temperatures above 27-30! (Kumar *et al.*, 2021). Similarly, reproduction and development of *Cyrtobagous salviniae*, a bio-control agent of *Salvinia molesta* may get affected due to rising temperature (Allen *et al.* 2014). Decreased plant palatability of Alligator weed (*Alternanthera philoxeroides*) under drought has reportedly caused reduction in population growth of its bio-agent *Agasicles hygrophila* suggesting that drought can reduce the biological control of Alligator weed indirectly by interrupting plant–insect interaction (Wei *et al.* 2015).

Mitigation strategies

Existing weed management strategies, to be effective, need specific environmental conditions that are becoming less predictable in the present scenario of changing climate. Owing to their greater adoption potential, weeds are likely to out-compete the crops under changing climate & resources. The conditions of changing climate might necessitate the adoption of new agronomic practices to enhance weed competitiveness.

Preventive measures: Seeds of most crops are contaminated with weeds, especially where weed seeds resemble the shape, size and color of crop seeds. Minimizing weed seed contamination with crop seed is the primary step in preventing the possible weed competition with emerging crop.

Cultural practices: Adjusting the sowing/planting date is one of the effective strategies to mitigate the adverse effects of climate change on crop production. Manipulating the sowing or planting time in such a way that the conditions for weed germination or emergence are not favorable. For example, early sowing of wheat by two weeks reduces the problem of *Phalaris minor* and *Avena fatua* in north-western part of the Indo-Gangetic plains because these weeds require low temperature for germination (Dinesh Jinger *et al.* 2016). Direct seeding is the preferred option for rice cultivation in the scenario of water shortage which is aggravating day by day due to global warming. However, more than 90% of the yield reduction in rice is attributed to weed competition. Experimental results of Agronomy Division, Faculty of Agriculture, SKUAST-Kashmir showed that earlier sowing of DSR (10th May) was more effective than late sowing (3rd June) with respect to growth characteristics, yield, weed population per unit area, dry weed biomass and economics (Mir *et al.* 2024).

Crop diversification and climate resilient crops cultivars: Competitiveness against weeds differs with crops and crop cultivars. Crop diversification and cultivation of weed smothering crops is equally important for weed management. Instead of traditionally–adopted cropping systems, inclusion of climate-resilient and weed smothering crops (i.e. millets and small millets) in a cropping system helps in minimizing the weed infestation to a great extent. Cultivars resilient to climate change conditions especially drought, flooding, high temperature can overcome the weed competition to some extent. For example, temperature-insensitive cultivars can cope up with high temperatures

Challenges ahead

Increased weed proliferation and aggressiveness: Elevated atmospheric CO_2 levels enhance the growth and reproductive potential of many weed species, particularly C_3 plants, which may outcompete crops for resources such as light, water, and nutrients. This increased weed biomass will demand more intensive management efforts, complicating weed control strategies, especially in regions already struggling with high weed infestations.

Herbicide resistance and reduced efficacy: Climate change is expected to exacerbate the ongoing issue of herbicide resistance. Rising temperatures and elevated CO_2 levels can reduce herbicide efficacy by altering weed physiology, growth stages, and herbicide absorption rates. Weeds may evolve resistance more quickly, rendering conventional chemical controls less effective and increasing the reliance on higher doses or alternative herbicides, which could raise environmental concerns.

Shifts in weed phenology and distribution: As temperatures increase and precipitation patterns change, weeds will likely shift their geographical range, leading to the invasion of new areas and crops. These shifts in weed distribution, particularly by invasive species like *Lantana camara* and *Parthenium hysterophorus*, may create new challenges for farmers unfamiliar with these weeds, further complicating their management and increasing production costs.

Complex interactions between weeds, crops, and climate extremes: The interaction between weeds, crops, and multiple environmental stressors such as drought, heatwaves, and floods complicates predictions and management strategies. These stressors may enhance the competitive advantage of certain weed species, while others might decline, creating unpredictable and site-specific weed dynamics that require localized management solutions.

Impact on biological weed control: Changes in temperature and CO_2 levels may also affect the effectiveness of biological control agents, such as insects and pathogens used to manage invasive weeds. Altered climatic conditions may impact the life cycle, efficacy, or survival of these agents, reducing their reliability as a weed management tool under climate change.

Adaptation of weeds to environmental stresses: Many weed species exhibit a high degree of adaptability, which allows them to thrive under various environmental stresses, including drought and high temperatures. This ability to rapidly adapt may enable weeds to continue proliferating even under extreme conditions, making it difficult for current management practices to keep pace with their evolving characteristics.

Resource constraints and economic costs: Addressing these growing weed management challenges will require substantial investment in research, extension services, and infrastructure. Farmers, particularly in developing regions, may face financial barriers in accessing new technologies and adopting integrated weed management practices. Additionally, rising herbicide costs and the need for more frequent applications may further strain economic resources in agricultural systems.

Knowledge gaps and uncertainty in long-term impacts: While the effects of elevated CO_2 and temperature on certain weed species are well documented, there remains considerable uncertainty about how climate change will affect the full spectrum of weed species, their interactions with crops, and their responses to management practices over time. Long-term studies are needed to fully understand these complex interactions and to develop more robust and predictive weed management models.

Development of climate-resilient management practices: The need for novel, climate-resilient weed management practices is urgent. Traditional herbicide-based approaches may not be sustainable in the face of rising resistance and reduced efficacy under climate change. There is a need to integrate cultural, mechanical, and biological control strategies with chemical management to create more holistic and adaptive weed management systems that can withstand future environmental changes.

Conclusion

The rising atmospheric CO_2 levels and increasing global temperatures are significantly altering weed biology and ecology, creating complex challenges for agricultural systems, particularly in weed management. Enhanced weed growth, shifted distribution patterns, and increased herbicide resistance require innovative and adaptive management strategies. The interplay of elevated CO_2, temperature, and other environmental stressors leads to unpredictable weed dynamics, complicating effective control methods. Conventional herbicide approaches may become less effective, highlighting the need for alternative practices such as cultural, mechanical, and biological controls. Developing resilient, climate-adaptive weed management strategies is crucial for maintaining crop productivity amid these changes. However, knowledge gaps persist regarding the long-term effects of climate change on weed species and their management, underscoring the importance of ongoing research and localized, sustainable solutions. Moving forward, a multidisciplinary approach that integrates scientific research, policy innovation, and farmer education is essential to address these emerging challenges. Stakeholders must invest in climate-resilient agricultural technologies and practices to adapt to evolving weed dynamics. A proactive and integrated strategy will be vital in mitigating the adverse effects of climate change on weed management, thereby safeguarding global food security.

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REVIEW ARTICLE

Crop-weed competition and herbicide bioefficacy: Implications in a changing climate

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ABSTRACT

Weeds in general cause 10-90% crop yield losses and are economically more harmful than insects, fungi or plant disease. Therefore, management of weeds in all agro-ecosystems is imperative to obtain sustainable crop production and to ensure food security to the increasing population. The agriculture practices and agricultural productivity are strongly impacted by the weather and climate change and likely to impact conventional aspects of farming practices and cropping systems. According to an estimate, approximately 10% yield losses caused by the weeds will be equal to the approximately ~2294 million metric tons. Global climate change, mainly increasing temperature and elevated carbon dioxide levels and its associated impact on weed management is one of the greater challenges which is expected to play an important role in the agricultural production systems across the globe. Due to the differential response of C_3 and C_4 plants under increasing CO_2 levels and temperature; chemical weed management strategies need to be revised to manage these weeds in the crop field. Reduced bioefficacy of several pre- and post-emergence herbicides of different mode of action under increasing CO_2 levels and temperature is reported such as, acetochlor, atrazine, bispyribac-sodium, carfentrazone, cyhalofop-butyl, fenoxaprop-p-ethyl, glufosinate, glyphosate, metsulfuron, paraquat, penoxsulam, pinoxaden, tribenuron-methyl etc. Decreased bioefficacy of herbicides due to higher temperatures is reported due to increased metabolism in targeted plants. Besides this, weed flora shift, crop-weed competitions and interference, optimization of herbicide doses, development of herbicide resistance in weeds, are some other major challenges in developing weed management package of practices under climate change scenarios. Changing climate is now a reality and poses a greater challenge which may further intensify weed problems due to the competition and adaptability in diverse climate situations than the crops. An integrated and holistic approach would be imperative to tackle weeds under climate change scenarios specifically in response to elevated CO_2 and rising temperature in the coming future.

Keywords: Climate Change, Global warming, Herbicide efficacy and metabolism, Resistance Temperature-dependent sensitivity, Weed management

INTRODUCTION

The global population reached nearly 8.2 billion by mid-2024 and is expected to reach over 9 billion by 2050 (UN News 2024). Weeds is considered as one of the most significant biotic constraints in crop production currently faced in global agriculture and cause approximately 30% crops yield losses (Sondhia and Mishra 2024) and the degree of losses varies by crop, cultivar, weed species, weed infestation level, location, and farming practices (Soltani *et al.* 2016). Climate change, characterized by elevated CO_2 (eCO_2) levels, increasing temperatures, and water scarcity, along with enhanced greenhouse gas (GHG) emissions, has emerged as a significant concern which has potential impact on agricultural production and pest dynamics as it affects the physical environment and ecosystems (Carbonbrief 2024). Atmospheric CO_2 level have been increasing at an unprecedented rate, reached to 426 parts per million (ppm) in mid-2024 (https://www.co2.earth/daily-co2), and are projected to exceed 700-1000 ppm by the end of the 21st century (IPCC 2014). Global surface temperature has increased faster since 1970 with an increase of 0.8°C to 1.3°C from 1850–1900 to 2010–2019 and over this period, greenhouse gases (GHGs) contributed a warming of 1.0°C to 2.0°C (IPCC, 2023), with future projections indicating an increase of 1.1 °C to 6.4 °C by the end of 21st century (IPCC, 2014) (**Figure 1**). Global warming has substantially affected the crop-weed interaction and crop productivity (Sondhia *et al.* 2024; Srikanth *et al.* 2024a, 2024b). Elevated temperatures (eT) is likely to be positively correlated with the altered weeds' growth and biology, phenology, dispersal and demography than the crop (Keller and Shea 2021). It has been reported that apart from eCO_2 levels, and rising temperature; greenhouse gas emissions, may also affect nutrient availability for plant growth and development (Reeves 2017).

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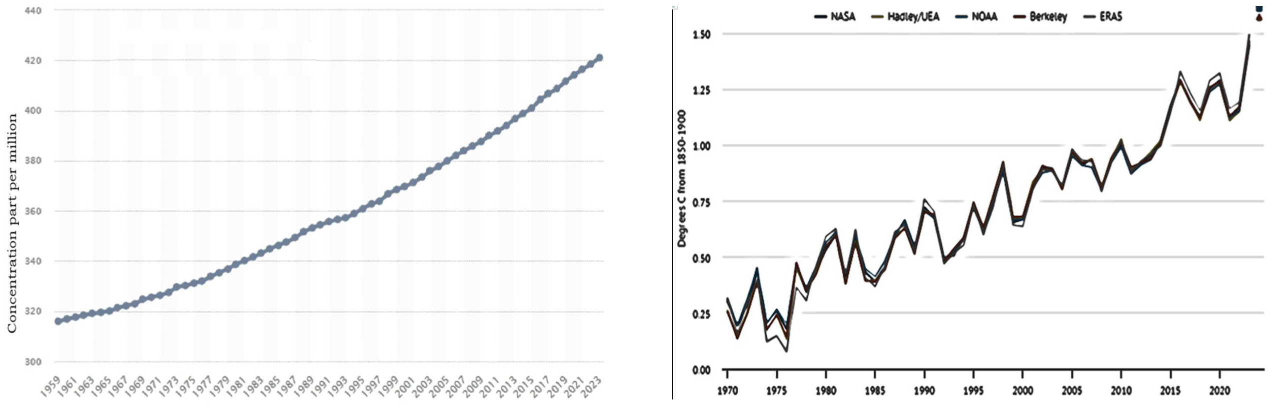

Figure 1. Average CO_2 level (ppm) since 1959 to 2023 (Source statistica 2024) and temperature level between 1980 to 2024 (Source: CarbonBrief 2024).

Currently chemical weed management practices are widely adopted due to its higher weed control efficiency and will be likely to be adopted more frequently under climate change conditions. Globally, usage of herbicides occupies 44% of the total agrochemicals and it is 30% in India (Sondhia 2014). It has been described that successful chemical weed management relies not only on the chemical properties of a herbicide but also on its interaction with the plant and the environment. Herbicide absorption into the target plant largely depends on its interaction with atmosphere, soil, or the soil–atmosphere interface. Several environmental factors such as temperature, moisture, relative humidity, and solar radiation influence a plant's physiologic status and its susceptibility to herbicides. Climate change is expected to result in varying growth rates for both crops and weeds, which may have significant impacts on crop production and weed management. Among various pests, weeds are most responsive to the increasing CO_2 concentrations in Earth's atmosphere. Crop-weed interactions and competition are likely to vary depending on various regions and cropping systems. It has also been reported that increased CO_2 concentrations and temperature can reduce the herbicide bioefficacy against many weeds (Ziska *et al.* 2019). Among various climate change factors, assessment of the effects of global climate change factors particularly of eCO_2 concentrations and rising temperature on agricultural practices is particularly important to understand the vulnerability of crop production across the glob and to anticipate and adapt practices that maximize agricultural production in future climate scenarios. Therefore, the impact of climate change mainly due to eCO_2 and temperature on weed management and herbicide efficacy and its mitigation strategies on weeds and weed management is described here.

Impact on C_3 and C_4 plants

Ziska *et al.* (2019) described that eCO_2 and climate change will impose strong selection pressures on weeds and they will often have the capacity to respond with rapid adaptive evolution. In addition, shifts in the efficacy of biological constraints (*e.g.*, pathogens) and resultant selection shifts in affected weed species, climate-induced phenological shifts in weed distribution, demography, and suitability relative to crop systems; and understanding and characterization of epigenetics and the differential expression of phenotypic plasticity versus evolutionary adaptation may be required to develop effective weed manage practices in future. Many weeds have the C_4 pathway, which shows a minimal response to CO_2, whereas crops often have the C_3 pathway (**Table 1**), which shows a stronger response. Due to fertilization effect of rising CO_2 on plant photosynthesis, the conversion of ongoing CO_2 to sugars will stimulate C_3 photosynthesis and plant growth (~85% of plant species, including many weeds) and it was hypothesized that crops would outcompete weeds as CO_2 rose (Ziska *et al.* 2019) and at higher temperatures and increased drought, C_4 weeds can still benefit (Valerio *et al.* 2013) relative to C_3 crops (Elmore and Paul 1983) (**Table 2)**.

Additional evidence suggests that adaptation to recent changes, particularly the rapid increase in CO_2, i.e. 20% increase since 1980 (Waryszak *et al.* 2018), might have already altered the crops and weeds competition and adaptability. Comparisons of six cultivated and six wild or weedy biotypes of rice (*Oryza sativa* L.) indicated a greater overall growth response among wild relative to cultivated rice (*Oryza sativa* L.) to 300 to 400 ppm increases in CO_2 suggesting that rapid evolution of weedy biotypes may have increased their evolution relative to the crop. Higher seed yields were also recorded for Stuttgart, a weedy biotype, relative to ClearfieldTM, a cultivated rice line (Ziska *et al.* 2010, Franks *et al.* 2018), Seed of two temporally distinct populations of wild oat (*Avena fatua* L.) demonstrated different competitive abilities against a cultivated oat (*Avena sativa* L.) line at current CO_2 levels (Ziska 2017).

Seed of the annual weed birdsrape mustard (*Brassica rapa* L.) (C_3) collected before and after a severe drought demonstrated that drought exerts strong selection pressure, and *B. rapa* responded by evolving earlier flowering and lower water-use efficiency within a few generations (Franks 2011). Similarly, in a much wetter environment, the limestone grassland of Britain, 13 years of drought led to evolution of drought escape in the common weed buckhorn plantain (*Plantago lanceolata* L.) (C_3) (Ravenscroft *et al.* 2015). The annual invasive grass foxtail brome (*Bromus madritensis* L.), populations subjected to eCO_2 evolved through reduced stomatal conductance, allowing them to lose less water but still obtain sufficient CO_2 in the elevated environment, demonstrating rapid adaptive evolution to eCO_2 (Grossman and Rice 2014). This shift demonstrates that weeds are more competitive with crops, and has the potential to lower crop yields. As climatic conditions evolve, the composition of weed communities is also expected to change and may lead to a weed shift or a mixed population of C_3 and C_4 weed species, which further complicates weed management strategies through herbicides due to varying levels of herbicide selectivity and efficacy. Uneven and erratic rainfall and drought conditions may shift the timing of weed germination and growth, making it more difficult to manage weed infestations.

Differential response to herbicides of C_3 and C_4 weeds

C_3 and C_4 weeds exhibit differing responses to reported under eT and eCO_2 in climate change, potentially leading to shifts in weed populations that

Table 2. List of some important C_3 and C_4 weeds found in various crops

C_3 weeds		C_4 weeds	
Scientific name	Common name	Scientific name	Common name
Abutilon theophrasti	Velvet leaf, Chinese jute	*Amaranthus cviridis*	Slender amaranth
Alternanthera philoxeroides (Mart.) Griseb (C_3/C_4)	Alligator weed	*Amaranthus spinosus*	Spiny pigweed
Alternanthera paronychioides (C_3-C_4)	Smooth chaff flower	*Amaranthus viridis*	Slender amaranth
Anagallis arvensis	Scarlet pimpernel	*Amaranthus palmeri* S. Watson	Palmer amaranth
Ageratum conyzoides	Goat weed	*Amaranthus retroflexus*	Pig weed, Red root
Agropyron repens	Couch grass	*Boerhavia diffusa*	Red spiderling
Aegilops cylindrica	Jointed goat grass	*Cynodon dactylon* (L.) Pers.	Bermudagrass
Asphodelus tenuifolius	Onion weed	*Cyperus articulatus* L. (CYPAR)	Jointed flatsedge
Argemone mexicana	Mexican poppy	*Cyperus iria*	Rice flat sedge
Ammannia baccifera	Monarch redstem	*Cyperus rotundus* L.	Purple nutsedge
Alternanthera sessilis	Sessile joyweed	*Cyperus esculentus*	Yellow nutsedge, tiger nut,
Avena fatua	Wild oat	*Chloris barbata* Swartz. (CHRBA)	Swollen fingergrass
Bromus inermis Leyss	Bromegrass	*Digitaria sanguinalis* (L.) Scop. (DIGSA)	Large crabgrass
Bidens pilosa	Spanish needles	*Dactyloctenium aegyptium*	Crowfoot grass
Brassica rapa L.)	Birdsrape mustard	Digitaria ciliaris (Retz) Koel	Crab grass
Commelina benghalensis	Day flower,	*Dinebra retroflexa* (Vahl) Panz	Viper grass
Convolvulus arvensis	Field bindweed	*Echinochloa crus-galli* (L.) Beauv	Barnyard grass
Cirsium arvense	Canada thistle	*Euphorbia hirta*	Garden spurge
Chenopodium album L.	Lambsquar-ters	*Eleusine indica (L.)* Gaertn.	Indian goosegrass
Chloris barbata	Purple topchloris	*Echinochloa colona* (L.) Link	Jungle rice
Cyperus difformis	Small flower umbrella sedge	*Fimbristylis dichotoma*	Fimbry, fimbristyle
Chromolaena odorata	Siam weed	*Fimbristylis millacea*	Lesser Fimbristylis
Eclipta prostrata	False daisy	*Imperata cylindrica* (L.) Raeuschel	Cogon grass
Euphorbia geniculata	Wild poinsettia	*Ischaemum rugosum*	Wrinkled duck beak
*Eichhornia crassipes(*Mart.*) Solms*	Water hya-cinth	*Leptochloa chinensis*	Red sprangletop
Festuca arundinacea Schreb.	Tall fescue	*Paspalum orbiculare* Forst. (PASOR)	Ricegrass paspalum
Ipomea spp.	Water spinach	*Panicum virgatum* L.	Switchgrass
Monchoria vaginalis (Burm. f.) Persl.	Monchoria	*Panicum maximum* Iacq. (PANMA)	Guineagrass
Plantago lanceolata L.	Buckhorn plantain	*Portulaca oleracea*	Common purslane
Parthenium hysterophorus(C_3-C_4)	Congress grass	*Paspalum orbiculare* Forst	Ditch millet
Physalis minima	Sunberry	*Paspalum distichum*	Knot grass, water finger grass
Phyllanthus niruri	Stone breaker	*Rottboellia cochinchinensis (*Lour*)*	Itchgrass
Phalaris minor	Little seed canary grass	*Setaria glauca* (L.) Beauv.	Fox tail
Phalaris arundinacea L.	Reed canarygrass	*Setaria viridis* (L.) Beauv. (SETVO	Green foxtail
Rumex dentatus	Aegean dock Jangli palak	*Sorghum halepense* (L.) Pers.	Johnsongrass
Rumex acetosella L.	Red sorrel	*Saccharum officinarum* L.	Tiger grass
Striga asiatica	Witchweed	*Saccharum spontaneum*	Wild sugarcane
Tridax procumbens	Coat buttons	*Trianthema portulacastrum*	Horse purslane
Xanthium strumarium	Common cocklebur		

threaten crop productivity (Umkulzhum *et al.* 2024) (**Table 2**). Germination and growth of *Amaranthus patulus* (C_4) was higher at 25°C to 30°C, however, under eCO_2 conditions, germination and growth of *A. patulus* was not significantly different. Weed defines a mechanism also reported as a result of leaf thickening, and closure of stomata, thereby reduceing the amount of foliar-applied herbicide that is directly absorbed by plants (Jackson *et al.* 2011). Quackgrass (*Elymus repens,* (C_3) was reported to be more tolerant to glyphosate under eCO_2 concentration (720 µmol/mol). Another prominent effect of eCO_2 is 50% reduction in stomatal conductance in some plants, which can alter the transpirational flow and reduce the efficacy of both foliar- and soil-applied herbicides.

Increased CO_2 can also induce morphological, physiological, and anatomical changes in plants that could affect herbicide absorption and translocation rate (Manea *et al.* 2011). It is reported that plants (C_3 and C_4) grown under eCO_2 have thicker cuticle and increased leaf pubescence (Ainsworth and Long, 2005). These traits could reduce herbicide entry into plant leaves and further affect its efficacy. Apart from that, climate change is causing increases in weed biomass and shifts in population dynamics, and hence some species becoming more aggressive, while others may decline (Umkulzhum *et al.* 2024). While C_4 plants may benefit under eT, the broader effects of climate change on weed dynamics remain complex, with potential negative impacts on crop yields and ecosystem health. Species such as *Parthenium hysterophorus* (C_3/C_4) and *Eichhornia crassipes* have been identified as potential future threats due to their adaptability to changing climates. C_4 weeds may likely to expand into new regions, predominantly in mid-latitude dryland ecosystems, where their suitability under changing conditions will increase (Anderson *et al.* 2024).

The genetic diversity of weeds allows them to adapt more readily, enhancing their invasive potential, whereas, C_4 weeds are more tolerant to rising temperatures, enabling them to flourish as global temperatures increase. C_3 weeds, such as *Amaranthus retroflexus* and *Chenopodium album*, thrive under eCO_2, and are becoming more competitive against crops (Rakhmankulova *et al.* 2023). Higher CO_2 levels enhance C_4 photosynthesis, boosting biomass production and giving them a competitive advantage over C_3 crops (Umkulzhum *et al.* 2024). Increased temperature had a greater effect on plant survival than eCO_2 level. It is reported that under eT, eCO_2 level, glyphosate was more rapidly translocated out of the treated leaf to shoot meristems and roots and suggested that glyphosate may not be effective for weed control (Matzrafi *et al.* 2019).

Decreased efficacy of paraquat is reported to velvetleaf and large crabgrass at increased UV radiation due to lower absorption and efficacy (Wang *et al.* 2006). Efficacy of linuron was reported to be reduced by 15% in wild buckwheat (*Polygonum convolvulus*) (C_3) at eCO_2 levels (Archambault *et al.* 2001). In contrast, atrazine application in high air temperatures is reported to be more effective to control velvet leaf and common ragweed (Fluttert *et al.* 2022). However, high soil temperatures primarily affect the efficacy of soil-applied herbicides by decreasing permeability and increasing volatility and microbial breakdown. Impact of high soil temperature (25‘“C), is reported to increased volatilization of triallate from 14 to 60% and 7 to 41% in sandy and loamy soils, respectively (Atienza *et al.* 2001). Roots growth are reported to be stimulated and may reach deeper soil layers at eCO_2 levels henceforth prevents the uptake of soil-applied herbicides. Ziska *et al.* (2004) reported high root: shoot ratio of field-grown Canada thistle (*Circium arvense*) (C_3) under eCO_2 levels, which reduced the efficacy of glyphosate due to the dilution effect caused by large volume of roots. However, in few cases, high temperatures could enhance root uptake of herbicides due to a decrease in soil organic matter and high evaporation rates (Miraglia *et al.* 2009).

Impact of elevated temperature on herbicides bioefficacy against weeds

In the field, higher survival of musk thistle, with more production of capitula, and taller heights were reported under eT than at ambient temperatures (Zhang *et al.* 2011). The interaction effect of temperature and genotype on the translocation of ^{14}C-cyhalofop-butyl was not significant. It is also reported that under eT, *E. colona* will establish faster and compete with the rice crop more vigorously early in the season as *E. colona* is a C_4 plant (Giussani *et al.* 2001) and it responds more to high temperature than the rice, which is a C_3 crop. Keller and Shea (2021)

Table 2. C_3 and C_4 photosynthetic pathway of various crops (Still *et al.* 2003)

C_3	C_4
Alfalfa, Barley, Cotton, Groundnut, Oats, Pea, Rye, Rice, Sunflower, Sorghum, Soybean, Tobacco, Wheat Chilli, Carrot, Cucumber, Garlic, Lettuce, Onion, Potatoes, Spinach, Sugar Beets Tomato, Pumpkin,	Maize, Millets, Cassava (Some Varieties), Sugarcane, Sorghum, Sweet Potato (Some Varieties),

demonstrated that under eT, musk thistle (*Carduus nutans*) was survived through early flowering, grew to taller heights, and production of more flowering capitula compared to plants grown under ambient conditions, A changing climate may alter weed growth and spread directly through differential selective pressures on weed species and indirectly through changes in the abiotic and biotic aspects of the ecosystems or through mediated changes in human management. Direct selection pressures are responsible for how eCO_2 and higher temperatures differentially alter weed growth, leaf production, plant height, and seed production (Liu *et al.* 2017). In warmer regions, under increases in temperature, weeds are also likely to select for tolerance or avoidance of drought and heat (Franks *et al.* 2018).

Higher temperature stimulates stomatal conductance, reducing the viscosity of epicuticle waxes, thus increased the penetration and diffusion of herbicides which result in changes in the composition and the permeability of the cuticle (Rodenburg *et al.* 2011). However, mostly higher temperatures enhance herbicide metabolism, which consequently decreases herbicidal activity on targeted plants. Under higher relative humidity, cuticle hydration and stomatal conductance increases, therefore the permeability and translocation of hydrophilic herbicides increases into the leaves. Similarly, under higher irradiance, stomata stay open, photosynthetic rate increases consequently increasing absorption, penetration and subsequent phloem translocation of post-emergence systemic herbicides in weed tissue. Drought may cause an increase in cuticle thickness and leaf pubescence, which subsequently reduces herbicide absorption into the leaves. Rainfall after post-emergence herbicides application might affect their efficiency through dilution and washing out effects. Increased frequency and intensity of precipitation will further have a negative effect on absorption, translocation, and activity of preemergence herbicides.

Successful use of herbicides for weed management depends on environmental conditions that prevails before, during, and after the herbicide application. The herbicides persistence in different environmental conditions vary significantly, ranging from those that break down quickly into nontoxic by-products, to those that persist in the environment with toxic/nontoxic metabolites (Sondhia *et al.* 2023). Climate change impact related to increasing temperature will become more pronounced, as certain herbicides can be vulnerable to volatilization, which may cause them to loos efficacy (**Table 3**). Under such conditions excess and extensive herbicides use may be required for effective weed management, however this may further burden the environmental load as well as contribute in development of resistance in weeds to herbicides.

Apart from CO_2, and temperature, other environmental factors, such as light, soil moisture, relative humidity, rainfall and wind can also directly affect herbicide efficacy by altering the penetration and translocation of herbicides within the plant or indirectly by changing the growth and physiological characteristics of the plant. While foliar herbicides are influenced by many environmental factors, soil-applied herbicides are influenced mainly by soil moisture and temperature (Varanasi *et al.* 2015). However, in a reported case, the absorption of ^{14}C-cyhalofop-butyl into leaves of *Echinochloa* sps. seedlings was not declined under eCO_2 and absorption in herbicide-susceptible and multiple-resistant *E. colona* does not change under eCO_2 or eT (Rodenburg *et al.* 2011). Elevated CO_2 or eT increases the resistance level of *E. colona* to cyhalofop-butyl which is a ACCase-inhibitor (Refatti *et al.* 2019).

Impact of elevated CO_2 on weeds and herbicide bioefficacy

Carbon dioxide-induced changes in leaf morphology or variation in root: shoot ratio can affect herbicide uptake and distribution. Elevated CO_2 stimulated root over shoot growth of Canada thistle [*Cirsium arvense* (L.) Scop.], due to diluting effect on shoot-applied herbicide and failed to kill roots, which resulted in regeneration of the whole plant (Ziska *et al.* 2004). Similar increasing trend in root: shoot ratio have been observed for several other invasive weeds in response to eCO_2 (Ziska *et al.* 2019). Higher CO_2 concentration levels have been shown to be beneficial mostly to C_3 weed species such as Japanese honeysuckle (*Lonicera japonica* Thunb.) (Belote *et al.* 2003), cherry laurel (*Prunus laurocerasus* L.) (Hattenschwiler and Korner 2003), red brome (*Bromus rubens* L.) (Smith *et al.* 2000), mile-a-minute (*Mikania micrantha* Kunth.), Chinese wedelia (*Wedelia chinensis* L. Pruski.), and *Dalmatian toadflax* [*Linaria dalmatica* (L.) Mill.] (Blumenthal *et al.* 2013), however enhanced growth of beach morning glory [*Ipomoea pes-caprae* (L.) R. Br.] which is a C_4 weed is also reported (Song *et al.* 2009). The effects of climate change on herbicide efficacy may also depend on herbicide mode of action. Elevated CO_2 could alter pigment production, photosynthesis, and overall metabolic activity. In contrary, atrazine (photosystem II inhibitor) and amitrole (pigment inhibitor), become more effective where CO_2 or temperature stimulate plant growth. Contrariwise, there is general recognition that rising CO_2 and/or rising temperatures could reduce protein levels in a wide range of plant tissues (Loladze 2014) which result in less demand for aromatic and branched-chain amino acids that caused declines in glufosinate and glyphosate efficacy (Varanasi *et al.* 2015).

Perennial weeds may become more difficult to control in increasing CO_2 concentration and rising temperature, if increased photosynthesis stimulates greater production of rhizomes and other storage organs. Zeng *et al.* (2011) reported altered competition between rice and barnyard grass (C_4) in paddy fields in favour of rice under eCO_2 concentration due to enhanced biomass, tillers, leaf area index (LAI) and net assimilation rate (NAR), absolute uptake of C, N, P, K of rice, but reduced in barnyard grass after elongation. CO_2 differentially affects the extent of *E. colona* (C_4) injury between resistant and susceptible genotypes from cyhalofop-butyl treatment. Under eCO_2, cyhalofop-butyl did not completely kill the susceptible plants, however, the herbicide efficacy on resistant plants also declined significantly (Scott *et al.* 2018). At eT, the efficacy of cyhalofop-butyl on the susceptible genotype remained high, but the efficacy on the resistance genotype declined significantly to about 50% (Rodenburg *et al.* 2011). Enormous research reports showed reduction in stomatal conductance and transpiration, improved water-use efficiency, higher rates of photosynthesis, and increased light-use efficiency under eCO_2 in plants (Wang 2022).

Combined impact of elevated CO_2 and temperature on weed and herbicide bioefficacy

The ideal range for spraying most herbicide is reported from 20ºC to 30ºC due to favouring absorption and its fluidity in membranes and the optimum activity of the enzyme Rubisco (Ribulose 1,5 bisphosphate carboxylase oxygenase), which is responsible for carbon fixation in the plant. Advancement in the seasonal timing of stem elongation, flowering, and growth cessation is reported under eT (Keller and Shea, 2021). Research indicates that currently used herbicides may lose efficacy against C_3 and/or C_4 weed under eCO_2 and eT, and suggest necessary modifications in weed management strategies (Kumar *et al.* 2023, Sondhia *et al.* 2024). Mowing is widely recommended to reduce musk thistle seed production and plant height, which reduces dispersal distances of wind-dispersed seeds and plant height (Skarpaas and Shea 2007).

Matzrafi *et al.* (2019) reported decreased efficacy to ACCase inhibitors pinoxaden under eT. The levels of the inactive glucose-conjugated pinoxaden product (M5) were found significantly higher under high than low temperature and demonstrated an increased risk for the evolution of herbicide-resistant in weeds under eT. Reduced efficacy of herbicides at high temperature generally may be due to increased metabolism as a consequence of maximal physiological conditions (Godar *et al.* 2015). The activity of mesotrione on Palmer amaranth (C_4) declined when the temperature increased from 25 to 40°C. Reduction in activity of pinoxaden on *Brachypodium hybridum* (C_3) under high temperature is correlated with significantly higher levels of the glucose-conjugated metabolite in *B. hybridum* compared to low temperature along with faster metabolism of pinoxaden at eT.

Weeds with C_3 and C_4 photosynthetic pathways may exhibit distinct responses to higher CO_2 levels and temperatures, which can affect the dynamics of crop–weed competition. Elevated CO_2 and temperatures can reduce herbicide efficacy by influencing absorption and translocation within plants. In our study undertaken in open top carbon chambers (OTC) at Directorate of Weed research, Jabalpur; growth of the wheat was significantly reduced by interference of *P. minor* under eT, eCO_2 and eT+eCO_2 conditions. *P. minor* (C_3) interference significantly reduced the relative water content of wheat by 19.0% to 15.5% under eT and eT+eCO_2 compared to weed free ambient. *P. minor* interference significantly reduced the wheat yield (45.9%) under eT conditions compared to ambient. The rate of photosynthesis was significantly reduced under eT in comparison to weed free ambient in the presence of *P. minor* (**Figure 2**) (Sondhia *et al.* 2024).

Relative water content (RWC) and membrane stability index (MSI) of wheat was also reduced remarkably (15.7% and 3.25%, respectively) at eT and combination of eCO_2 and eT by *P. minor* interference compared to weed free ambient (**Figure 2**). However, eCO_2 had a positive impact on the rate of photosynthesis of *P. minor* which increased by 22.37% in comparison to ambient. Overall, eCO_2 had a positive impact on growth and biomass production of *P. minor* in comparison to ambient, eT and e CO_2+eT. These results predict that management of *P. minor* weed in wheat crop under eCO_2 and temperature will be a challenge in a futuristic climate change scenario (Sondhia *et al.* 2024). Weed competition and cyhalofop-butyl + penoxsulam bioefficacy (x, 1.5x and 2x doses) impact was evaluated under eCO_2 and eT and their combined effects among, *E. colona*, *Alternanthera paronychioides, Dinebra retroflexa* and *Cyperus iria* weeds with rice crop under FACE. Significant reduction in cyhalofop-butyl + penoxsulam efficacy and yield was found especially with *E. colona* (**Figure 3**) (Sondhia *et al.* 2024).

In addition to its positive impact on weed growth, climate change factors could influence the efficacy of many herbicides, making weed management a major challenge for sustainable crop production (Varanasi *et al.* 2015). Environmental factors such as CO_2, light, temperature, relative humidity, and soil moisture differentially affect the uptake, translocation, and activity of different herbicide chemistries. Differential response of same mode of action of herbicides is reported in literature. However, neither temperature nor CO_2 affect cyhalofop-butyl absorption into the leaf or efficacy

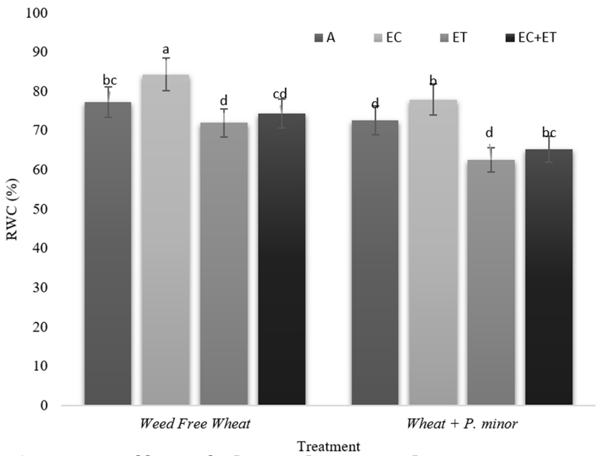

Figure 2. Effect of elevated CO_2 and temperature on relative water content of wheat and *Phalaris minor* in open top chambers

against *Echinochloa colona* genotypes (Refatti *et al.* 2019). In order to predict precise impact of climate change factors especially, eCO_2, eT and, their interactions on herbicides is necessary for implications for weed management in future climate scenarios.

The efficacy of the soil-applied herbicides (Alachlor, ethalfluralin, linuron, and metolachlor) in *A. patulus*, and foliar herbicides (Glufosinate-ammonium, bentazone, and mecoprop) was reported to be higher at 30 °C; in contrarily, glyphosate isopropylamine showed similar efficacy regardless of the temperature (Park *et al.* 2021). Reduced glyphosate sensitivity was observed in *Conyza canadensis* (C_3) and *Chenopodium album* under eT, eCO_2 level, and the combination of both factors. Photosynthetic capacity is also expected to increase further when CO_2 and temperature are not limiting. High atmospheric CO_2 or high temperature reduces sensitivity of weed species to various herbicides. A higher weed pressure will also enhance application frequencies and volumes. In addition, increased temperature and CO_2 can change the leaf surface characteristics by increasing leaf thickness, or changing the viscosity of the cuticle wax, with subsequent reductions in herbicide absorption (Ziska *et al.* 2019). Under eT and eCO_2 the ecological dynamics are also likely to be affected and that there is a close coupling between ecological and evolutionary dynamics (Ravenscroft *et al.* 2015).

Impact on herbicide persistence and dissipation

The efficacy of herbicides is greatly influenced by soil properties including moisture and climate change (Sondhia 2014, Robinson, 2019). Effective pre-emergence herbicides are mainly dependent on

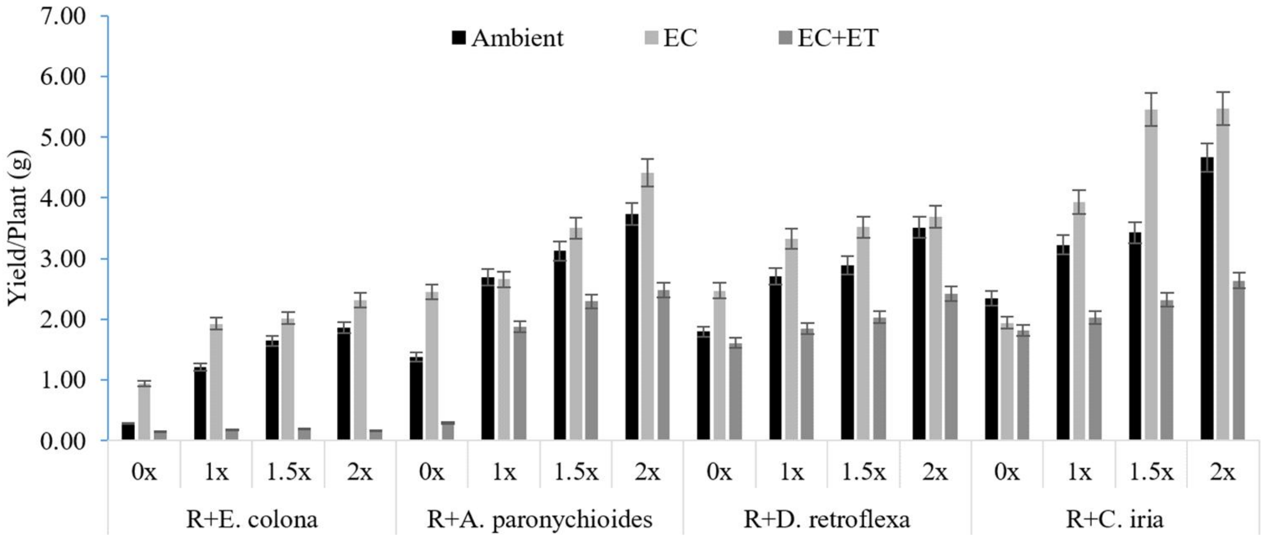

Figure 3. Effect of crop-weed interaction under elevated CO_2 and temperature on rice yield

soil moisture content for movement into the zone of weed seed germination. Sunlight tends to degrades mostly pre-emergence herbicides on the soil surface, and less moisture availability may result in poor weed management. Herbicides, after their application, undergo biochemical degradation (Sondhia 2013). Under dry conditions, microbial degradation slows and herbicide persistence in the soil is prolonged, however, in humid and warmer conditions, herbicide persistence will be shortened (Sondhia 2014, Sondhia and Waseem 2020).

Volatile herbicides are likely to dissipate quicker than less volatile herbicides (Sondhia 2023). Due to high vapour pressure of clopyralid, fluchloralin, pendimethalin, trifluralin, they will remain in the vapour and particulate form in the field atmosphere (**Table 3**). Temperature can affect herbicide performance directly through its effects on the rate of herbicide diffusion, viscosity of cuticle waxes, and physicochemical properties of spray solutions (Price 1983). The dissipation of 2,4-D, bromoxynil, and thifensulfuron-methyl increased with increasing temperature (Cessna *et al.* 2017). However, rise in temperature above 20 °C reduced the efficacy of carfentrazone against weeds (Sondhia *et al.* 2024). Dicamba and 2,4-D are prone to volatility, and can move long distances with slight breezes. A lower herbicide residue, due to quick dissipation in the soil and crops as a result of eCO_2, and eT will result in an increased vulnerability to weeds and in the future, necessitate more spray often during the crop growing season that will further enhance environmental contamination.

Table 3. Herbicide with higher volatilization property

Herbicide	Vapour pressure (mmHg)	Henry's law constant (Pa m^3/mol)
Alachlor	2.2 x 10^{-5}	3.20 x 10^{-3}
Anilofos	1.6 x10^{-5}	1.42 x10^{3}
Butachlor	2.9 x10^{-6}	3.74 x 10^{-3}
Clomazone	1.4 x10^{-4}	4.13 x 10^{-8}
Clopyralid	5.99 x10^{-4}	1.80 10^{-11}
Dicamba	1.25 x10^{-5}	1.0 x 10^{-4}
Fluchloralin	3 x10^{-5}	6.49 X 10^{-4}
Metamifop	1.13 x10^{-5}	0.065
Metolachlor	3.14 x10^{-5}	2.40 x 10^{-3}
Pendimethalin	3 x10^{-5}	2.73 x 10^{-3}
Pretilachlor	5 x10^{-6}	8.10 x 10^{-4}
Thiobencarb	2.2 x10^{-4}	3.68 x 10^{-2}
Trifluralin	1.99 x10^{-4}	10.2

Impact of greenhouse gas emissions on herbicide bioefficacy

CH_4 and N_2O are the major greenhouse gases and mostly responsible for global warming. Agriculture accounted for approximately 50% of the CH_4 and 60% of the N_2O global anthropogenic emissions in 2005 (IPCC 2014). Irrigated paddy fields assumed to be a major anthropogenic source of atmospheric CH_4 (IPCC 2014). Most soil-evolved N_2O is produced by nitrification and denitriûcation processes (Kool *et al.* 2010).

Impact of herbicides use to control weeds in croplands and their impact on greenhouse gas emissions were demonstrated by Jiang (2015). Decreaes in herbicides efficacy of acetochlor, fenoxaprop-p-ethyl + tribenuron-methyl under eCO_2, and significantly reduced N_2O emissions by 31% compared with no herbicide use in the wheat growing season due to low soil ammonium nitrogen and less abundance of denitrifying bacteria is reported. Bensulfuron-methyl and butachlor significantly reduced CH_4 emissions by 27% and 58% in rice growing season due to high soil nitrate nitrogen and urease activity.

Similarly, application of prosulfuron was found to decrease N_2O emissions over short period of time (Kinney *et al.* 2005). In contrary, butachlor inhibited CH_4 emissions by 20% in a direct-seeded flooded rice field and prosulfuron is reported to stimulate N_2O emissions and CH_4 consumption in a fertilized Colorado grassland soil by as much as 1600% and 1300%, respectively. Das and Debnath (2006) also demonstrated increased N_2O and CH_4 emissions due to combined application of the bensulfuron-methyl and pretilachlor. Methane oxidation in soil is an important ecological process. Methane gas, which is removed from the environment *via* reactions with the hydroxyl radicals in the troposphere 2, 3, and also biologically through oxidation by methanotrophic and to a lesser extent by ammonia oxidising bacteria in surface soils. 2,4-D has been shown to inhibit methane oxidation, an important ecological process in soil.

Impact on altered herbicide metabolism and resistance in weeds

In agronomic systems, herbicides represent strong selective pressures, and hence the evolutionary potential of weeds is rapid and resulted in widespread herbicide resistance (Ravet *et al.* 2018). Presently, 532 unique cases of herbicide-resistant weed globally and with 273 species (156 dicots and 117 monocots) (Heap 2019, Croplife 2024,). Climate changes may necessitate changes in adaptation of modified agronomic practices. Weeds have evolved resistance to 21 of the 31 known herbicide sites of action and to 168 different herbicides (weedscience.org/Home.aspx).

It is also concerning that cases of resistance, or multiple resistance to herbicides are increasing among key rice weeds, in comparison to other crops (Roma-Burgos *et al.* 2019). Based on literature it is expected that initially, increased temperatures could increase herbicide efficacy by accelerating absorption and translocation of foliar herbicides; along with induced rapid metabolism, which reduces herbicide efficacy in target plants (Johnson and Young 2002). Non-target-site-based resistance mechanisms in weeds cause reduced absorptionm translocation, enhances herbicide metabolism, and overproduction of herbicide target (Délye 2013) and greatly influenced by changes in climate (Roma-Burgos *et al.* 2019). Recently increasing cases of non-target-site-based resistance to acetyl-CoA carboxylase (ACCase) inhibitors is reported (Heap 2019) through detoxification and increased production of monooxygenases (cytochrome P450s), that facilitate phase I detoxification reactions and increased activity of glutathione-S-transferase (GST) enzymes, which in turn facilitate phase II detoxification (Délye 2013).

Through rapid metabolism, diclofop-methyl, pinoxaden, tralkoxydim are inactivated in plants through hydroxylation, by cytochrome P450s in phase I detoxification reactions (Wenger *et al.* 2012) and further conjugation by GTs or GSTs in phase II reactions (Brazier *et al.* 2002). Resistance to ACCase inhibitors in large crabgrass (*Digitaria sanguinalis* L.) (C_4) is reported due to overexpression of ACCase (Laforest *et al.* 2017). Few other studies have shown reduced herbicide efficacy under eCO_2 for C_3 and C_4 weedy species (Manea *et al.* 2011). Reduced efficacy of glyphosate under eCO_2 against *Eragrostis curvula* (Schrad.) Nees(C_4) and *Paspalum dilatatum* Poir (C_4) is reported (Manea *et al.* 2011). Therefore, to mitigate rapid resistance evolution in weed, management practitioners must implement measures to reduce the herbicide selection pressure.

Reported experimental evidence demonstrated increasing gene flow between herbicide-resistant crops and weedy relatives under climate change. In a long-term USDA study comparing between cultivated and weedy rice at three different CO_2 concentrations (300, 400 and 600 ppm) showed greater synchronicity in flowering times and enhanced outcrossing rates between a cultivated rice mutant that is resistant to imidazolinone, ClearfieldTM 161 and a weedy red rice accession (StgS). Consequently, as CO_2 increased, the number of weedy herbicide-resistant hybrid offspring also increased (Ziska *et al.* 2019). Climate change may also alter the efficacy of weed biological control through changes in plant nutrient content, which often declines with eCO_2 alongwith increases in insect activity with temperature; and shifts in phenology of both agents and host weeds (Reeves 2017). However, adaptive responses to such changes are difficult to predict, because biological control agents and host weeds, both will have the potential to adapt to new selective pressures (Holt and Hochberg 1997).

Ziska *et al.* (2010) demonstrated that increasing CO_2 resulted in significant increases in initial leaf area and root weight of the red rice, as early as 27 d after sowing (DAS) at 500 ìmol/mol and showed a greater physiological plasticity and genetic diversity among red rice relative to cultivated rice. Significant interactive effects of CO_2 and water availability have also been reported which altered the competitiveness between C_3 and C_4 species due to decrease in specific leaf area and stomatal conductance under eCO_2 (Elizabeth *et al.* 2004). Wing *et al.* (2021) reported C_3 (*Abutilon theophrasti*) species may not have been at a disadvantage comparison to *Amaranthus retroflexus* (C_4), species in response to low CO_2 and severe drought. Furthermore, C_4 species may have an advantage over C_3 species in response to eCO_2 and severe droughts.

Weed management strategies under climate change

Climate change is expected to result in varying growth rates for crops and weeds, which may have significant impacts on weed management and crop production. However, impact of climate change on crop-weed interactions are likely to based on various region and cropping systems. To address these challenges, effective mitigation strategies to reduce eCO_2, eT and other greenhouse gases are crucial at global level. Shifts in temperature and CO_2 levels are anticipated to exert direct effects on weeds. These changes may alter the crop-weed diversity and interacting and may promote weed infestation. Therefore, a comprehensive understanding of how climate change particularly eCO_2, higher temperatures, along with other climate variable affects crop-weed dynamics is crucial for evaluating the vulnerability in crop production (Valerio *et al.* 2013). Consequently, information about changes in weed shifts, weed mortality, fecundity, and phenology can be used to make effective weed management strategies in various crops in context to climate change.

Reducing climate change variables by Robust policies and actions aimed should be adopted to address root causes of climate change. Carbon dioxide, high temperatures, and other climate variables all impact herbicide efficacy, but herbicide chemistries respond differently to these variables.

The target weed specie also matters; certain weeds become less susceptible to some herbicides and others more susceptible. When utilizing herbicides in a hot/dry or cool/wet seasons, effective weed management practices become increasingly important. Hence, best management practices include identification of correct weed species, differential response of C_3/C_4 weeds and understanding use of optimized doses of herbicides at certain interval according to weather conditions, along with use of suitable adjuvant/surfactant and the right nozzle. However, such frequent applications will have negative impacts on environment and also enhance chances of a development of herbicide resistance in weeds at a faster rate, creating further challenges for weed management.

Therefore, understanding the effects of climate change on weed growth and herbicide activity is important to optimize herbicide applications for weed management in increasing carbon dioxide and temperature. The Intergovernmental Panel on Climate Change (Porter *et al.* 2014) emphasized use of physical, cultural, or biological weed control under Climate Change. Mechanical weed control techniques, such as hand-pulling, hoeing, tilling, and mowing, are widely used methods for limiting the spread and growth of weeds (Ross and Lembi 2009), but their effectiveness under climate change is undefined (Birthisel *et al.* 2021). Weed management by Drones or Robotic coupled with by improved plant-weed recognition software and sophisticated global positioning system which are currently not the popular weed management practice will be further researched as a potential means to control weeds under climate change scenario (Raja *et al.* 2020).

Additionally, herbicide effectiveness against weeds may be affected by changes in CO_2, rainfall patterns and temperature which alter herbicide selectivity, efficacy and could lead to a mixed population of C_3 and C_4 weed species and further complicating weed management strategies. Use of non or less volatile formulation of herbicides may also be encouraged to avoid dissipation and rapid metabolism due to eCO_2 and temperature. Use of adjuvant, low volatile herbicides and their mixtures, slow release herbicide formulation may also be studied to be used for effective weed management under eCO_2 and temperature.

Reduction of the soil seedbank with use of herbicide mixture with multiple herbicide modes of action will be beneficial and this will also limit in rapid herbicides resistance evolution in weeds. Supplementing herbicides with mechanical weed control where possible, crop rotation with weed-competitive crops, use of weed-competitive cultivars, use of weed-suppressive cover crops, and other recommended practices for integrated weed management will further contribute in effective weed management under climate change. Elevated temperature and eCO_2 levels also responsible in affecting phenology and life cycle of many plants species (Brownsey *et al.* 2017), hence weed management practices especially timing of application of herbicide should be optimized for better weed management (Hatfield *et al.* 2011, Sondhia 2024).

Use of non-genetically modified or non GM crop specific for a specific herbicide can be used for effective weed management under climate situation, however, this may enhance herbicide persistence. Raising herbicide resistant crops can also significantly change weed community composition. Projected climate change scenario particularly eCO_2 and eT is of major concern and will require extensive research to understand impact of frequent use of herbicides for weed control and environmental sustainability. Comprehensive extensive research efforts that include ecological, physiological, and molecular analyses are needed to study the interactive effects of different climate variables on plant growth and herbicide performance. Adaptive management has the potential to help to tackle these changes in the systems (Williams & Brown, 2012). Integrating physical, chemical and biological control management practices under e CO_2 and temperature should be encouraged and adopted. There is also a strong need for research on development of integrated and more sustainable weed management practices in current and future climates for minimizing risk of weeds and to safeguarding the environment. Use of advanced technologies for real-time weed detection and precision herbicide application can increase management efficiency while minimizing environmental impacts (Rao and Korres 2023). Adoption of climate resilient and or stress-tolerant crop varieties, use of micro-irrigation, crop diversification, raised-bed planting, nutrient-smart practices, crop residue management may also contribute in margining weeds in climate change scenario.

Conclusions

Future weed management and agricultural production are likely to threatened by continuous rising CO_2 levels and resulting changes in global precipitation, temperature, relative humidity, and radiation. The competition among weed species and crops is influenced by changes in atmospheric CO_2, temperature, precipitation, and other changing growth factors. In addition, interactions among these environmental traits can have unanticipated consequences in weed growth and evolution. Most weed spread through seeds however, many weeds reproduce by vegetative propagation. Even some weeds produce allelopathic compounds that enable them to coexist and compete with crops. Due to predicted reduced efficacy of currently used herbicides; crop growth and productivity will be severely affected. Therefore, a broader understanding of the potential interactions between crops and weeds in context of climate change, particularly elevated CO_2, and high temperature, is essential to achieve higher crop production. The rapid increase and spread of herbicide resistance is another mega challenge under changing climate. Demographic behaviours, including germination, seed biology, life span, and fecundity will be influenced by increasing atmospheric CO_2 and temperature and will affect selection and adaptation processes. To tackle these challenges a more efficacious approach on basic research in weed biology to understand weed evolution, crop-weed interaction, effectiveness of herbicides, along with other weed management practices is required for deriving refined weed management strategies for ensuring higher crop productivity in future. A number of mitigation and adaptation strategies can be adopted to reduce the adverse impact of climate change on agricultural sustainability.

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REVIEW ARTICLE

Weed management in conservation agriculture systems under changing climate scenario

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ABSTRACT

Conservation agriculture (CA) improves crop-water and energy productivity, profitability, environmental quality, and preserves natural resources for future food security and poverty reduction. However, weeds are a major challenge for large-scale CA adoption. Changes in tillage and planting systems in CA shift weed populations, favouring small-seeded and perennial grasses. Weeds like *Trianthema portulacastrum* and *Cyperus rotundus* in direct-seeded rice, and *Rumex dentatus*, *Medicago denticulata*, and *Avena ludoviciana* in wheat, become more common, though *Phalaris minor* declines. Weed management, especially early in CA adoption, heavily relies on herbicides like paraquat, glufosinate ammonium, and glyphosate. However, crop residues can reduce herbicide efficacy, and overuse can lead to herbicide resistance. These problems are further exaggerated under the changing climatic scenario which requires deeper knowledge and understanding. Since C_4 weeds are more competitive, therefore, would be dominant under elevated temperatures and pose yield penalties. Under changing climatic scenarios such as increased temperature, delayed or late onset of rainfall, prolonged drought and elevated CO_2 levels are major concerns for weed management and crop production. Therefore, sustainable CA requires integrated weed management using both chemical and non-chemical approaches.

Keywords: Conservation agriculture, Crop diversification, Crop residue retention, Tillage, Weed management

INTRODUCTION

India's rapidly growing population is expected to reach 1.5 billion by 2030, making it the most populous country. To feed this population, 345 million tons of food grains will be required (Mishra *et al.* 2021). Meeting this demand will be challenging due to limited resources, current agricultural practices, and growing threats like climate change, water scarcity, and shrinking farm sizes. Abiotic and biotic stresses also limit production, with weeds being the top biotic stressor, causing up to 37% yield loss—greater than losses from pests (29%), diseases (22%), and others (12%) (Mishra and Choudhary 2022). Weed severity is influenced by management practices like tillage, crop rotation, row spacing, fertilization, herbicide use, and soil and environmental conditions. Conventional agriculture, heavily reliant on intensive tillage, faces land degradation and climate variability challenges. While tillage offers short-term benefits like improved soil tilth, aeration, and weed control, it is unsustainable in the long term, leading to soil degradation, erosion, reduced water infiltration, and higher production costs. Intense tillage accelerates organic matter breakdown, particularly in warmer climates, degrading soil health over time. Rising atmospheric levels of carbon dioxide (CO_2) and increasing temperatures are anticipated to have both direct and indirect effects on agricultural production, sustainability, water availability, and ultimately, food security (Chauhan *et al.* 2014). The greenhouse gases (GHG; CO_2 and methane) are at an unprecedented high, posing significant ecological challenges in the present context. Climate change with intensive cropping systems would reduce crop yields and soil organic carbon under future climate (Zhang *et al.* 2022). Globally, to meet the food demand, intensive farming (excessive irrigation, fertilization and tillage) has been widely adopted to enhance crop productivity. These practices reduce the soil organic carbon (SOC) and degrade soil quality and also change the weed flora (Waqas *et al.* 2020, Choudhary 2024). Crop straw burning is another problem associated, this releases large amounts of CO_2 and minimizes the potential for sustainable crop production (Zhang *et al.* 2021). Elevated levels of GHG will certainly influence the geographic range expansions, alterations in species life cycle and weed shift dynamics. Similarly, this change will alter the structure and composition of weed communities.

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Peters *et al.* (2014) categorized shifts in weedy vegetation into three primary types: range shifts, niche shifts, and trait shifts, which manifest across different scales, including landscape, community, and population levels. Climate change is expected to influence weed biology, ecology, and competitive dynamics, leading to complex interactions between crops and weeds that will require the implementation of alternative adaptive strategies. There is widespread agreement that climate change is likely to result in divergent growth patterns between crops and weeds, particularly because many prevalent weeds utilize the C_4 photosynthetic pathway, enhancing their competitive advantage. Nevertheless, the situation is nuanced, shaped by the diverse adaptive mechanisms exhibited by weedy species (Ramesh *et al.* 2017). There is a need for technologies that can conserve resources and also mitigate the impact of climate change. Under the circumstances, conservation agriculture (CA) is a potential option. CA can buffer the negative effects of climate change and secure crop yields in some regions (Zhang *et al.* 2022). In CA no-tillage and straw retention are effective measures to mitigate the impact of climate change, they reduce GHG emissions, sequestrate carbon, conserve biodiversity and provide ecosystem services (Pathak *et al.* 2021), it also optimizes soil properties, minimize runoff, restrict soil erosion and provides a sustainable growing environment for crops (Wang *et al.* 2020). Similarly, using herbicides has reduced the need for tillage, paving the way for no-tillage or CA systems (Chhokar *et al.* 2021). The comparison between conventional and conservation agriculture has been given in **Table 1**.

Conservation agriculture focuses on reducing soil disturbance and conserving soil moisture to enhance crop production. It is based on three core principles: (1) minimal soil disturbance, (2) permanent soil cover with previous crop residues, and (3) diversified crop rotations. CA has been recognized globally as a sustainable farming practice that can increase yields. Despite its benefits, weed control remains a significant challenge for CA adopters (**Table 2**). CA alters tillage, crop establishment methods, and management practices, which in turn affect the microclimate, leading to changes in weed flora. These changes influence weed emergence patterns, seed bank composition, distribution, dispersal mechanisms, and competition dynamics, making weed management more complex compared to conventional systems (Mishra *et al.* 2022, Choudhary 2023). Weeds can cause significant

Table 2. Tangible and non-tangible benefit of conservation agriculture at scale

Parameters	Impact at scale
Tangible	
Tillage	Saving of 3 tillage /season; total pass of tractor (60-75%)
Fuel consumption	Saved 60-75%
Water use	Saved 25-30%
Electricity consumption	Saved 25-30%
Soil erosion	>90% saving
Labour requirement	Reduction of 25-30%
Production cost	Saving of Rs. 8000/season, Rs. 24000/per year
Weed severity	20-35% less
Seed rate	Saving of 10-15%
Nutrient saving	Continuous retention of crop residues may lead to savings of 20% N fertilizer
Yield	Improved 10-12%
Net returns	Higher by Rs. 32000-45000/ha
Energy productivity	Improved 10-15%
Saving of time	10-12 days each season, 20-22 d in a year
Carbon stock	Saving of 2-4.5 Mg C/ha
Earthworm population	Significantly increased
Quality of harvested produce	Improved
Non-tangible	
Soil compaction	Decreased
Infiltration rate	Improved
Crop residue burning	Completely stopped
Environment	Positive (Air quality index improvement)
Water quality	Improved
Groundwater recharge	Improved
Non-point pollution	Drastically reduced
Eutrophication	Reduced

Table 1. A comparison of some issues between conventional tillage and conservation agriculture

Issues	Conventional agriculture (CT)	Conservation agriculture (CA)
Soil disturbance	High	Low
Soil surface	Bare surface	Permanent cover
Erosion	High soil and wind erosion	Low soil and wind erosion
Water infiltration	Low	High
Diesel use and costs	High	Low
Production costs	High	Low
Timeliness	Delayed operation	Timeliness of operation more optimal
Yield	Lower (where delayed planting)	Same or higher (if planted on time)
Weeds	Less perennial weeds but trigger germination	Early-stage weed problem, but decreased with time

yield losses, ranging from 25-79%, depending on weed aggressiveness (Mtambanengwe *et al.* 2015, Nandan *et al.* 2020, Chhokar *et al.* 2021). Since there is an inverse relationship between weed pressure and crop yield, effective weed management in CA is crucial to achieving optimal yields. Therefore, effective weed management in CA is important to obtain good crop yields.

Effect of conservation agriculture principles on weeds

Effect of zero tillage (ZT) on weed seed bank: In conventional tillage, weed seeds are buried deep in the soil, with many found up to 50 cm below the surface. These buried seeds often have lower germination rates due to limited access to light, moisture, and nutrients, and may remain dormant for years (Santín-Montanyá *et al.* 2016). However, once these seeds reach the surface, they can compete with crops. In ZT, most weed seeds remain on the soil surface due to the absence of tillage (Choudhary 2023). Seeds closer to the surface may germinate sooner in favourable conditions but are also more vulnerable to weather and predation, leading to higher mortality rates (Choudhary 2016). Herbicides can effectively control these surface-level weeds, reducing crop-weed competition (Nichols *et al.* 2015). Tillage also influences the timing and synchronization of weed seed emergence. Depending on factors like soil moisture and temperature, some tillage practices can either accelerate or delay weed emergence. Repeated tillage can deplete the seed bank by promoting germination and exhausting viable seeds over time, whereas in ZT systems, the seed bank is typically three times smaller. However, perennial weeds are more common in ZT systems (Feledyn-Szewczyk *et al.* 2020). Improper tillage can also bring buried seeds back to the surface, replenishing the seed bank. Studies show that 67.1-164.8% more weed seeds germinate from the soil surface than from deeper layers, though this varies by weed species. Conventional tillage (CT) tends to distribute weed seeds more evenly throughout the soil profile. The adoption of specific cultural practices can exert selection pressure on certain weed species, potentially altering the composition of the soil seed bank over time (Mashavakure *et al.* 2020, Winkler *et al.* 2022).

Predation of weed seeds (natural enemies) and desiccation: In ZT systems, the absence of tillage and the retention of crop residues create a favourable environment for beneficial insects like field crickets and black ants. These insects feed on weed seeds that remain on the soil surface, gradually reducing the weed seed bank, unlike in CT (Carbonne *et al.* 2023). They particularly prefer older seeds from species such as *Echinochloa* spp., *Chenopodium album*, and *Amaranthus viridis*. Additionally, in ZT, weed seeds left on the soil surface are more exposed to desiccation due to weather extremes, which can alter their viability and reduce their emergence by affecting moisture, light exposure, and microbial activity (Singh *et al.* 2015, Travlos *et al.* 2020). This helps to reduce crop-weed competition.

Limited weed seed wash-off: In ZT systems, with higher soil organic matter and crop residues, promote better infiltration and percolation, minimizing runoff. This limits the wash-off of weed seeds from the field, helping to prevent weed seed dispersal and reducing the spread of weeds to nearby fields. Consequently, the weed seed bank may be enriched in ZT, but the spread of weeds is restricted.

Effect of tillage on weeds

Switching from intensive tillage to reduced or ZT significantly alters weed population dynamics (Chhokar *et al.* 2021). Reduced tillage favours the establishment of perennial weeds due to undisturbed root systems, and small-seeded annual weeds become more problematic as they remain on the soil surface (Choudhary *et al.* 2016). While ZT combined with crop rotation generally suppresses weeds more effectively than CT, the retention of crop residues can encourage weed establishment. For instance, *Convolvulus arvensis* populations in reduced-tilled fields increased by 11.2-39.1% in soybean, 0.9-4.2% in wheat, and 11.9-24.4% in maize, with 77% of seeds concentrated at a 0-10 cm depth (Rusu *et al.* 2015). Despite these changes in weed populations, yields remained similar across tillage systems. Sepat *et al.* (2017) observed the highest weed density and biomass in soybean under ZT with a flatbed, though over time, CT with a flatbed showed higher weed severity. In continuous ZT, wild oats (*Avena ludoviciana*) and *Chenopodium album* populations decreased, though the seed bank was concentrated at a 0-20 cm depth in the rice-wheat system (Mishra and Singh 2012). Rotational tillage resulted in lower weed density compared to continuous ZT. While ZT systems saw increased densities of *Rumex dentatus*, they had fewer *Phalaris minor* (Chhokar *et al.* 2007, Shyam *et al.* 2014).

ZT tends to increase the density and biomass of both annual and perennial weeds due to the presence of weed propagules from the previous season, allowing them to establish earlier in favourable conditions, making control more difficult later (Choudhary and Kumar 2019). Minimum tillage (MT) recorded higher densities of dicot weeds compared to CT, though overall weed densities (both monocot and dicot) were lower in MT than CT (Choudhary and Kumar 2014). On the other hand, CT displaces most weed seeds and propagules, leading to lower weed density and biomass. Rotational tillage has been shown to significantly reduce the density of weeds like *Cyperus iria*, *Avena ludoviciana*, *Medicago hispida*, *Solanum sarrachoides*, and *Amaranthus powellii* compared to continuous MT and ZT (Peachey *et al.* 2006). An absence of weed control grasses and sedges tended to dominate in ZT-DSR and broadleaves in puddled TPR. However, herbicide and manual weeding significantly dominance of sedges over broadleaves and grasses in ZT-DSR, underscoring the need for specialized weed control methods in these systems (Hossain *et al.* 2020).

Effect of tillage on productivity: Crop yields are generally higher under CT compared to conservation tillage (MT and ZT), largely due to more effective weed control. However, despite the lower production costs associated with MT and ZT, the economic yield may not always offset these savings due to severe weed pressure. For instance, Panasiewicz *et al.* (2020) observed a 75% decrease in cereal yields, which significantly reduced the adoption of MT and ZT. In contrast, Chaghazardi *et al.* (2016) found that wheat and chickpea performed better under MT and ZT, suggesting that these practices can be efficient for achieving higher yields while conserving soil and water. Chhokar *et al.* (2014) noted that rice yields are consistently higher in transplanted conditions compared to direct-seeded rice (DSR), primarily due to water stagnation, the early head start of seedlings, delayed weed emergence, and more effective weed control. Yield losses due to weeds in DSR can reach up to 97%, while losses in transplanted rice are typically capped at 33%.

Effect of crop residue on weeds

Retention of crop residues on the soil surface reduces light penetration, preventing the germination of photoblastic weed seeds, and lowering weed pressure by 15-20% (Sahu *et al.* 2022). A thick, uniform layer of crop residue effectively suppresses weed germination, delays weed emergence, and promotes crop vigour. Weed management can be further enhanced by optimizing the amount of crop residue applied to the soil surface (Chauhan *et al.* 2012). Crop residues release allelochemicals and block light transmission to the soil, aiding in weed suppression. However, in some cases, crop residues can stimulate weed germination, complicating weed management in ZT systems. Prolonged retention of crop residues increases soil organic matter, maintaining optimal moisture and moderate soil temperatures, which may favour certain weed species. For instance, Chauhan and Abugho (2012) observed that weeds like *Echinochloa crus-galli* and *Cyperus iria* could escape control under ZT and MT when crop residues were present. However, applying 6 t/ha of crop residues significantly reduced the populations of *Chenopodium album* by 83%, *Rumex dentatus* by 88%, and *Phalaris minor* by 45% compared to bare soil (Kumar *et al.* 2013, Sharma and Singh 2014). While herbicides are effective at controlling weeds, their efficacy is reduced when residues are loose rather than anchored.

Effect of crop residues on seed bank: The presence of crop residues alters the weed seed bank. Plots with retained crop residues showed a reduction in weed seed density by 22% in the rainy season, 29.8% in winter, and 30.3% in summer at a soil depth of 0-15 cm compared to bare land. Retaining 50% of crop residue in potato fields significantly reduced the weed seed bank, with further reductions observed as the residue layer thickened (Jalali 2013). The thickness and uniform application of crop residues regulates soil temperature, delaying the germination and emergence of small-seeded annual weeds while creating favourable conditions for crops (Chauhan *et al.* 2012, Choudhary and Kumar 2019). As mulch, crop residues can suppress weed biomass by 20-40.5% compared to bare soil, reducing herbicide usage and leading to a 70% suppression of weed density in CA (Mtambanengwe *et al.* 2015).

As crop residues decompose, they release nutrients that enhance crop growth over weeds, further reducing weed competition (Choudhary and Bhagawati 2019). Over time, crop residue retention improves soil organic matter (SOM), promoting the build-up of soil microbes and flora in CA systems, as supported by higher SOM levels (Oliveira *et al.* 2024). In ZT, crop residue retention reduces evaporative water loss, conserving 10-15% more water and potentially saving 1-2 irrigations. However, crop residues can interfere with pre-emergence herbicides, reducing their effectiveness (Chauhan *et al.* 2012, Singh *et al.* 2022). In ZT, the lack of weed seed burial and poor incorporation of soil-applied herbicides further diminish their efficacy, leaving most weed seeds on the soil surface. This requires special attention to control established, particularly perennial, weeds. Certain crop residues, such as wheat straw, release chemicals like hydroxamic acid, which inhibit the germination of other weed species on the surface. Additionally, other residues can block light penetration, reducing weed germination by 15-45% (Scavo and Mauromicale 2021).

Effect of crop diversification on weed dynamics

Crop rotation disrupts weed life cycles by creating unfavourable conditions for weeds adapted to specific crops. Different crops have unique growth habits, rooting depths, and canopy structures that help suppress weed growth (Derksen *et al.* 2002). Some crops release allelopathic chemicals that inhibit weeds, while cover crops act as living mulch, suppressing weeds during fallow periods. Vigorous crops with dense canopies can also outcompete weeds for light, water, and nutrients. Crop diversification reduces weed resistance to herbicides and improves soil health, promoting stronger crop growth, which further aids weed control. In contrast, monoculture with uniform management practices allows specific weed species to dominate, potentially becoming tolerant or resistant to frequently used herbicides (Khamare *et al.* 2022, Nath *et al.* 2024). These issues can be addressed by adjusting the sowing window, seed rates, row spacing, and herbicide application methods to minimize weed pressure. Crop diversification, including cereals, pulses, and oilseeds, can reduce herbicide usage, while cover crops and perennial forages provide additional benefits for weed management (Choudhary *et al.* 2016).

Effect of cropping systems on seed bank and weed severity

Weed seed banks and dynamics are influenced by crop rotation and management practices. The seed bank variation is greater in the upper soil layers and reflects the effectiveness of weed management. Poor management leads to an increase in the seed bank, complicating future control efforts. Effective input management reduces weed densities; for example, medium-input systems had 15 species and 145 plants/m², while high-input systems had 11 species and 66 plants/m² (Koocheki *et al.* 2009). Proper herbicide use at the right dose and time can deplete weed seed banks by preventing reproduction (Norris *et al.* 2001).

Effect of crop rotation on weeds

Including competitive crops in the system and modifying weed management strategies can inhibit weed seed germination and growth. Allelochemicals released from roots further suppress weed germination. Using a mix of annuals, perennials, and diverse herbicides is effective for weed control (Nichols *et al.* 2015). While cover crops may not have a major impact, delaying termination and using competitive species can reduce weed density by over 75% in CA systems (Alonso-Ayuso *et al.* 2018; Sahu *et al.* 2022). Rotating diverse crops also modifies herbicide use and traffic patterns, effectively controlling weed composition (Izquierdo *et al.* 2020).

Effect of cropping systems on productivity

The cereal-cereal cropping system is vital for food security in South Asia, but declining productivity threatens its sustainability (Kumar *et al.* 2021). To meet growing population demands, urgent efforts are needed to enhance productivity. Diversifying and intensifying cropping systems by incorporating green manuring, legumes, pulses, and oilseeds, especially in summer, is essential. Crop diversification alters weed emergence patterns, sustains or boosts yields, improves soil health, preserves natural resources, and optimizes resource use (Jat *et al.* 2012, Ghathala *et al.* 2014).

Weed management in CA under climate change

Preventive methods

This method includes practices to prevent weed entry into fields, such as using clean equipment, fully decomposed manure, weed-free seeds, cleaning irrigation canals, restricting livestock movement from infested areas, maintaining clean right-of-ways, cutting reproductive weed parts before seed dispersal, and enforcing strict weed quarantine laws to block invasive species. These measures aim to keep weeds out of crops.

Cultural methods

Sustainable weed management focuses on reducing weed establishment and competition, not just control. Practices like tillage, mulching, intercropping, and crop rotation, though challenging, are essential in CA. Using crop residues as mulch in CA limits weed germination, but the non-inversion of soil and micro-climate changes can encourage weed emergence, requiring sustainable strategies to manage weed establishment and competition (Sims *et al.* 2018).

Tillage: Tillage practices have varied effects on weed emergence and establishment. The CT disrupts perennial weeds but promotes annual weed germination. In contrast, ZT reduces *Phalaris minor* infestation but encourages *Avena ludoviciana* and perennial weed establishment. The differences in weed populations between ZT and CT largely depend on the weed seed bank and previous cropping systems (Mishra and Singh 2012). Continuous ZT with effective weed management is more profitable and energy-efficient, especially in soybean-wheat systems (Mishra and Singh 2009).

Stale seed bed: Eliminating established weeds significantly reduces future weed problems. In ZT systems with stale seedbeds, weed control in CA is effective. Under irrigated conditions, watering the field 10–15 days before planting encourages weed germination, allowing them to be killed using non-selective herbicides like glufosinate ammonium or paraquat. This practice reduces the weed seed bank and minimizes future weed issues by up to 80%, giving crops a competitive advantage (Pittelkow *et al.* 2012).

Competitive crop cultivars: The inclusion of fast-germinating, early-vigour crop cultivars helps cover the ground quickly, limiting empty spaces where weeds can grow. This reduces crop-weed competition for resources like moisture, light, CO_2, space, and nutrients. Compared to traditional varieties, competitive crop varieties typically reduce weed pressure by 25-30%.

Crop residues: Use of previous crop residues, either loose residues (as mulch) or anchored residues covers the soil and provides effective weed management. These residues delay the germination and emergence of the weeds by the time the crop becomes competitive. However, thickness and material type are also important. Uniform application with optimum thickness decreases weed growth and favours crop. While, a thin layer or sparsely distributed crop residue may stimulate the emergence of certain weeds, like wild oats (Chauhan and Abugho 2012, Choudhary and Bhagawati 2019). Under CA, delayed emergence of weeds less impacted the crop yield and only a few weeds could reach the reproductive stage and contribute to the weed seed bank. It also restricts the evaporative loss and conserves 10-15% in soil moisture. However, this is not the only solution to control weeds, additional herbicide use may be necessary for season-long weed management.

Intercropping: The inclusion of short-duration, fast-growing legumes with long-duration, wide-spaced crops effectively suppresses weeds. Intercropping provides early ground cover and competes with emerging weeds by reducing light availability, similar to the effect of cover crops. Selecting suitable intercrops like cowpea, blackgram, greengram, or soybean is crucial to balance light, water, and nutrient needs, ensuring optimal resource use without reducing main crop yields (Choudhary *et al.* 2016). Although intercropping increases labour requirements for weeding, as seen in maize-cowpea systems, it remains a valuable technique for weed suppression in diverse cropping systems (Lai *et al.* 2012).

Cover crops: In CA, growing and incorporating short-duration legumes like mungbean, cowpea, blackgram, sesbania, and sunhemp during fallow periods can significantly reduce weed pressure (Kumar *et al.* 2012). These legumes encourage weed emergence during their growth, creating a stale seedbed effect that reduces weed populations for future seasons (Anderson 2005). In India, Sesbania cover crops, producing up to 30 t/ha in 60 days, have effectively controlled most weeds (Mahapatra *et al.* 2004).

Crop diversification: Planting crops in rotation on the same land disrupts weed species that thrive in monoculture systems, restricting weed buildup. Varying management practices can break weed growth cycles and prevent the dominance of a single species. Crop rotation introduces diverse competition for resources, soil disturbance, mechanical damage, and allelopathic effects, creating an unstable environment for weeds (Chhokar and Malik 2002). In rice-wheat systems, rotating non-rice crops significantly reduces *Phalaris minor* infestations in wheat. Including crops like Egyptian clover, potato, sunflower, or annual rape for 2-3 years also helps reduce *Phalaris minor* infestations in wheat.

Mechanical measures

Land levelling and Happy Seeder: In CA, laser land levelling ensures uniform moisture distribution, promotes seed germination, and enhances crop growth while reducing weed infestation. In contrast, uneven fields often lead to patchy crop growth and higher weed densities. Jat *et al.* (2003) found that precisely levelled wheat fields had a weed density of 200/m², compared to over 350/m² in non-leveled fields. Precision levelling can reduce labour requirements for weeding by up to 75%.

The 'Happy Seeder' is an advanced no-till seed drill designed for sowing seeds in standing crop residue. It integrates stubble mulching with seed and fertilizer application, cutting the crop residue in front of the sowing tines, opening slits, and drilling fertilizers and seeds at the desired depths. Seeding with this machine conserves moisture, controls weeds, and also retains organic matter. Adoption of the Happy Seeder can decrease weed density by 26.5% compared to rotavator sowing and by 47.7% compared to conventional practices (Singh *et al.* 2013).

Herbicide-based weed management

Herbicides are essential in CA due to their cost-effectiveness, affordability, low labour requirements, and ability to control difficult weeds. However, concerns over herbicide resistance and non-point pollution are significant. To mitigate these issues, it is important to adopt herbicide rotation and include other reliable weed management strategies. Non-selective herbicides can be applied to eliminate emerging weeds before or after planting but before crop emergence. The presence of crop residues can reduce herbicide efficacy, so early post-emergence herbicides combined with need-based hand weeding have proven effective for weed management (Choudhary *et al.* 2016). Nevertheless, over-reliance on herbicides and continuous use of similar types can shift weed populations from easily controlled species to more resilient ones, leading to the development of herbicide-resistant biotypes. This shift can make weed management particularly challenging in the early years of CA adoption (Vahid 2014). A list of recommended herbicides for various crops suitable for use in CA is provided in **Table 3**.

Integrated weed management

Weeds pose a significant threat in CA, a problem that is exacerbated by issues such as herbicide resistance and shifts in weed flora when relying solely on one management method. The adoption of multiple strategies—referred to as "many little hammers" in integrated weed management (IWM)—creates conditions that favour crops. Successful and effective IWM strategies include preventive approaches, false seedbed practices, appropriate row spacing and sowing windows, competitive crop cultivars, crop residue retention, allelopathic intercropping, cover crops, crop rotation, efficient water and nutrient management, and the need-based use of pre- or post-emergent herbicides alongside manual weed removal before seed set. Additionally, innovative methods such as strategic tillage and harvest weed seed control can be explored to manage weeds effectively. Integrating these practices can enhance crop competitiveness and develop sustainable weed management strategies within CA-based cropping systems. Lessons learned in weed management related to cropping systems are presented in **Table 4**.

Conclusions

In modern agriculture, while food production has significantly increased, the natural resource base is at risk, production costs have risen, and environmental pollution has become a major concern. The CA offers an alternative that addresses these issues, but it faces challenges, particularly with weed management during the initial years of adoption.

Table 3. List of promising herbicides for weed control in different crops (pre-emergence: 0-3 DAS; post-emergence: 18-22 DAS) (Source: DPPQS, 2023)

Weed management in rice

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Pendimethalin 30% EC	1000-1500 g/ha	3300-5000 ml/ha	PE	Annual grasses and some BLWs
Azimsulfuron 50% DF	35 g/ha	70 g/ha	PoE	Broad-spectrum weed control
Bispyribac-sodium 10% SC	20-25 g/ha	200-250 ml/ha		Broad- spectrum weed control
Carfentrazone-ethyl 40% DF	25 g/ha	62.50 g/ha		BLWs and sedges
Cyhalofop-butyl 10% EC	75-80 g/ha	750-800 ml/ha		Grasses only
Florpyrauxafen- benzyl 2.7% EC	21.25-37.5 g/ha	1250-150 ml/ha		Broad spectrum weed control
Metamifop 10% EC	100 g/ha	1000 ml/ha		Grasses
Propanil 80% DF	2000-3000 g/ha	2500-3750 g/ha		Broad-spectrum weed control
Ready mix				
Pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG	600 + 15 g/ha	2000 g/ha	PE	Broad-spectrum weed control
Bispyribac-sodium 20% + pyrazosulfuron-ethyl 15% WDG	20+15 g/ha	100 g/ha	PoE	Broad-spectrum weed control
Bispyribac-sodium 38% + chlorimuron-ethyl 2.5% + metsulfuron methyl 2.5% WG	43 g/ha	100 g/ha		Broad-spectrum weed control
Florpyrauxifen-benzyl 1.31 + penoxsulam 2.1% OD	15.63+25 g/ha	1250		Broad-spectrum weed control
Florpyrauxifen-benzyl 2.13 + cyhalofop butyl 10.64% EC	150 g/ha	1250 ml/ha		Broad-spectrum weed control
Penoxsulam 1.02% + cyhalofop-butyl 5.1% OD	120-135 g/ha	2000-2250 ml/ha		Broad-spectrum weed control
Triafamone 20% + ethoxysulfuron 10% WG	44+22.5 g/ha	225 g/ha		Broad-spectrum weed control

However, strict adherence to three fundamental principles—minimal soil disturbance, permanent soil cover, and crop diversification—can help minimize weed problems. In CA, most weed seeds remain on the surface, potentially leading to severe infestations; however, these seeds are also vulnerable to desiccation, predation, and effective weed management practices. To ensure CA is effective, productive, profitable, and sustainable, controlling weed flora in the early years is crucial. Additionally,

Weed management in maize

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Atrazine 50% WP	0.5–1.0 kg/ha	1000-2000 ml/ha	PE	BLWs and grasses
Pyroxasulfone 85% WG	127.5 g/ha	150 g/ha		Grasses and BLWs
Halosulfuron-methyl 75% WG	67.5 g/ha	90 g/ha	PoE	Sedges
Tembotrione 34.4% SC	120 g/ha	286 ml/ha		Broad-spectrum weed control
Topramezone 33.6% EC	25.2-33.6 g/ha	75-100 ml/ha		Broad-spectrum weed control
Mesotrione 2.27%+ atrazine 22.7%	875	3500 g/ha		Broad-spectrum weed control
2,4-D-amine salt 58% SL	500 g/ha	860 ml/ha		BLWs and sedges
2,4-D-sodium salt 80% SL	500.3 g/ha	1250 g/ha		BLWs and sedges
2,4-D-ethyl ester 38% SL	900 g/ha	2650 ml/ha		BLWs and sedges
2,4-D-ethyl ester 20% WP	900 g/ha	5000 ml/ha		BLWs and sedges
Ready mix				
Halosulfuron-methyl 5% + atrazine 48% WG	56.25+540 g/ha	1125 g/ha		Broad-spectrum weed control
Mesotrion 2.27% + atrazine 22.7% SC	875 g/ha	3500 ml/ha		Broad-spectrum weed control
Topramezone 1% + atrazine 30% SC	775 g/ha	2500 ml/ha		Broad-spectrum weed control

Weed management in soybean

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Clomazone 50% EC	750-1000 g/ha	1500-2000 ml/ha	PE	Grasses and BLWs
Diclosulam 84% WDG	22-26 g/ha	26.2-30.9 g/ha		BLWs and sedges
Flumioxazin 50% EC	125 g/ha	250 ml/ha		Grasses and BLWs
Metolachlor 50% EC	1000 g/ha	2000 ml/ha		For grasses
Metribuzin 70% WP	350-500 g/ha	500-750 g/ha		Grasses and BLWs
Pendimethalin 30% EC	700-1000 g/ha	2500-3300 ml/ha		Grasses and some BLWs
Pendimethalin 38.7% EC	580-677 g/ha	1500-1750 ml/ha		Grasses and some BLWs
Pyroxasulfone 85% WG	127.5 g/ha	150 g/ha		Grasses and BLWs
Sulfentrazone 39.6% SC	360 g/ha	750 ml/ha		Grasses and BLWs
Ready mix				
Pendimethalin 30%+imazethapyr 2% EC	900+60 g/ha	3000 ml/ha		Grasses and BLWs
Sulfentrazone 28%+ clomazone 30% WP	350+375 g/ha	1250 ml/ha		Broad-spectrum weed control
Sole application				
Bentazone 480 g/l SL	960 g/ha	2000 ml/ha	Early PoE	2-3 leaf stage of weeds, BLWs
Chlorimuron-ethyl 25% WP + surfactant	9 g/ha	36 g/ha	3-15 DAS	Controls BLWs and sedges
Clethodim 25% EC	120-180	500-700 ml/ha	PoE	For grasses
Fenoxaprop-p-ethyl 9.3% EC	100 g/ha	1111 ml/ha		Grasses
Fluazifop-p-butyl 13.4% EC	125-250 g/ha	1000-2000 ml/ha		Grasses
Fluthiacet-methyl 10.3% EC	13.6 g/ha	125 ml/ha		Grasses and BLWs
Haloxyfop-R-methyl	108-135 g/ha	1000-1250 g/ha		Grasses
Imazethapyr 10% SL	100 g/ha	1000 ml/ha		Grasses, sedges and BLWs
Imazethapyr 70% WG + surfactant	70 g/ha	100 ml/ha		Grasses, sedges and BLWs
Propaquizafop 10% EC	50-75 g/ha	500-750 ml/ha		Grasses
Quizalofop-ethyl 5% EC	37.5-50 g/ha	750-1000 ml/ha		Grasses
Ready mix				
Fomesafen 12% +quizalofop-ethyl 3% SC	180+45 g/ha	1500 ml/ha		Broad-spectrum weed control
Fluazifop-p-butyl 11.1%+fomesafen 11.1% SL	250 g/ha	1000 ml/ha		Grasses and BLWs
Fluthiacet-methyl 2.5%+quizalofop-ethyl 10% EC	12.5+50 g/ha	500 ml/ha		Grasses and BLWs
Imazethapyr 35% + imazamox 35% WG	70 g/ha	70 g/ha		Grasses and BLWs
Propaquizafop 2.5% + imazethapyr 3.75% ME	50+75	2000 ml/ha		Grasses and BLWs
Quizalofop-ethyl 7.5%+ imazethapyr 15% EC	32.5+65.6 g/ha	437.5 ml/ha		Grasses and BLWs
Quizalofop-ethyl 10% EC+ chlorimuron-ethyl 25% WP (twin pack) + surfactant	37.5+9 g/ha	375 ml/ha + 36 g/ha		Grasses and BLWs
Sodium-acifluorfen 16.5% + clodinafop-propargyl 8%	165+80 g/ha	1000 ml/ha		Grasses and BLWs

Weed management in greengram and blackgram

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Fenoxaprop-p-ethyl 9.3% EC	56.25-67.5	625-750 ml/ha	PoE	Controls most grasses
Imazethapyr 10% SL	75-100	750-1000 ml/ha		Grasses and BLWs
Quizalofop 5% EC	50	1000 ml/ha		Grasses only
Clodinafop-propargyl 12.5% EC	125	1000 g/ha		Grasses only
Propaquizafop 10% EC	75-100	750-1000 ml/ha		Grasses only
Ready mix				
Imazethapyr + imazamox	70	100 ml/ha		Grasses and BLWs
Propaquizafop 2.5% + imazethapyr 3.75% ME	50 + 75	2000 ml/ha		Grasses and BLWs
Fomesafen 17.5% + clodinafop-propargyl 12.5% ME	175+125	1000 ml/ha		Grasses and BLWs

Weed management in sugarcane

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Atrazine 80% WDG	2000	2500 g/ha	PE	BLWs & grasses
Atrazine 50% WP	500-2000	1000-4000 g/ha		BLWs & grasses
Diuron 80% WP	1600-3200	2000-4000 g/ha		Broad-spectrum weed
Ametryne 80% WDG	2000	2500 g/ha		Broad-spectrum weed control
Metribuzin 70% WP	1050-1400	1500-2000 g/ha		Broad-spectrum weed control
Metribuzin 70% WG	1400-2000	2000-3000 g/ha		Broad-spectrum weed control
Sulfentrazone 39.6% SC	720	1500 g/ha		Control of BLWs and sedges
Clomazone 50% EC	750-1000	1500-2000 ml/ha		BLWs & grasses
Clomazone 22.5% + metribuzin 21% WP	563+525	2500 ml/ha		BLWs & grasses
Hexazinone 13.2% + diuron 46.8% WP	1200	2000 g/ha		Broad-spectrum weed control
Ready mix				
Amytrin 73.1%+ trifloxysulfuron-sodium 1.8% WG	937.5-1125	1250-1500 g/ha		Broad-spectrum weed control
Sulfentrazone 28% + clomazone 30% WP	700+750	2500 g/ha		BLWs and sedges
Sole application				
Halosulfuron-methyl 75% WG	60-67.5	80-90 g/ha	PoE	Sedges
Metsulfuron-methyl 20% WP and WG	6	30 g/ha		BLWs and sedges
2,4-D-amine salt 58% SL	3500	6300 ml/ha		Broad-spectrum weed control
2,4-D-sodium salt 80% WP	2000-2600	2500-3250 ml/ha		Broad-spectrum weed control
2,4-D-ethyl ester 38% EC	1200-1800	3530-5290 ml/ha		Broad-spectrum weed control
Ready mix				
Halosulfuron-methyl 12% + metribuzin 55% WG	54+247.5	450 g/ha		Grasses and sedges
Mesotrione 2.27% + atrazine 22.7%	875	3500 g/ha		BLWs and grasses
Topramezone 1% + atrazine 30% SC	930	3000 g/ha		BLWs and grasses
2,4 D-sodium salt 44%+ metribuzin 35% + pyrazosulfuron-ethyl 1% WDG	1320+1050+30	3000 g/ha		Broad-spectrum weed control

Weed management in cotton

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Diuron 80% WP	750-1500	1000-2200 g/ha	PE	BLWs and sedges
Pendimethalin 30% EC	750-1250	2500-4165 ml/ha		Grasses and some BLWs
Pendimethalin 38.7% CS	580.5-677.25	1500-1750 ml/ha		Grasses and some BLWs
Ready mix				
Pyrithiobac-sodium 3.1% + pendimethalin 34% ZC	650-742	1752-2000 ml/ha		For BLWS and grasses
Sole application				
Fenoxaprop-p-ethyl 9.3% EC	67.5	750 ml/ha	PoE	For control of grassy weeds
Propaquizafop 10% EC	62.5	625 ml/ha		For control of grassy weeds
Fluazifop-p-butyl 13.4% EC	125-250	1000-2000 ml/ha		For control of grassy weeds
Quizalofop-ethyl 5% EC	50	1000 ml/ha		For control of grassy weeds
Pyrithiobac-sodium 10% EC	62.5-75	625-750 ml/ha		BLWs
Glufosinate-ammonium 13.5% SL	375-450	2500-3300 ml/ha	PoE (directed spray)	For broad-spectrum weed control
Paraquat dichloride 24% SL	300-500	1250-2000 ml/ha	PoE (directed spray)	For broad-spectrum weed control
Ready mix				
Pyrithiobac-sodium 6% + quizalofop-ethyl 4% EC	75+50	1000-1250 ml/ha	PoE	For broad-spectrum weed control

Weed management in wheat

Recommended herbicides	Dose (g/ha)	Commercial dose (ml or g/ha)	Application time	Remarks
Sole application				
Pendimethalin 30% EC	1000-1500	3300-5000 ml/ha	PE	Controls grasses and some BLWs
Pyroxasulfone 85% WG	127.5	150 g/ha		Controls mostly grasses and some BLWs
Ready mix				
Pendimethalin 35% + metribuzin 3.5% SE	875+87.5	2500-3000 ml/ha		BLWs & grasses
Sole application				
Isoproturon 50% WP	1000	2000 ml/ha	PoE (30–35 DAS)	Grassy weeds
Isoproturon 70% WP	1000	1330 ml/ha		Grassy weeds
Metribuzin 70% WP	175-210	250-300 g/ha		Grasses and BLWs
2, 4-D-amine salt 58% SL	500-750	860-1290 ml/ha		BLWs & sedges
2, 4-D-sodium salt 80% WP	500-840	625-1000 ml/ha		BLWs & sedges
2, 4-D-ethyl ester 38% EC	450-750	1320-2200 ml/ha		BLWs & sedges
Metsulfuron-methyl 20% WP	4	20 g/ha		BLWs & sedges
Pinoxaden 5.1% EC	40-45	800-900 ml/ha		Grassy weeds
Carfentrazone-ethyl 40% DF	20	50 g/ha		BLWs & sedges
Clodinafop-propargyl 15% WP and DF	60	400 g/ha		Grassy weeds
Sulfosulfuron 75% WG	25	33.3 g/ha		Controls both grasses and BLWs
Fenoxaprop-p-ethyl 10% EC	100-120	1000-1200 ml/ha		Grassy weeds
Ready mix				
Carfentrazone 20% + sulfosulfuron 25% WG	20+25	100 g/ha		BLWs & grasses
Metsulfuron-methyl 10% + carfentrazone-ethyl 40% DF	25	50 ml/ha		BLWs & sedges
Mesosulfuron-methyl 3% + idosulfuron-methyl-sodium 0.6% WG	12+2.4	400 ml/ha		BLWs & grasses
Sulfosulfuron 75%+ metsulfuron-methyl 5% WG	30+2	40 g/ha		BLWs & grasses
Clodinafop-propargyl 15%+metsulfuron-methyl 1% WP	60+4	400 g/ha		BLWs & grasses
Metribuzin 20% + clodinafop-propargyl 9% WP	120+54	600 g/ha		BLWs & grasses
Metribuzin 42% + clodinafop-propargyl 12% WP	210+60	500 g/ha		BLWs & grasses
Fenoxaprop 7.77%+ metribuzin 13.6% EC	100+175	1250 ml/ha		BLWs & grasses
Halauxifen-methyl 20.8% + florasulam 20% WG	12.76	31.23 g/ha		BLWs

Table 4. Lesson learned in weed management under conservation agriculture

Particulars	Constraints /Changes	Possible solution
Weed shift	Annual to perennial weeds	De-establishment of perennial weeds
Tough to kill weeds	Weed escape or not being controlled	Manual removal of escaped weeds
Late emergence of weeds	Retention of crop residues prolonged weed emergence	Strategic weed management, change in weed management practices
Weed seed bank	Enrichment of weed seed bank	Encourage seed predation or weed seed harvest
Mono-tonus weed management	Overreliance on herbicides	Integrated weed management to be practiced
Over-reliance on herbicides	Continuous use of non-selective herbicides	As per the weed flora herbicide needs to be applied/rotated
Use of a similar mode of action of herbicide	Use of similar herbicides for a prolonged period	Herbicide rotation with different modes of action is required
Crop cultivars	Similar types of crop cultivars	Selection of weed-competitive cultivars
Non-efficacy of pre-emergence herbicides	Use of less spray volume	As per crop residue load, spray volume may be increased
Herbicides formulation	EC formulation of herbicides	Use of granular or CS formulation of pre-emergence herbicides under optimum moisture condition
Herbicide efficacy	Poor efficacy of herbicides	Use of at least 500 L/ha of spray volume for pre-emergence and 375 L/ha for post-emergence herbicides
Nozzle	Use of hollow cone nozzles	Flat-fan or flood-jet nozzles to be used
Sprayer	Gun sprayer for large area spraying	Due to high pressure so much drift takes place and the desired quantity of herbicide cannot reach to target site, hence, avoid gun sprayer for herbicide application
Herbicide	Similar types of herbicides	Use of low dose high potency herbicides for broad-spectrum weed control and the least environmental hazards
Ineffective control of broad-spectrum weeds	Use of similar kinds of herbicides	Use of pre-mix/ready mix or tank mix application of compatible herbicide for broad-spectrum weed control
Mono-tonus use of days old herbicides	Continuous use of recommended herbicides	Smart selection of herbicides, based on weed flora

depleting the weed seed bank can reduce weed severity. Essential strategies for effective and sustainable weed management in conservation agriculture include using non-selective herbicides before seeding, applying pre-and post-emergence herbicides with appropriate competitive cultivars, incorporating cover crops between rows, and utilizing other non-chemical approaches.

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REVIEW ARTICLE

Impact of climate change on soybean and associated weed interactions

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ABSTRACT

Soybean is an important oilseed crop, known to be fourth most cultivated crop globally, contributing to approximately 53% of total oil production. As a rainfed crop, soybean is particularly susceptible to the impacts of climate change. Climate change is expected to result in higher temperatures, elevated CO_2 levels and altered rainfall pattern. As per IPCC Synthesis Report 2023, climate change may increase global temperatures by 1.5°C between 2021 and 2040 under high-emission scenarios. Without substantial mitigation efforts, the consequences could be catastrophic, leading to a 3.6-4.4°C rise in global temperatures and CO_2 concentrations could rise to levels 2-4 times higher than those recorded in the past 0.8 million years, resulting in unprecedented climate changes. This climate change (elevated CO_2) is found to have a positive impact on soybean seed yield (increase 32-37%) under weed-free conditions, however, under weedy condition seed yield of soybean may be reduced by 30% by C_3 weeds and 45% by C_4 weeds. Thus, C_4 weeds are more competitive to C_3 crops such as soybean under climate change condition. Elevated temperature was found to have more direct and positive impact on growth of most of the weed species, while it negatively impacted the soybean growth and yield parameters. However, interaction effect of CO_2 and temperature was beneficial to both weeds and soybean. Apart from this, interaction of rainfall and temperature play a critical role in soybean productivity, where the simulation study advocates that increase in 1°C temperature with rainfall remaining constant, leads to a decline in productivity by 10-15%. Anticipating potential damage from weed to soybean is crucial for formulating effective and sustainable weed management strategies. Therefore, it is vital to address soybean-weed interactions and weed management in the context of climate change, as there has been inadequate research conducted in this area.

Keywords: Elevated CO_2, Crop-weed interaction, Elevated temperature, Emission, Rainfall, Soybean, Weed management

INTRODUCTION

Soybean (*Glycine max* L.) is an important oilseed and legume crop which possesses C_3 photosynthetic cycle. It is the fourth most cultivated crop globally, contributing to approximately 53% of total oil production (Beta and Isaak 2016). In India, the major weed flora of soybean is categorized into broad-leaf (*Commelina benghalensis, Eclipta prostrata*, *Phyllanthus niruri*, *etc*.), grasses (*Echinochloa colona, Ischaemum rugosum etc.*) and sedges (*Cyperus iria*, and *C. rotundus*) (Prachand *et al.* 2014, Patel *et al.* 2019, Dass *et al.* 2019, Chander *et al.* 2023a,b). These, weeds not only diminish the quality but also reduce the yields and also complicate the crop harvesting (Swinton *et al.* 1994, Boydston *et al.* 2008, Pawar *et al.* 2022). *E. colona* and *I. rugosum* are prominent weed species that lead to substantial yield losses and decline in the seed quality of soybean (Alarcon-Reverte *et al.* 2013). Yield reduction in soybean due to weeds can range from 33% to 100% (Billore *et al.* 1999), depending on weed type, intensity and the duration of competition with the crop. For instance, Oerke (2006) reported a global soybean production loss of 37% due to weed competition whereas Gharde *et al.* (2018) estimated that weeds cause losses of 1559 million USD in soybean in India.

There is a growing concern about soybean yield in India, as the current average stands at only 1.15 tons per hectare (Anonymous 2024), which is significantly lower than that of other major soybean-producing countries. As a rainfed crop, soybean is particularly vulnerable to the impacts of climatic

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factors such as drought and extreme temperatures (Billy and Khanna 2018). These environmental stresses have become critical factors influencing food security by severely affecting crop productivity (Ribeiro *et al.* 2020). Climate change is expected to result in higher temperatures, elevated carbon dioxide (CO_2) levels, and rainfall is predicted to be erratic- in terms of amount, frequency, and intensity. These factors play a crucial role in the growth and development of plant species directly or indirectly affecting both crops (C_3 or C_4) and their competing weeds (C_3 or C_4) by affecting their vegetative growth, vigour and competitiveness (Raza *et al.* 2019; Sreekanth *et al.* 2024). Global warming defined as the continuous increase in the Earth's average temperature, is a primary driver of climate change (IPCC 2019). The rising temperatures impose significant constraints on crop growth and productivity, with high temperatures during key stages such as flowering and grain filling reducing yields and quality (Kaushal *et al.* 2016). As temperature extremes become more frequent and intense, particularly in tropical regions, the challenge of maintaining global food security grows more urgent (Sun *et al.* 2019). Also, global warming has already caused shifts in cultivation zones and contributed to the loss of genetic variability in crop species. This poses a direct threat to biodiversity and food security, leading to more unpredictable crop yields and ecosystem degradation (Khoury *et al.* 2014).

Understanding the relationship between climate change and agricultural productivity requires not only identifying temperature thresholds that threaten crop yields but also developing models that predict the impacts of extreme weather events, such as heat waves and droughts, on crop performance (Schauberger *et al.* 2021). Moreover, the combined effects of increased atmospheric CO_2 and higher temperatures on crop yields are complex. While elevated CO_2 can boost plant growth under certain conditions, its interaction with heat stress and water shortage often leads to diminished crop productivity (Degener 2015). Water availability is crucial to sustaining crop growth and any future scenarios of global warming must consider the shifts in irrigation and rainfed areas, particularly for key crops such as maize, wheat, rice, and soybean (Sloat *et al.* 2020). As temperatures continue to rise, and extreme weather events become more frequent, crop productivity is likely to decline. For example, for every 1°C increase in temperature, global maize yields decrease by 7.4%, wheat by 6.0%, rice by 6.2% and soybean by 3.1% (Parthasarathi *et al.* 2022). When combined with drought, these temperature increases result in even more substantial losses across cereal and non-cereal crops (Brás *et al.* 2021). As such, future agricultural practices must incorporate holistic strategies, including breeding for enhanced stress tolerance, to ensure food security in the face of ongoing climate change.

High temperatures negatively affect key physiological processes such as photosynthesis, transpiration, and respiration, ultimately leading to reduced yields in major food crops (Hatfield and Prueger 2015, Schauberger *et al.* 2017). The optimal temperature for soybean during its flowering and seed-filling stages is 30/22°C and deviations from this range can adversely affect plant growth and productivity (Thenveettil *et al.* 2024). The effect of increased temperature, CO_2 and their interaction on soybean and associated weeds (C_3 and C_4) have positive and negative impacts (Tungate *et al.* 2007, Chander *et al.* 2023). Rising CO_2 and temperatures may shift dominant weed species and aggravate weed problems (Ziska and Dukes 2011). An increase in CO_2 concentration has been shown to enhance net photosynthesis in C_3 plants, while C_4 plants exhibit a smaller response (Bowes 1996, Ghannoum *et al.* 2000). However, this generalization is not universal, as studies have reported differential responses among crops and weeds with the same photosynthetic pathways. For example, Ziska (2000) found that in a C_3 weed and C_3 crop interaction, the C_3 weed exhibited a greater overall response than the C_3 crop, resulting in reduced seed yield for soybean grown under elevated CO_2. Similarly, Patterson and Flint (1980) reported that increased atmospheric CO_2 might enhance the competitive impact of C_3 weeds in C_4 crops, while reducing the impact of C_4 weeds in C_3 crops.

Given the global importance of soybean, it is crucial to understand how climate change, particularly temperature and CO_2 will affect soybean productivity and behaviour of associated weeds. The goal of this review is to provide insights into the impact of climate change on soybean and its associated weed flora.

Current status of climate change: projections and potential impacts

The IPCC Synthesis Report-2023 underscores the growing challenges of climate change, noting the increasing probability that global temperatures could exceed 1.5°C between 2021 and 2040, particularly under high-emission scenarios (Bacchin *et al.* 2023 and IPCC 2023). Human-induced warming reached 1.31°C by 2023, driven by greenhouse gas emissions at record levels (Forster *et al.* 2024). Projections indicate that without significant mitigation efforts, CO_2 concentrations could reach levels two to four times higher than those observed in the last 0.8 million years, leading to unprecedented climatic changes (Raviraja 2023). According to the Intergovernmental Panel on Climate Change (IPCC), the global atmospheric CO_2 concentration to 730-1000 ìmol mol^{-1} by the end of the 21st century (Gianessi 2013, Varanasi *et al.* 2015). Further, if emissions remain unchecked, global temperatures could rise by 3.6 to 4.4°C by the end of the 21^{st} century (Adak *et al.* 2023), with severe consequences for biodiversity, food security, water availability, agricultural or ecological drought *etc*. (**Figure 1**).

C_3 and C_4 plant physiology in relation to climate change

C_4 grasses are predicted to become more dominant in mid-latitude drylands due to increased climatic suitability, while C_3 grasses may decline in these regions (Anderson *et al.* 1993). In terms of weed physiology, C_3 weeds generally respond more positively to increased CO_2, which enhances their photosynthetic rates under optimal moisture conditions, potentially increasing their competitiveness against C_4 crops while C_4 weeds exhibit greater thermal tolerance, allowing them to thrive under elevated temperatures, which could expand their distribution range (Keerthi *et al.* 2023). Under elevated CO_2 in spite of enhanced photosynthesis in C_3 weeds, they may also encounter oxidative stress in high-temperature environments which may reduce their overall growth (Rakhmankulova *et al.* 2023) while, C_4 weeds biomass will be higher due to photosynthetic efficiency under elevated temperatures, even if they too face stress from combined climate factors (Rakhmankulova *et al.* 2023, Sendall *et al.* 2024). As climatic conditions evolve, these interactions will likely necessitate changes in weed management strategies.

C_3 and C_4 plants utilize different photosynthetic pathways that influence how they adapt to changing environmental conditions. C_3 crops, such as rice, wheat, and soybeans, tend to exhibit increased photosynthetic efficiency under elevated CO_2 levels, primarily due to reduced photorespiration and improved CO_2 assimilation (Drake *et al.* 1997). While elevated CO_2 can improve water-use efficiency and mitigate some of the effects of drought in C_3 crops, C_4 crops may experience less benefit due to their naturally high water-use efficiency under normal

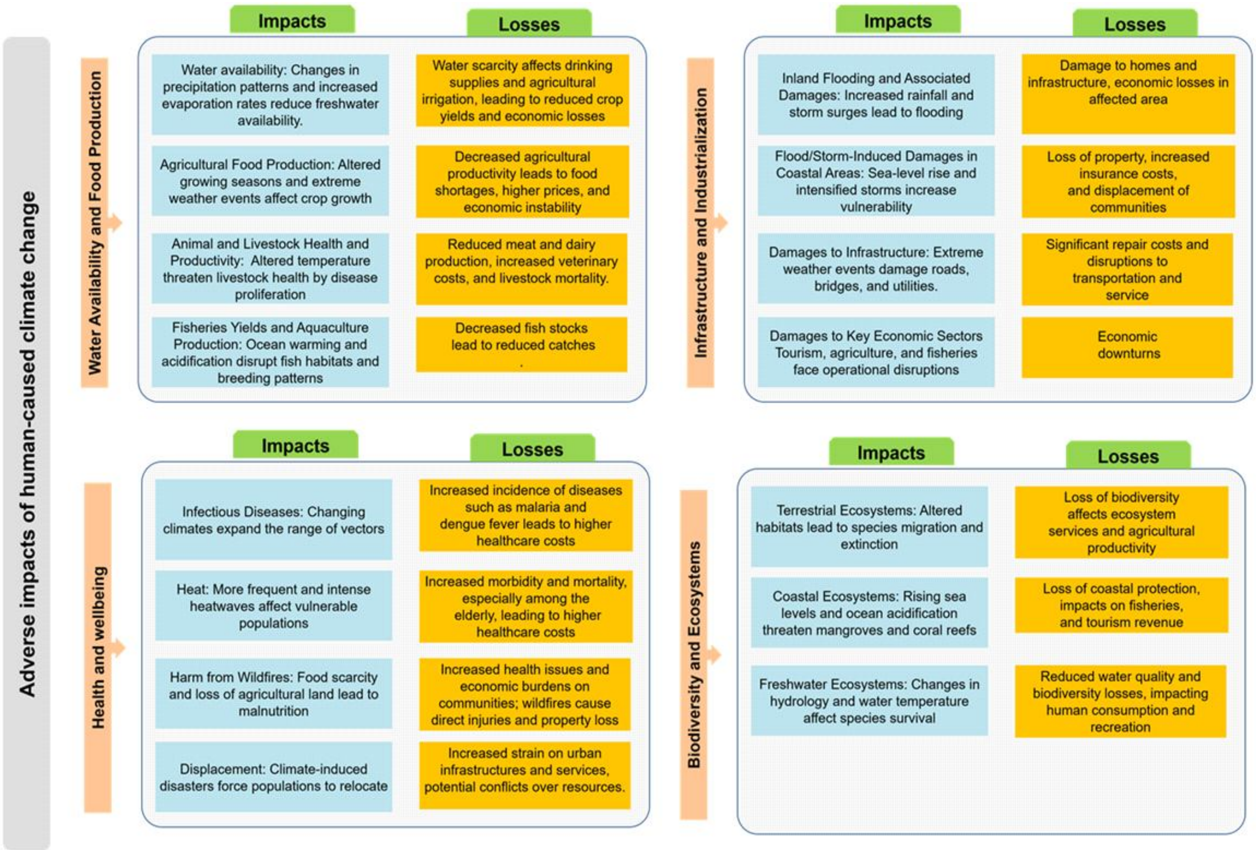

Figure 1. Impact and losses by climate change caused by anthropogenic activity

conditions (Leakey *et al.* 2019, van der Kooi *et al.* 2016). Moreover, elevated CO_2 may worsen drought sensitivity in C_4 plants by increasing leaf area, which can raise water demand (Burkart *et al.* 2011). Given the complexity of these responses, predicting how C_3 and C_4 crops will fare under future climate conditions remains challenging.

Impact of elevated CO_2 on soybean and associated weeds

Weeds and crops may react differently to CO_2 enrichment due to interactions between CO_2 enrichment and other environmental parameters like temperature, availability of water and nutrients and so on (Patterson and Flint 1980, Zangerl and Bazzaz 1984, Naidu 2015, Naidu and Murthy 2014). The photosynthetic pathway is an important consideration, especially because many of the world's most troublesome weeds are C_4 plants, which tend to photosynthesize more effectively at higher temperatures and, as a result, are probably better able to utilize higher CO_2 levels than C_3 plants, which include crops (Alberto *et al.* 1996). Increasing CO_2 concentrations would benefit C_3 crops such as rice, wheat, and soybeans, making them more competitive than C_4 weeds. However, when both crops and weeds share the same photosynthetic pathway, weed growth has been found to improve when CO_2 levels rise. Ziska noted that when *Abutilon theophrasti* and soybean were grown in competition with each other at greater CO_2 levels, the competition benefited the soybeans, as seen by higher pod numbers/plant (Ziska 2013). However, when another ubiquitous plant, *Chenopodium album*, was cultivated in a Canadian grassland environment, CO_2 enrichment failed to induce higher growth in *C. album* (Taylor and Potvin 1997).

Lal *et al.* (1999) have found that soybean yield increased by 50% when doubling CO_2 level based on the CROPGRO simulation model. In one study, it was shown that, when CO_2 concentration was doubled, the total biomass production was increased by 40% with no changes in the C/N ratio whereas nitrogen content was improved (29%) due to enhanced atmospheric nitrogen fixation in soybean (Torbert *et al.* 2004). This study directed that although biomass and nitrogen content were increased, there was no need to change (increase or decrease) the fertilization application in soybean. In a different study, Ziska (2000) examined the impact of competition between 'Round-up Ready' soybean and a C_3 weed (*C. album*) and a C_4 weed (*Amaranthus retroflexus*), cultivated under both ambient and elevated CO_2 levels (ambient+250 ppm). Under weed-free conditions, increased CO_2 levels led to increased soybean growth and yield compared to ambient CO_2 conditions. However, both weed species significantly decreased soybean growth and yield at all CO_2 levels. At high CO_2, *C. album* caused a 28 to 39% drop in soybean seed production compared to the weed-free control. Similarly, the dry weight of *C. album* rose by 65%. Conversely, with *A. retroflexus*, soybean seed yield losses decreased from 45 to 30% as CO_2 levels increased, although weed dry weight remained constant. This study implies that rising CO_2 levels may modify yield losses caused by weed competition, and that weed control will be critical in realizing any possible rise in soybean crop yield, when climate change happens. It appears that the crop would profit from higher CO_2 only when the weed is C_4 and the crop is C_3, but in all other circumstances, weeds are projected to outsmart crop in a crop-weed competition situation. Thus, while rising CO_2 levels definitely boost weed development in general, weed-crop competition connections should be assessed on an individual basis. In another study, Santos *et al.* (2017) discovered that the projected increases in atmospheric CO_2 levels should not affect these traits, after atmospheric CO_2 concentrations reach 800 ppm, *Euphorbia heterophylla* being more aggressive than soybeans. However, it has been discovered that increasing CO_2 levels in the environment increases the aggressiveness of soybean cultivation in comparison to *E. heterophylla*. Chander *et al.* (2023) have revealed that elevated CO_2 (550 ppm) has positive impact on root nodules (32.17%), plant height (13%), plant dry weight (13.42%), number of pods per plant (7.88%), yield (36.61%) of soybean under weed-free conditions, whereas very little increment was observed in the presence of weeds. Elevated CO_2 also had positive impact on plant height (25.73%; 40.79%), plant dry weight (62.63%; 16.21%) and number of tillers/plant (85.92%; 56.76%) of two weed species *E. colona* and *I. rugosum*, respectively, hence yield of soybean infested with these two weed species at elevated CO_2 was decreased by 31.12%. Lenka *et al.* (2017) reported that at elevated CO_2 (550 ppm), the leaf area, biomass at harvest and grain yield were significantly improved by 143%, 47% and 51%, respectively, in soybean over ambient conditions.

Morgan *et al.* (2005) reported that when soybean was grown in Free-Air Carbon Dioxide Enrichment (FACE) facility (550 ppm CO_2), there was increase in net primary production *i.e.* biomass (17-18%) and yield (15%), but it was less than the previous open-top chamber experiment. Similarly, Davis and Ainsworth (2012), demonstrated that in FACE experiment soybean plant height was slightly higher in weedy (9%) and weed free (11%) condition in elevated CO_2 (550 ppm). They point out that the proportion of soybean yield was greater in weedy condition compared to weed-free condition at elevated CO_2, it may be due to the interference being moderated by increased CO_2 and more reduction in interference was found in *Amaranthus rudis* (37%) than *C. album* (11%). Thus, study implies that C_4 weed (*A. rudis*) has non signification interference, whereas C_3 weed has greater interference with significant difference due to photosynthetic advantage at elevated CO_2. They also suggested that C_3 and C_4 weed communities were equally likely to dominate at ambient CO_2 condition whereas greater chance of C_3 weed community (90% chance) to dominate under elevated CO_2 condition. Based on the 30-year (1980-2010) climatic data, Mohanty *et al.* (2017) suggested that with increase in CO_2 concentration (750 ppm) soybean yield was increased (30%).

Impact of elevated temperature on soybean and associated weeds

It is predicted that the global earth's surface temperature will upsurge by 1.5-4.0°C, which is correlated with doubling CO_2 concentration and greenhouse effect over 21st century (IPCC 2023). This increased temperature will lead to water stress and subsequently plant growth will suffer due to evapo-transpiration (Billore 2019). Plants with the C_4 photosynthetic pathway, which are predominant weeds, will have a competitive edge over staple food crops, *viz*. rice, wheat, soybean etc., which are primarily C_3, under high temperatures. Hence, its crucial to understand how soybean and associated weeds will behave under increased temperature.

Chander *et al*. (2023) found that with rise in temperature of 2°C, the plant height, plant dry weight, number of pods/plant and yield of soybean were reduced by 6.25%, 19.44%, 26.67% and 5.48% respectively in weed free condition compared to ambient condition in open top chamber. In contrast when soybean grown with two weeds (*E. colona* and *I. rugosum*), the plant height, plant dry weight, number of pods/plant and yield was decreased by 49.47%, 47.80%, 95.42% and 56.40% respectively. It happened due to enhanced impact of elevated temperature on the growth (plant height, plant dry weight and the number of tillers) of *E. colona* and *I. rugosum* (**Table 1**). Similarly, Lenka *et al*. (2017) observed that with increase in temperature of 2°C, the leaf area, biomass at harvest and grain yield were increased by 281%, 31% and 30%, respectively in soybean. Seed index (100 seed weight) of soybean was significantly increased at elevated temperature. Chen *et al*. (2013) used the climate data of temperature, radiation and rainfall from 820 weather stations and production data from 2001-2009 in China and simulated that reduction in soybean yield (5-10% and 8-22%) was more prominent than corn in slow warming scenario (2-5%) and fast warming scenario (5-15%), respectively. In another study of simulation of climatic and production data of soybean (1980-2010), it is indicated that with 10% increase in temperature along with low rainfall, the soybean yield was reduced by 10% (Mohanty *et al*. 2017). They predicted that declining the temperature by 1°C (from the base) and increasing the rainfall (>10%) encouraged the soybean productivity, however with rise in temperature by 1°C with constant rainfall led to decline in soybean productivity (10-15%). In their study, Tungate *et al*. (2007) examined how temperature affected *Sida spinosa*, *Cassia obustutifolia*, and soybean. They found that while all species showed an upward tendency in root: shoot ratios as temperatures rose, weeds consistently exhibited higher ratios. When growth was at its highest, the root: shoot growth ratio for soybean (at 32/27°C) was 0.8, while for *S. spinosa* (at 36/31°C) and *C. obustutifolia* (at 36/31°C), it was 1.3 and 1.6, respectively. Tremmel and Patterson (1993) also studied the variation in diurnal temperature (high: 28/22, 30/23, 31/24 and 32/26°C; ambient: 24/18, 26/19, 27/20 and 28/22°C) and elevated CO_2 (700 ppm) on soybean and associated weeds, *viz*. *Sorghum halepense*, *Elytiga repens*, *Amaranthus retroflesus*, *Cassia obtusifloia* and *Abutilon theophrasti*. They noted that the growth responses of these species to temperature were more clear-cut than their reactions to CO_2. Leaf area and biomass were significantly lower at high temperature than ambient in *E. repens*, however, contrasting results were observed for other species for plant height and leaf area with greater significance.

Impact of elevated CO_2 and their interaction with temperature and rainfall on soybean and associated weeds

Research conducted in Central India using open-top chambers, Chander *et al*. (2023) found an increase in biomass of soybean (7.62%), *I. rugosum* (27.83) and *E. colona* (9.65%) under the combination of elevated temperature and CO_2 (**Table 1**). The increased biomass may be due to the higher rate of carboxylation and reduced rate of photorespiration (Bhattacharyya and Roy 2013). Chander *et al*. (2023) also reported that the combination of elevated CO_2 and temperature has positive impact on seed yield (7.6% increase) and number of pods/plant (4.24%), this may be due to the greater ability to fix atmospheric nitrogen in presence of root nodules (Hikosaka *et al.* 2011). Future research on C_3 and C_4 crop-weed competition under changing climatic circumstances is vital, as the current study's findings suggest that C_4 weeds may become more competitive with C_3 crops. Lenka *et al.* (2017) found that elevated CO_2 and temperature significantly increased leaf area (259%), biomass at harvest (47%) and grain yield (65%) compared to elevated CO_2 alone. Heinemann *et al.* (2006) studied the effect of diurnal variation of temperature (20/15, 25/20 and 30/25°C) and elevated CO_2 (700 ppm) on growth and development of soybean. They found that soybean flowered two days early at 25/20°C and elevated CO_2 condition compared to ambient condition, however no change in flowering was observed in other temperature and CO_2 combination. This early flowering seemed to be owing to the strong effect of temperature than elevated CO_2 (Sionit *et al.* 1987a,b, Baker *et al.* 1989). They advocated that the biomass growth rate was higher at low temperature (20/15°C) and elevated CO_2, which was also supported by Sionit *et al.* (1987b). In contrast, at higher temperature regime (30/25°C), the biomass growth rate was higher at ambient situation than increased CO_2 condition, due to the soybean's reduced response to increased CO_2 over time because of biochemical limitations (Pritchard *et al.* 1999). Seed weight was improved at 20/15 and 30/35°C temperature regime by 7.5% under increased CO_2, though the improvement was smaller at higher temperature regime (Heinemann *et al.* 2006). Tremmel and Patterson (1993) found that biomass was significantly higher in soybean and all the weeds except *S. halepense* at elevated CO_2 and ambient (26/19°C) or high temperature (30/23°C). Elevated CO_2 and temperature (30/23°C) had a much greater positive impact on biomass than leaf area at early harvest, with substantial overall response, but no visible impact of CO_2 at later harvest stage was observed. At early harvest stage, *S. halepense* had no noticeable impact of elevated CO_2, however at later harvest leaf area was greater at elevated CO_2 and high temperature (30/23°C), indicating significant interaction of CO_2 and temperature. In *C. obtusifolia* the significant interaction of CO_2 and temperature

Table 1. Impact of elevated CO_2 (EC), elevated temperature (ET) and combination (EC+ET) on soybean and associated weeds compared to ambient condition

Crop/weed species	Trait	CO_2 level (ppm)	Elevated temperature (°C)	Percent increase (+)/decrease (-)			Reference
				EC	ET	EC+ET	
Glycine max	Yield	660	-	+50	-	-	Lal *et al.* 1999
Glycine max	Total biomass production	730	-	+40	-	-	Torbert *et al.* 2004
Glycine max	C/N ratio	730	-	+29	-	-	Torbert *et al.* 2004
Glycine max	Leaf area	550	2	+143	+281	+259	Lenka *et al.* 2017
Glycine max	Biomass at harvest	550	2	+47	+31	+47	Lenka *et al.* 2017
Glycine max	Grain yield	550	2	+51	+30	+65	Lenka *et al.* 2017
Glycine max (Amaranthus retroflexus)	Biomass	Ambient	-	-36	-	-	Ziska 2000
Glycine max (Chenopodium album)	Biomass	Ambient	-	-23	-	-	Ziska 2000
Glycine max (weed-free)	Biomass	Ambient+ 250	-	+32	-	-	Ziska 2000
Glycine max (Amaranthus retroflexus)	Seed yield	Ambient	-	-45			Ziska 2000
Glycine max (Chenopodium album)	Seed yield	Ambient	-	-28			Ziska 2000
Glycine max (Amaranthus retroflexus)	Seed yield	Ambient+ 250	-	-30	-	-	Ziska 2000
Glycine max (Chenopodium album)	Seed yield	Ambient+ 250	-	-39	-	-	Ziska 2000
Glycine max	Productivity	-	1	-	+10-15	-	Mohanty *et al.* 2017
Glycine max (weed-free)	Biomass	550±50	2	+13.4	-	+7.62	Chander *et al.* 2023
Glycine max (weed-free)	Root nodules	550±50	2	+32	-25	-	Chander *et al.* 2023
Glycine max (weed-free)	Plant height	550±50	2	+13	-6.25	+6.73	Chander *et al.* 2023
Glycine max (weed condition)	Plant height	550±50	2	+3.4	-49.5	-6.01	Chander *et al.* 2023
Glycine max (weed-free)	Dry weight	550±50	2	+13.4	-19.4	+7.62	Chander *et al.* 2023
Glycine max (weed condition)	Dry weight	550±50	2	-16.4	-47.8	-18.7	Chander *et al.* 2023
Glycine max (weed-free)	Pods/plant	550±50	2	+7.88	-26.7	+4.24	Chander *et al.* 2023
Glycine max (weed condition)	Pods/plant	550±50	2	-42.4	-95.4	-49.7	Chander *et al.* 2023
Glycine max (weed-free)	Seed yield	550±50	2	+37.6	-5.48	+7.16	Chander *et al.* 2023
Glycine max (weed condition)	Seed yield	550±50	2	-31.1	-56.4	-33.4	Chander *et al.* 2023
Echinochloa colona	Plant height	550±50	2	+25.7	+10.79	+28.2	Chander *et al.* 2023
Echinochloa colona	Dry weight	550±50	2	+62.6	+64.9	+9.65	Chander *et al.* 2023
Echinochloa colona	No of tillers/plant	550±50	2	+85.9	+146	+33.8	Chander *et al.* 2023
Echinochloa colona	Biomass	550±50	2	+62.6	+64.9	+9.65	Chander *et al.* 2023
Ischemum rugosum	Plant height	550±50	2	+40.5	+26.4	+32.9	Chander *et al.* 2023
Ischemum rugosum	Dry weight	550±50	2	+16.2	+37.2	+27.8	Chander *et al.* 2023
Ischemum rugosum	No of tillers/plant	550±50	2	+56.7	+89.2	+24.3	Chander *et al.* 2023
Ischemum rugosum	Biomass	550±50	2	+16.2	+37.2	+27.8	Chander *et al.* 2023

was observed for biomass, though no impact was observed in leaf area. Conversely, in *A. theophrasti,* a negative impact of CO_2 and temperature interaction was observed for leaf area.

Conclusion

The studies on the impact of climate change on soybean and its associated weeds are limited. However, the available studies have confirmed that both soybean and its associated weeds respond differently to climate change. Weeds typically supersede over soybean due to their superior adaptation and positive effect of climate change. Additionally, weeds show intraspecific variation and physiological plasticity due to which they also have competitive advantage over soybean. Both elevated CO_2 and temperature, have encouraging impact on growth parameters of C_3 and C_4 weeds, however, C_4 weeds causing less interference with soybean than the C_3 weeds. Also, elevated CO_2 has positive impact on soybean but is negatively impacted by elevated temperature. In addition to this, elevated CO_2 was found to have a positive impact on soybean seed yield (increase 32-37%) under weed free condition. However, under weedy condition seed yield of soybean may be reduced by 30% by C_3 weeds and 45% by C_4 weeds. Studies have also shown that, elevated CO_2 and temperature interacted positively, benefiting both soybean and weed species. One simulation study suggests that, 10% increase in temperature combined with low rainfall can reduce soybean yield by 10%. Conversely, a decrease in temperature by 1°C and an increase in rainfall of more than 10% can enhance soybean productivity. Thus, it indicates the critical interplay between temperature and rainfall in determining soybean yields and underscores the need for adaptive management strategies in response to changing climatic conditions. Anticipating potential damage from weed to soybean crop is essential for implementing sustainable weed management strategies. Hence, more studies are required to understand and, simulate soybean-weed interaction and develop weed management approaches in climate change scenario.

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REVIEW ARTICLE

Weed management and conservation agriculture in cotton-based systems: Implications on soil quality and climate change mitigation

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ABSTRACT

Conservation agriculture (CA), characterized by reduced tillage, continuous soil cover through mulching or cover cropping, and crop rotation, is established as a sustainable approach for enhancing soil health and agricultural resilience, particularly in cotton-based systems. Several studies indicated that CA in cotton systems played a crucial role in climate mitigation by enhancing soil carbon sequestration and mitigating greenhouse gas (GHG) emissions. CA practices reportedly increased soil organic carbon (SOC) levels, which helped stabilize atmospheric CO_2 Additionally, CA minimized energy-intensive inputs by reducing reliance on machinery, thereby further lowering CO_2 emissions. With reduced tillage, weed management became more challenging but remained essential for productivity, soil health, and sustainability. Research showed that weed management practices in CA systems influenced soil physical, chemical, and biological properties. CA was found to improve physical attributes such as bulk density, soil structure, aggregation, and hydraulic conductivity, which enhanced porosity, root growth, and water infiltration. CA-based weed control helped in stabilizing the soil pH, reducing electrical conductivity, increasing cation exchange capacity, and enhancing SOC, thereby improving nutrient retention. Reliance on herbicides in CA-based cotton systems was shown to impact soil microbial diversity and enzyme activity, varying with herbicide type and frequency of application. Some herbicides temporarily inhibit soil microorganisms and enzyme functions (*e.g.*, dehydrogenase, urease, phosphatases). However, mulching and organic residue retention in CA systems demonstrated positive effects on soil microbial biomass carbon (SMBC) and microbial activity. CA practices gradually stored carbon by sequestering CO_2 in SOC, thereby stabilizing carbon and supporting biodiversity.

Keywords: Climate change, Conservation agriculture, Cotton, Soil quality, Weed management

INTRODUCTION

Conservation agriculture (CA) is based on three key principles: (1) minimal soil disturbance or no tillage/direct seeding, (2) continuous soil cover with crops, cover crops, or mulch, and (3) crop rotation and cover crop use (FAO 2015). Over time, agricultural innovations have contributed to intensifying food production in CA-based systems (Muoni *et al.* 2013). Conservation agriculture, which recommends zero tillage ZT coupled with crop residue mulching and diversified crop rotation, has come forward as a sustainable management system that could revert physical soil degradation in resource poor farms across very different agro-ecological conditions (FAO 2012).

Reducing tillage intensity and frequency in CA often leads to increased weed infestations. Compared to conventional tillage (CT), zero tillage (ZT) results in more weed seeds accumulating on the soil surface, encouraging higher weed germination. Weed infestations change with the adoption of practices such as sowing techniques, tillage methods, weed control strategies, residue management, and input application.

Cotton is India's most important commercial crop, with the country being the world's leading cotton producer. India cultivates cotton in 13.06 million hectares, accounting for about 40% of the global cotton-growing area. About 67% of India's cotton is grown in rain-fed areas, while the remaining 33% is cultivated on irrigated lands (Ministry of Textiles 2023). The adoption of conservation agriculture (CA) in cotton (*Gossypium hirsutum*) systems offers both agronomic and environmental benefits (Ferdush *et al.* 2024).

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Rising temperatures, especially warmer nights, impact the cotton, where higher night temperatures lower yields by increasing respiration rates more than photosynthesis, despite cotton's drought tolerance (Nouri *et al.* 2021). Climate change has already reduced agricultural productivity growth by 21% over the past 50 years (Ortiz-Bobea *et al.* 2021). Without long-term solutions, issues such as GHG emissions, soil degradation, and dwindling groundwater will worsen. Thus, systemic solutions integrating climate-smart, regenerative practices are needed to protect soil health and sustain production (Jat *et al.* 2022). South Asia's future food security will depend on efficient, climate-smart practices like Conservation Agriculture (CA), which aligns with the United Nations' Sustainable Development Goals (SDGs) (Roy *et al.* 2022). Over the last two decades, CA has been recognized in South Asia as a strategy for increasing productivity, profitability, soil health, and climate resilience, contributing to "sustainable intensification" (Bell *et al.* 2018).

With the reduction in tillage, reliance on herbicides for weed management in CA cotton increases. Herbicide use is a vital component of cotton grown under reduced-till systems. More than one million kg of herbicide-active ingredients are applied annually to achieve weed-free cotton fields in Australia (Charles 1991). Herbicide use is an essential management practice in cotton growing and multiple applications of a wide array of herbicides in a single season are a common practice.

Soil health is an inherent component of conservation agriculture maintaining the capacity of soil to function as the dynamic living system within the ecosystem and land management practices, sustaining crop productivity, regulating water and air quality, controlling soil nutrient cycling, and improving plant and animal health (Daryanto *et al.* 2018, Wade *et al.* 2022). This review provides a brief summary of current knowledge regarding the impact of weed management practices on soil properties within conservation agriculture (CA)-based cotton cropping systems, as derived from globally published peer-reviewed studies.

Effect of weed management in conservation agriculture (CA) on soil attributes in cotton-based system

Weed management practices play a crucial role in determining soil physical properties in cotton-based cropping systems, especially under conservation agriculture (CA).

Soil physical properties

Bulk density: Bulk density of soils, an essential indicator of soil compaction and porosity, significantly influences root penetration and water movement. Studies in the semi-arid regions of Telangana found that conservation tillage combined with mulching reduced bulk density compared to conventional tillage, enhancing root growth and water infiltration (Srinivasarao *et al.* 2014a). In rainfed cotton systems mulching with crop residues decreased bulk density, particularly in areas with hard-setting soils, such as parts of Maharashtra and Karnataka (Patil *et al.* 2017a).

Rao *et al.* (2016) observed that reduced tillage systems under CA lowered bulk density by improving soil structure and reducing compaction. Retaining crop residues also contributed to reduced bulk density, as increased organic matter promoted soil biota, which enhanced porosity (López-Garrido *et al.* 2011). Although bulk density assessments prior to annual tillage did not differ significantly between no-till and conventional tillage systems, Nouri *et al.* (2019) observed that cone penetration resistance was greater under tilled systems.

Soil structure and aggregation: Soil structure, defined by the arrangement of soil particles into aggregates, plays a crucial role in water retention and nutrient availability. Lal (1991) emphasized that no-tillage and cover crops improve soil resilience by modifying structural characteristics such as aggregate stability, pore size distribution, and soil ped arrangement.

In cotton-growing regions with loamy soils, Bhattacharyya *et al.* (2015a) observed that mulching with organic residues helped stabilize fine soil particles, promoting better aggregate formation and reducing soil erosion risks. Similarly, Sharma *et al.* (2018a) reported that conservation agriculture (CA) practices involving mulching and minimal disturbance improved soil aggregation in Haryana, which enhanced organic carbon sequestration and reduced erosion. Minimal tillage and herbicide applications significantly improved the geometric mean diameter (GMD) of soil aggregates, highlighting the role of minimal disturbance in maintaining soil stability (Rao *et al.* 2009).

In Gujarat, Patra *et al.* (2016) found that retaining cotton stalk residues increased organic carbon content and microbial activity, which promoted soil aggregation. Studies by Rathore *et al.* (2020) in India and Ferreira *et al.* (2019) in Brazil also showed that crop residue retention improved aggregate stability, leading to better water infiltration and reduced erosion in cotton systems. Better soil aggregation supports both root penetration and soil resilience, essential for the long-term sustainability of cotton cropping systems under CA.

Mitigating climate change involves lowering atmospheric GHG concentrations by addressing emission sources. Soil plays a key role in climate change mitigation and carbon-climate interactions. Intensive tillage practices break down soil macroaggregates, speeding up carbon loss from the soil and increasing GHG emissions. Whereas, CA systems by minimizing or eliminating tillage, enhance carbon sequestration in the soil, decrease gaseous emissions, and support environmental sustainability.

Soil penetration resistance: Weed management practices like mechanical weeding and frequent tillage often increase soil compaction, leading to higher penetration resistance. However, under CA, practices such as herbicide use or mulching help reduce soil compaction. Mitchell *et al.* (2012) found that minimizing soil disturbance in cotton fields in the USA led to more friable soils, lowering penetration resistance and improving root growth and yields.

CA combined with crop residue retention reduced soil compaction in semi-arid regions and mulching helped retain soil moisture and reduced surface sealing, significantly lowering penetration resistance (Ghosh *et al.* 2010). Similarly, minimal tillage with mulching in rainfed cotton fields reduced compaction (Rajanna *et al.* 2015). In the Indo-Gangetic Plains, Kaur *et al.* (2016) noted that residue retention with reduced tillage lowered penetration resistance in cotton-wheat systems by maintaining soil porosity. Similar results in central India were reported by Chaudhary *et al.* (2014), where residue retention improved soil structure and reduced compaction. Long-term CA practices, including residue retention, have consistently lowered penetration resistance (Sarkar *et al.* 2007, Mondal *et al.* 2019).

Rao *et al.* (2013) found that no-tillage combined with mulching reduced penetration resistance, improving water-use efficiency. Similarly, Dahiya *et al.* (2018) and Srinivasarao *et al.* (2014a) observed deeper root growth and improved nutrient uptake due to lower penetration resistance. Penetration resistance increased with depth, it stayed below harmful levels under controlled traffic systems in irrigated cotton, promoting healthy root growth (Bennett *et al.* 2017).

Hydraulic conductivity and infiltration rate: Studies in Africa (Kassam *et al.* 2017) and India (Kumar *et al.* 2020) highlighted that mulching enhanced soil organic matter and reduced surface sealing, leading to better water infiltration. No-tillage systems under CA, paired with effective weed control, improve soil structure and porosity, promoting higher hydraulic conductivity (Blevins *et al.* 2013). These improvements are critical for enhancing cotton yields, particularly in arid and semi-arid regions where water management is essential.

Using cotton stalk residues as organic mulches in CA cotton fields reduced the weed density as well as significantly improved hydraulic conductivity. The increased organic matter from mulches enhanced soil porosity, facilitating better water infiltration and reducing surface runoff Singh *et al.* (2018). In Zambia, Thierfelder and Wall (2010) found that CA plots had significantly higher infiltration rates compared to conventionally ploughed plots in the cotton-maize rotation system.

Soil physico-chemical properties

CA practices like reduced tillage, mulching, and residue retention under CA play a critical role to stabilize pH, reduce salt accumulation, and enhance the soil CEC by increasing organic matter.

Soil pH: Soil pH is critical for nutrient availability, directly affecting cotton growth. Organic residues maintained soil pH close to neutral, optimal for cotton. Crop residues buffer pH fluctuations and enhance microbial activity, which promotes overall soil health (Kumar *et al.* 2017a). In Karnataka, Rajanna *et al.* (2015) observed that reduced tillage and mulching kept soil pH in the 6.5-7.0 range, enhancing nutrient availability in semi-arid rainfed cotton fields. Similarly, Doran *et al.* (2014) reported that organic mulches in Australian cotton fields stabilized soil pH.

Electrical conductivity (EC): Holland *et al.* (2015) found that CA practices kept EC within sustainable limits, improving crop performance, particularly in arid conditions in US cotton-based systems. Crop residue mulching in cotton reduced surface evaporation, maintaining moisture levels and preventing salt accumulation in surface layers (Patil *et al.* 2017b). Singh *et al.* (2019) also noted that no-tillage combined with organic mulching in cotton significantly lowered EC.

Cation exchange capacity (CEC): CEC is a key indicator of soil fertility, reflecting the soil's ability to retain and exchange essential nutrients. In semi-arid ecosystems, Rao *et al.* (2018) observed that conservation tillage combined with residue retention significantly increased soil organic carbon, thereby enhancing soil CEC in cotton systems. Crop residue mulching improved soil CEC in rainfed cotton fields in central India by increasing soil organic matter (Bhattacharyya *et al.* 2015a). Li *et al.* (2013) also demonstrated that CA practices adopted in cotton in China increased CEC, indicating improved nutrient retention due to crop residue accumulation.

Soil organic carbon (SOC) and carbon pools: Weed management practices under CA minimize the soil disturbance and incorporate organic matter and enhance SOC levels. Lal (1997) highlighted the role of SOC in improving soil resilience through enhanced nutrient cycling and aggregation. Govaerts *et al.* (2009) in Mexico and Singh *et al.* (2020) in Gujarat demonstrated that reduced tillage with residue retention improved stable carbon pools, enhancing SOC retention. Similarly in US cotton fields, Franzluebbers *et al.* (2004) noted increases in SOC and stable carbon due to reduced tillage. Lal *et al.* (2015) and Blanco-Canqui *et al.* (2017) found similar results in the United States and Brazil, where reduced tillage and mulching in cotton systems increased SOC, improving soil fertility and long-term carbon sequestration. Conversion of all agricultural land to conservation tillage globally could sequester 25 Gt C over the next 5 decades which is equivalent to 1,833 Mt CO_2-eq/yr, making CA one of the significant opportunities from all sectors for mitigating global GHG concentrations (Baker *et al.* 2007).

Weed management practices also influence carbon pool dynamics. In Punjab, no-till and residue retention enhanced both pools, promoting microbial activity in the labile pool and carbon sequestration in the stable pool (Sharma *et al.* 2017). Similarly, CA practices in Mediterranean and sub-Saharan African cotton systems increased stable carbon pools, highlighting the benefits of minimal soil disturbance on long-term carbon sequestration (Álvaro-Fuentes *et al.* 2009, Six *et al.* 2002).

Herbicide use combined with reduced tillage helped to maintain higher SOC by reducing mechanical weeding and carbon oxidation (Rao *et al.* 2019a). Patil *et al.* (2017b) reported that mulching in rainfed cotton fields increased SOC and labile carbon, promoting soil fertility. Crop residues in cotton fields improved labile carbon, which supports microbial activity, and stable carbon, which contributed to long-term carbon storage (Bhattacharyya *et al.* 2018).

In addition to reducing wind erosion, conservation practices—such as no-till, reduced tillage, and cover cropping—have been shown to decrease net greenhouse gas emissions (Paustian *et al.* 1997). Keeping plant residue on the soil surface helps protect sequestered carbon by minimizing tillage (Schomberg and Jones 1999). Roberts and Chan (1990) observed lower CO_2 emissions in less-intensive tillage simulations compared to more intensive ones. Long-term no-till combined with cover crops can lead to lower soil CO_2 losses, increasing soil organic carbon levels and contributing to the sustainability of cotton production, especially in regions like the Texas High Plains (McDonald *et al.* 2019).

Impact on nutrient availability

Weed management practices in conservation agriculture (CA) have a significant impact on the availability of macro and micronutrients in cotton-based systems by improving nutrient cycling, organic matter retention, and microbial activity.

Macronutrients: Mupangwa *et al.* (2017) showed that crop residue mulching in Southern African cotton systems increased nitrogen availability. Residue retention and no-till practices in India reduced nitrogen losses, improving nitrogen availability (Parihar *et al.* 2018, Nthebere *et al.* 2023). In systems rich in labile substrates, bacteria efficiently decompose organic matter, accelerating nitrogen mineralization (Moore *et al.* 2003, Doles *et al.* 2001). Chivenge *et al.* (2015) reported that mulching boosted phosphorus availability in sub-Saharan African cotton systems through increased microbial activity. Improved phosphorus retention in Indian cotton fields using residue management, especially in phosphorus-deficient soils was noticed by Dwivedi *et al.* (2017). Mwila *et al.* (2018) noted improved potassium availability in Zambia due to steady nutrient release from organic residues. Similarly, Pathak *et al.* (2020) reported that mulching in rainfed cotton systems in India helped retain potassium and reduce leaching. In addition, additional advantages of CA in rainfed systems are reduced nutrient losses along eroded soil with intense rainfall events (Pathak *et al.* 2021). Nitrogen leaching and runoff losses can also be cutdown under CA systems and thereby reducing the need for fertilizer N by 30–50 % (Crabtree, 2010) and has potential to reduce nitrous oxide emissions and mitigate climate change as well.

Micronutrients: Mulching and reduced tillage increased zinc availability in Indian and Ethiopian cotton systems by enhancing microbial activity (Behera *et al.* 2016, Teferri *et al.* 2019). Similarly, Nyamangara *et al.* (2014) found that reduced tillage improved iron availability in Zimbabwean cotton fields. Jha *et al.* (2019) demonstrated that residue mulching enhanced iron availability in India by maintaining soil moisture. Acharya *et al.* (2018), Mbatha *et al.* (2020) both found that CA practices improved copper availability by promoting organic matter retention. Saha *et al.* (2016), Gupta *et al.* (2021) also reported improved manganese availability in cotton systems through mulching and no-till practices, enhancing soil moisture and microbial activity.

Impact of CA in cotton: Reduced GHG emissions, mitigating climate change

In India, conservation agriculture (CA) in cotton based cropping systems could be a vital strategy for climate mitigation, primarily by enhancing the soil's carbon sink, reducing greenhouse gas (GHG) emissions, and minimizing high energy inputs. CA achieves these goals through increased SOC levels and lower CO_2 output due to reduced machinery use. CA practices improve soil nutrient availability, reduce fertilizer needs and thus lowering N_2O emissions. Enhanced soil moisture retention also lowers irrigation demand, saving electricity and reducing associated GHG emissions. CO_2 emissions primarily result from soil tillage and fuel use, crop residue burning, and production of fertilizers and pesticides.

Conservation tillage is particularly effective, as intensive tillage accelerates organic matter decomposition, increasing CO_2 emissions, while reduced tillage slows this process and retains soil carbon (Reicosky *et al.* 1997). Reducing tillage intensity can cut CO_2 emissions and improve carbon sequestration (Reicosky *et al.* 1997). Conservation tillage techniques, such as leaving crop stubble on the soil, help prevent erosion, add organic matter, and conserve moisture (Farooq *et al.* 2011).

Beyond agricultural benefits, CA plays a role in reducing GHGs, enhancing carbon storage, and supporting biodiversity. By enabling gradual sequestration of atmospheric CO_2 into SOC, CA practices stabilize carbon (Pathak *et al.* 2021). In rainfed regions, which cover about 55% of India's arable land and provide around 40% of food production, degraded soils with low SOC and nutrient deficiencies are common. Cotton, widely grown in these dryland areas, benefits substantially from CA practices that improve soil health and sustain productivity.

Impact on soil microbial population, activity and diversity

Soil microorganisms contribute immensely to soil health and quality, and secrete soil enzymes which play a pivotal role in nutrient cycling and transformation in the soil (Wu *et al.* 2016). Application of herbicides manifested adverse effects on non-target organisms including microorganisms such as bacterial, fungal, actinomycetes and free-living nitrogen-fixing organisms *i.e.*, *Azotobacter* and *Azospirillum* (Latha and Gopal 2010). Herbicides may not influence the overall size of the microorganism pool but selectively affect specific groups of biota resulting in modifying the balance of soil microbial populations and consequently nutrient availability, pest & disease incidence and crop growth (Gupta and Roberts 2003). However, Wardle and Parkinson (1990) reported that herbicides may increase or stimulate the population growth of microorganisms and activities given the ability of the microorganisms to utilize herbicides as a source of carbon and other required nutrients.

A study by Chaudhari *et al.* (2020) in a cotton-greengram system showed that inter-cultivation combined with hand weeding (IC + HW) at various intervals significantly increased soil microbial population and activity, particularly when followed by pendimethalin application. The same observations were also reported by Sivakumar *et al.* (2021). Nthebere *et al.* (2024) observed a decline in microbial activity in cotton-maize-Sesbania CA systems due to herbicide application, with recovery noted after 60 days as toxicity decreased. This aligned with the study by Bowels *et al.* (2014) and Jarvan *et al.* (2014). Such patterns suggest that herbicides at recommended rates do not permanently inhibit microbial activity (Lupwayi *et al.* 2004, 2009; Nalayini *et al.* 2013, Tejashree *et al.* 2018). The influence of pre-emergence herbicide diuron was higher in black soils than in red soils on soil bacterial counts (Faizullah *et al.* 2020a).

Conservation agriculture (CA) practices are associated with increased microbial diversity due to reduced tillage, promoting fungal dominance in systems with surface crop residue (Frey *et al.* 2003, Moore *et al.* 2003, Paustian *et al.* 2000, Holland 2004). Blanchart *et al.* (2004) and Six *et al.* (2006) emphasized the role of these organisms in creating stable soil aggregates and organo-mineral complexes. Earthworm activity, in particular, is stimulated by the absence of tillage, leading to reduced physical damage and habitat disturbance (Castellanos-Navarrete *et al.* 2012).

Research has shown that climate change markedly influences microbial community composition and biomass (Ochoa-Hueso *et al.* 2018), enzyme activity levels (Burns *et al.* 2013), and the functional traits of soil microbes (Bai *et al.* 2019). These shifts in microbial communities due to climate change have profound implications for nutrient cycling processes. Yet, most studies have primarily examined these effects in natural or semi-natural ecosystems, leaving significant gaps regarding the impact of climate change on soil microbial communities within agroecosystems (Poll *et al.* 2013). Notably, bacteria within microbial communities exhibit greater sensitivity to water stress, such as drought, compared to fungi (De Vries *et al.* 2012). However, substantial uncertainty remains about the specific effects of climate change on soil enzyme activity.

Soil enzyme activity

Soil enzymes play a pivotal role in energy transfer through the decomposition of soil organic matter, nutrient recycling and are vital indicators of soil health, soil pollution and ecological restoration (Wu *et al.* 2016). In the studies on *Bt* cotton fields treated with various herbicides, it was reported that pendimethalin-treated soils exhibited higher soil dehydrogenase activity (DHA), indicating lower toxicity compared to other herbicides (Atri *et al.* 2006, Veena *et al.* 2010, Tejashree *et al.* 2018). Srinivasarao *et al.* (2014b) observed increased DHA in cotton systems under no-till and mulching practices due to improved microbial conditions in the soil supported from the study by Wang *et al.* (2018) from China. Zhang *et al.* (2015) reported higher urease activity under reduced tillage in Australia. Rao *et al.* (2019b) observed increased urease activity, where crop residue mulch combined with minimal tillage provided a conducive environment for nitrogen retention and microbial activity. Application of diuron as pre-emergence herbicide to cotton significantly reduced the soil urease activity till 30 DAS (Faizullah *et al.* 2020b).

Sharma *et al.* (2018b) found significantly higher phosphatase activity in no-till systems with crop residue retention in Punjab, India, while García-Ruiz *et al.* (2012) observed in Mediterranean cotton fields. In conservation agriculture (CA), Sebiomo *et al.* (2011) reported increased acid phosphatase (AcP) activity in *Bt* cotton treated with pendimethalin, attributed to microbial adaptation to the herbicide. A 46% increase in AcP and a 61% increase in alkaline phosphatase activity under no-till systems, indicating that reduced tillage boosts phosphatase activity (Balota *et al.* 2004). Activity of soil acid phosphatase enzyme was inhibited by the application of diuron where the reduction of activity increased with the increase in dosage of the chemical to cotton crop. While the activity of the alkaline phosphatase remained unaffected (Varsha *et al.* 2019).

Fluorescein diacetate (FDA) hydrolysis, a measure of overall microbial activity, was significantly higher in cotton fields under CA with mulching in Maharashtra (Kumar *et al.* 2017b). This was linked to improved microbial habitat, a finding confirmed by Paz-Ferreiro *et al.* (2011) in Spanish cotton systems under CA, where mulching supported higher microbial activity. Beta-galactosidase activity, crucial for organic carbon turnover, was found to be enhanced by mulching in Indian cotton systems (Bhattacharyya *et al.* 2015b). Kandeler *et al.* (2017) reported similar results in German cotton fields, where reduced tillage and mulching promoted microbial activity and organic matter decomposition.

Climate warming could accelerate enzyme actions (Wallenstein and Weintraub 2008), but it may also reduce enzyme production by soil micro-organisms (Allison *et al.* 2010) and heighten enzyme denaturation (Nottingham *et al.* 2016). Additionally, drought conditions can influence enzyme activity, as microorganisms under drought stress tend to allocate nutrients and energy towards synthesizing osmolytes and maintaining internal stability rather than enzyme production (Schimel 2018).

Effects on SMBC and SMBN

Soil microbial biomass carbon (SMBC) and nitrogen (SMBN) are essential indicators of soil microbial activity and overall health, particularly in conservation agriculture (CA) systems. Yadav *et al.* (2015) from Madhya Pradesh (India) found that IWM significantly increased SMBC and SMBN in cotton systems by providing organic matter from cover crops, while reduced herbicide use minimized microbial suppression. Similarly, higher SMBC and SMBN in IWM-managed cotton systems compared to conventional systems, attributed to increased nitrogen mineralization and carbon cycling (Patel *et al.* 2018). Rusinamhodzi *et al.* (2018) further demonstrated that combining herbicide use with cover cropping enhanced microbial biomass in cotton systems, mitigating the negative impacts of herbicide-only systems. Conversely, continuous glyphosate use, without organic matter input, led to reduced SMBC and SMBN over time (Weaver *et al.* 2007).

Gupta and Roberts (2003) reported that SMBC decreased after herbicide application but increased as the cotton season progressed, suggesting cotton-induced stimulation of microbial activity. Nthebere *et al.* (2024) further supported these results, showing varying effects of herbicides on SMBC. Long-term adoption of CA practices, including residue retention, boosts microbial biomass. Lal (2015) observed significantly higher SMBC and SMBN in Indian cotton systems that had adopted CA for over a decade. Silva *et al*. (2019) reported long-term benefits in cotton systems, highlighting the role of reduced tillage and cover crops in enhancing microbial activity. In India, Srinivasarao *et al*. (2014b), Nthebere *et al*. (2024) demonstrated that no-till practices with residue retention significantly increased SMBC and SMBN in cotton systems, while Bhattacharyya *et al*. (2013) confirmed the positive effects of reduced tillage in rainfed cotton areas. Franzluebbers *et al*. (1999), Das *et al*. (2018) reported similar findings, with no-till and leguminous cover crops like cowpea and pigeonpea significantly increasing SMBC and SMBN in cotton systems.

Several studies have reported metabolic quotient values (qCO_2) *i.e.*, soil organic carbon per unit microbial biomass were higher under herbicides treatments than in the control soils (without herbicide treatment) in cotton CA-based system (Gupta and Roberts, 2003). A reduction in SMBC contents and increase in qCO_2 values generally indicates a stress on the growth of microbial community. As the microbial community recovered from herbicide impacts by the final sampling the qCO_2 values lowered (Nthebere *et al.* 2024).

Weed dynamics and herbicide efficacy changes with climate change under CA

Climate change is marked by rising temperatures and unpredictable precipitation which influence the C_3 and C_4 species differently. In CA systems, where mechanical weed control is limited, dependence on herbicides grows. Herbicide effectiveness varies with factors such as light, CO_2 levels, temperature, moisture, and wind:

Light – High light intensity keeps stomata open, enhancing foliar herbicide uptake. More branching increases surface area for herbicide application, though thicker leaves under high light can impede herbicide diffusion (Riederer and Schoneer 1985).

CO_2 – Elevated CO_2 can reduce stomatal conductance by up to 50%, altering herbicide effectiveness due to leaf thickening and fewer open stomata, which limit penetration. Glyphosate efficacy, for instance, declines in C_4 weeds with increased root-to-shoot ratios under high CO_2 (Ziska 2008, Ziska *et al.* 2004).

Temperature – Higher temperatures can decrease cuticle viscosity, enhancing herbicide absorption, though they may also speed up herbicide metabolism, reducing efficacy (Price 1983, Kells *et al.* 1984).

Precipitation and soil moisture – Low soil moisture, common in cotton-based systems, reduces herbicide uptake due to greater adsorption to soil particles (Dao and Lavy 1978). Moisture stress further limits herbicide diffusion and absorption (Kogan and Bayer 1996).

Soil quality

Soil quality refers to the ability of soil to function within an ecosystem to sustain biological productivity, maintain quality of the environment, and enhance plant and animal health (Doran and Parkin 1994). Soil quality index (SQI) is widely used to assess these aspects, integrating physical, chemical, and biological properties of soil. Agricultural practices, particularly tillage, play a crucial role in influencing these properties, with no-till systems generally showing improved soil structure and overall quality compared to conventional tillage (Mulat *et al.* 2021). Assessing soil quality, especially under conservation agriculture (CA), helps in evaluating degraded soils and understanding changes brought by different management practices (Tesfahunegn 2014). While soil quality cannot be measured directly, SQI provides a comprehensive measure by quantifying soil's physical, chemical, and biological properties. This index relies on appropriate indicators of soil functions, and methods like Principal Component Analysis (PCA) are used to handle data dimensionality (Rezaei *et al*.2006). Numerous studies have demonstrated the positive impact of no-till practices on soil quality, although their effectiveness depends on adequate residue input, which can be limited in low-residue cropping systems (Blanco-Canqui *et al.* 2011, Wang and Shao 2013).

Cover crops offer significant benefits to agricultural ecosystems, improving soil organic carbon (SOC) sequestration, microbial activity, moisture retention, and reducing soil erosion and nutrient leaching. These improvements in soil health and quality are well-documented (Alhameid *et al.* 2019, Nouri *et al.* 2019, Singh *et al.* 2022). Parihar *et al*. (2020) found significantly higher SQI under permanent bed/zero tillage systems compared to conventional tillage, with strong correlations between SOC and other soil parameters.

In a comparative study, Edralin *et al*. (2017) reported better soil quality with adoption of CA compared to conventional tillage. This improvement was attributed to increased soil organic carbon, nitrogen, higher soil moisture retention, and lower soil temperature during dry periods, highlighting the benefits of CA for enhancing soil health. Nthebere *et al*. (2024) noted that, considering both crop productivity and soil quality, IWM was the better weed management option compared to sole chemical weed management resulting in the higher productivity for the cotton-maize system and sustained soil quality. Acosta Martinez *et al*, (2023) found the potential of no-tillage and crop residue mulching to improve soil health in cotton production in semiarid tracts, which are more prone to climate change impacts, and a platform for a soil health evaluation that links different soil health pointers with functions related to soil organic carbon, soil water, and nutrient cycling.

Conclusions

CA practices are essential for enhancing soil health and preventing degradation in cotton-based systems. Weed management practices under CA significantly affect soil enzyme activities, including dehydrogenase, urease, and phosphatase. Herbicides may temporarily suppress microbial activity and enzyme functions, though these effects are often short-lived. Balancing herbicide use with sustainable practices like mulching and crop rotation is crucial to maintain soil quality and productivity in cotton-based CA systems. Further research into the impacts of weed management on the soil microbiome and nutrient cycling is essential to improve the sustainability of these systems. Conservation agriculture (CA) in cotton is a sustainable farming approach that recycles crop residues, uses less water and energy, and reduces global warming. In addition to its benefits as an agricultural development strategy, conservation agriculture (CA) addresses climate change challenges and aids significantly in climate change mitigation. This includes reducing GHG emissions, promoting carbon sequestration, and supporting the conservation of soil biodiversity.

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REVIEW ARTICLE

Weed management under climate change in future grain millets

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ABSTRACT

Climate change is a natural phenomenon in earth's environmental system and used to happen over hundreds or thousands of years, but now it is happening within few decades due to increasing human population and associated activities which are responsible for production of more CO_2, methane, N_2O and small quantities of HFC's. This is expected to increase because the projected global population is 11.2 billion by the end of 21st century from the present 8.1 billion as on 2024. Under climate change, increased CO_2 is seen as an advantage for C_3 food crops but concomitant increase in temperature negated this impact favouring C_4 crop production, hence, most weeds which are C_4 in nature are threat to agriculture production. Unlike C_3 cereal crops which are the staple foods, millets being C_4 have advantage to compete with C_4 weeds and millets are more nutritious and drought tolerant. It is a real challenge to plant scientists to sustain and increase the food production. Hence, in this review an attempt is made to critically evaluate existing literature and provide insights to the researchers and policy makers to promote the millets to meet the food and nutritional security for the ever growing population.

Keywords: Climate change, Millets, Weeds, Weed management, Herbicides

INTRODUCTION

The energy required for all the living beings on earth is provided by an important physiological process called photosynthesis in Plants (autotrophs). During photosynthesis light energy is trapped and used to convert water, CO_2 and minerals into oxygen and energy rich compounds. These energy rich compounds are the source of energy for heterotrophs (humans, animals and all other living creatures).

In the whole process CO_2 is one of the important inputs present in the atmosphere. CO_2 is constantly being exchanged among the atmosphere, Ocean and land surface as it is being both produced and absorbed by many microorganisms, plants and animals. However, emission and removal of CO_2 by these processes tend to balance. But, the industrial revolution began in 1970 changed the balance of CO_2, since human activities have contributed substantially to climate change by adding CO_2 and other heat trapping gases (GHG) like methane and nitrous oxide.

The main human activity that emits CO_2 is the combustion of fossil fuels (coal, natural gas and oil) for energy and transportation to meet the needs of the growing population. In addition, certain industrial processes and land use changes also emit CO_2. Of the 3 important GHG's (CO_2, CH_4 and N_2O), CO_2 concentration substantially increased after the industrial revolution and concomitant increase in global population. According to the EPA, CO_2 accounts for 82% of all GHGs from human activities. The GHGs that impact the gradual warming of the earth's surface are those that stay in the atmosphere for a long period (like CO_2) and build up over time and the warming power of the gas and the length of time it stays in the atmosphere **(Table 1)**.

The atmospheric concentration of CO_2 is 0.04%, CH_4 is 0.002% and N_2O-0.00003%. Although the warming potential of other gases is more powerful than CO_2, its emissions dwarf those of other gases due to its large volume of emissions. Human activities have raised atmospheric CO_2 by 50%, meaning the amount of CO_2 is now 150% of its

Table 1. Global warming potentials and atmospheric lifetimes (years)

Green House Gases	Atmospheric Lifetime	Global warming potential over 100-year lifetime
Carbon Dioxide (CO_2)	50-200	1
Methane (CH_4)	12	21
Nitrous Oxide (N_2O)	114	289
Other	1-50,000	5-22,800

Source: Intergovernmental Panel on Climate Change, 2007 Report

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value compared to the pre-industrial era. This is greater than the natural CO_2 source. It has risen from 280ppm in late 1700's to 419ppm in 2023 and 422ppm in august, 2024. Increase in the amount of GHGs in the atmosphere attributed mainly to human activity, which caused an unbalance in the process called greenhouse effect. Hence, slowly the availability of the earth's atmosphere to absorb heat from the subsurface has increased and with it the temperature of the atmosphere. This is known as "Global warming".

Millets are a small grain which are predominantly grown and consumed after cereals in the world especially in Africa and Asia (Mishra 2015). There are an estimated 1.2 billion people who consume millet as a part of their diet [WFP]. Millet is a staple and it is a very good substitute for oats and cereals. Millets are rich in minerals and vitamins and pearl millet is a rich source of proteins. Another millet finger millet, is the only food grain which has 320 to 344 milligram Ca^{2+} for 100 gram of grain. Millets have a higher nutritional profile that ensures better health benefits (NAAS 2013). India is the World's largest producer of millet following China and Nigeria, and supplies 41% of global output (Kumar *et al.* 2019). The millets commonly grown in India include Sorghum, pearl millet, finger millet, barnyard millet, proso or common millet, foxtail/ Italian millet, kodo millet, little millet etc. The area, production and yield of millets in India is presented in **Table 2**.

The area under cultivation of millet declined due to a change in conversion of irrigated area for wheat and rice cultivation. Hence, unavailability of millets, low yield, change in consumption pattern under dietary habits resulted in fall in the levels of vit-A, protein and iron that lead to malnutrition. Millets occupy a relatively lower position in Indian agriculture, though they are important from the point of food and nutrition security, especially quality of food.

Millets are best options under hot and dry conditions compared to the cereals and predominantly grown in rainfed conditions. The key issue is controlling weeds, since during the rainy season there will be increased soil moisture and relatively high temperature that will favour the weed growth. The competition for resources (sunlight, water and nutrients) between crop and weed can result in lower yield and lower quality crops (Mishra *et al.* 2018). Higher growth of weeds may impede harvesting, increasing its difficulty and duration (Mahalingam *et al.* 2019).

Table 2. Area, production and productivity of millets in India (2022-23)

Crop	Area (m ha)	Production (mt)	Productivity (kg/ha)
Pearl millet	7.57	11.43	1510
Sorghum	3.54	3.81	1079
Finger millet	1.16	1.69	1454
Other minor millets	0.43	0.38	898
Total	12.70	17.32	-

(Source**:** https://www.indiastat.com/table/agriculture/season-wise-area-production-yield-nutri-cereals-in/1210178)

The management of weeds is very crucial to prevent the resource acquisition by weeds which are otherwise meant for crops. The yield loss due to weed can range from 15 to 97% (Dubey *et al.* 2023) in millets due to increased temperature and change in precipitation pattern (Vikarm *et al.* 2021 and Xiaoyan *et al.* 2018). In addition to this climate change can affect the efficacy of herbicides, by breakdown and effectiveness of herbicides. This needs change in use of alternative herbicides. So far, the findings suggest that, holistic approach is required to effectively control weeds to sustain the millet productivity.

Millets are termed as the "miracle grains" or "crops of the future", as they are not only grown under harsh conditions but are drought-resistant crops with fewer inputs. They are dual-purpose crops as they provide both food and fodder providing food security and economic efficiency of farming. Millets will contribute to mitigating climate change by reducing CO_2 in the atmosphere, whereas wheat being a thermally sensitive crop and paddy is a major contributor of climate change through Methane emission. Normally do not depend on use of chemical fertilizer and attract less pests and have a high nutritive value. Millets are superior to rice in terms of nutritional benefits. They are rich in fiber, protein, Vitamins and minerals and have a higher antioxidant content than rice. In fact, foxtail millet and kodo millet are suggested as substitutes for rice. And finger millet is a great substitute for Rice and Wheat for diabetes. And also millets help in curling obesity, lowers the risk of hypertension, cancers, helps in preventing constipation and have low glycemic index. Realizing the importance of millets **(Figure 1)** both from the point of food and nutrition security, Indian government has initiated a program "Initiative for nutritional security through intensive millet promotion-INSIMP a part of Rastriya Krishi Vikas Yojana-RKVY. And Indian government proposal to FAO in 2018, finally accepted by the United Nations General assembly and declared 2023 the "International year of millets".

Weeds under millets cropping systems

Climate change is one of the most important aspects that can cause alterations in weed

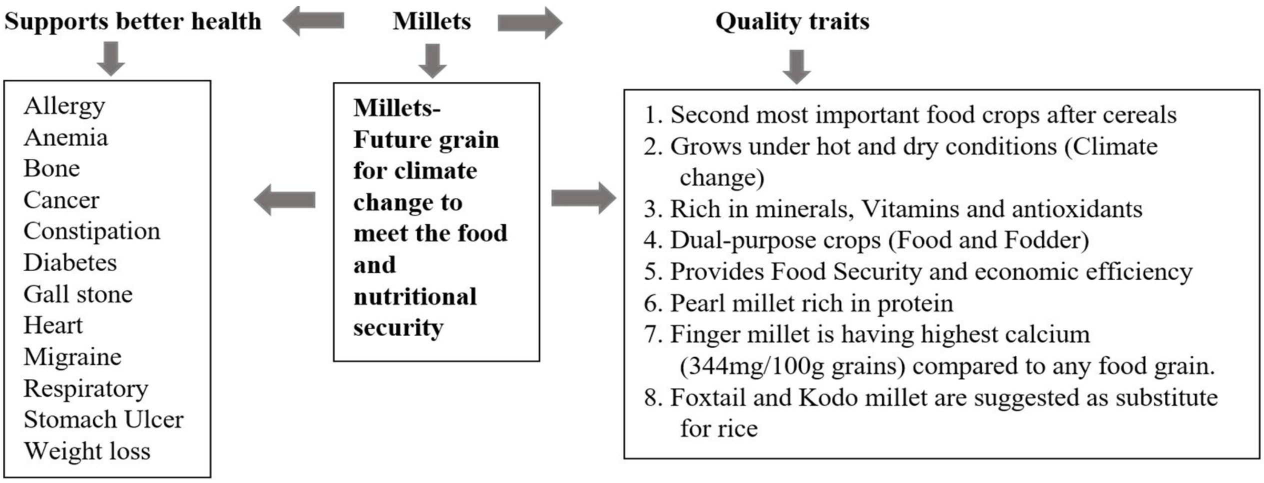

Figure 1. Quality attributes and health benefits of millets (Source: Shankar and Geetha, Unpublished data)

composition, growth, physiological development and infestation pressure. Under the circumstances many weeds may become aggressive and a few weed species may become inactive so that weeds with less phenotypic plasticity may experience population decline. The distribution of weeds depends on prevailing climate, management activities in neighboring fields, crop rotation and soil composition. Soil type is a major factor in deciding the type and variety of species growing in a particular area.

For most weeds the ideal temperature ranges from 10 to 35 °C. Initially when CO_2 levels started increasing, the scientists are of the opinion that food production will be enhanced because out of the top 15 food crops 12 are C_3 plants. C_3 plants are at an advantageous position over C_4 plants. Subsequently it was realized that there is a concomitant increase in temperature which changes the complete scenario of CO_2 fertilization impact on crop production (Jordan and Ogren, 1984, Osmond *et al.* 1982, Morgan *et al.* 2001). Weed - crop interaction has changed due to global climate change. The advantage envisaged for C_3 crops is nullified because of increase in temperature. Since, optimum temperature for photosynthesis is higher for C_4 (30-45^{o}C) than C_3 (10-25^{o}C) and more top millet weeds are C_4 **(Table 3)** and parthenium and striga weeds are C_3.

Weed infestation in agricultural field is one of the important biotic components hindering plant growth and productivity. They compete with cultivated crops for sunlight, water and nutrients etc. (eg: *Amaranthus Chenopodium*, Gajar Ghas *etc.)* and grow vigorously than crop plants. In addition, they harbor insects and pathogens, which attack crop plants. Weed infestation alone can reduce 50%yield in some crops. The total actual economic loss of about US$ 11billion was estimated due to weed alone in 10 major crops of India (and highest being in Rice US$ 4420 million).

Table 3. Major C4 weed species found in millets

C4 weeds	References
Cynodon dactylon	
Cyperus rotundus	Dhanapal *et al.* 2015;
Dactyloctenium aegyptium	Shubhashree &
Digitaria marginata	Sowmyalatha 2019;
Echinochloa crus-galli	Lekhana *et al.* 2021;
Euporbia hirta	Sukanya *et al.* 2021;
Elusine indica	Gurubasavaswamy *et al.*
Imperata cylindrica	2023
Monochoria vaginalis	
Elusine indica	

Climate change can also play a crucial role in weed distribution of both invasive and noxious weeds (Hakala *et al.* 2011) because it changes precipitation pattern and water availability (Rodenburg *et al.* 2011). Weeds are relatively constant and cause negative effects on agriculture, unlike other biotic stresses like insects and pathogens, which are random and irregular (Kostov and Pacanoski, 2007). Weeds can also cause extensive damage to non-agricultural land and to public health. Furthermore, weeds are known to produce harmful chemicals and serves as hosts for several insects pests and diseases (Swinton *et al.* 1994, Boydston *et al.* 2008).

Herbicides

Herbicides are commonly known as weed killers, are substances used to control undesired plants. The commonly used herbicides are alachlor, octachlor, butachlor, metachlor and propachlor. Most of them are hazardous except metachlor. There are 2 types of herbicides: selective (retard the growth of some plants) and non-selective (toxic to all plants). Herbicides are routinely applied because of their simplicity in use and greater efficacy (McErlich and Boydston. 2013). Glyphosate (N-Phosphonic methyl glycine) is a broad-spectrum herbicide that is absorbed by plant leaves and is systematic (translocated) within the plant. Glyphosate also known as the "Roundup" is the most widely used herbicide in the US. Nearly all herbaceous plants and most woody plants are susceptible to glyphosate which inhibits synthesis of 3 aa's necessary for plant growth. A large number of different classes of herbicides inhibits photosynthesis. 2, 4-Dichlorophenoxyacetic acid (2,4-D) is a common systemic herbicide used in the control of broad -leaf weeds. It is the most widely used herbicide in the world.

Crop-weed competition under climate change

Weeds tend to have higher genetic diversity and physiological plasticity than crops, allowing them to exhibit resilience and adapt better to changing CO_2 levels and higher temperature, often competing crops. Among various biotic factors, weeds cause the most substantial yield loss (34%), surpassing insect pests (18%) and diseases (Kaur *et al*. 2024). Climate change is having different effects on C_3 and C_4 photosynthetic pathways, modifying the dynamics of composition between crops and weeds. It has resulted in yield loss of 183 kg/ha in rice and 88 kg/ha in wheat (Waddington *et al*. 2010). The competition between weed and crop for limited resources such as water, light, space and nutrients leads to reduced growth, hindered development and yield losses in crops (Kaur *et al.* 2014). The positive effects of increased CO_2 on most crops are offset by high temperature, with no benefits observed for C_3 crops **(Table 4)**.

Weed management in millets

Millets are considered as "climate smart crops" since they are hardy and survive in high temperature and resistant to climate change. Weeds cause substantial crop losses particularly in less developed countries. Increase in temperature due to global climate change and high CO_2 concentration in atmosphere are likely to have a significant impact on weed biology and weed pressure which in turn will reduce crop productivity. Millets predominantly grown in rain-fed condition and nutrient deficient soils, face the risk of yield losses due to intense weed competition. So far several methods are followed to manage weeds in millets (Dubey *et al*. 2023). Agdag 1995, reported that narrow spacing (<30cm) in prosomillet found to increase the yield and within a crop varietal variation exists. Planting sorghum at higher densities (7.5 plants per meter) reduced weed density of *Echionochloa esculenta*.

Mishra *et al*. (2012) reported that the weed competitive cultivars in sorghum hybrid (CSH-16) out performed weeds by limiting the light availability. The intercropping rather than solo crop increases the usage of natural resources and superior weed control efficiency (65.8%), weed smothering efficiency (52%) and reduced weed dry weight in pearlmillet + black gram and finger millet and onion and increased yield (Vishalini *et al*. 2020). Cultivation of diverse crops season after season and leaving land fallow can suppress weeds to certain extent (Barberi and Lo Cascio 2001). Arora and Tomar (2012) reported soil solarization for 4-6 weeks is the most effective non-chemical and agronomical weed management practice for lowering weed seed bank.

Mulching inhibits penetration of sunlight to the soil slowing or preventing seed germination and growth of weed. It is more effective on small seeded annual weeds and perennial weeds such as *sorghum halpense* and *cynodon dactylon*. The striga weed (C_3 type) can be controlled by applying synthetic analogues of 'strigol' and 'strigol acetate', natural chemical stimulants suppresses weed growth. Preplant incorporation of analogues reduced 50% striga population in sorghum and ethylene treatment resulted in 90% reduction in striga seed bank (Das 2016).

Table 4. The response of C3 and C4 crops with C3 and C4 weeds under climate change scenario

Types of crops	Ambient CO_2	Climatic parameters		
		High CO_2 (> ambient CO_2)	High t°C (> ambient t°C)	High CO_2 + high temperature
C_3 crops alone	Normal	Better than C_4	No response /?	No response /?
C_4 crops alone	Better than C_3	No response	Better than C_3	Better than C_3
C_3 crop + C_3 weed	Reduced crop growth	C_3 crop better than C_3 weed	C_3 crop growth reduces	No response /?
C_3 crop + C_4 weed	Weed dominates C_3 crop	C_3 crop dominates	Weed dominates	Weed dominates
C_4 crop + C_3 weed	Better growth of C_4 crop	Weed dominates /?	Crop dominates	Crop dominates
C_4 crop + C_4 weed	No response /?	No response /?	Weed dominates	Weed dominates
C_3+ C_4 weeds in C_3 crop	No response /?	C_3 crop dominates	C_4 weed dominates	C_4 weed dominates
C_3+ C_4 weeds in C_4 crop	No response /?	C_3 crop dominates	C_4 weed dominates	C_4 weed dominates

Among the physical (mechanical) methods of weed management, tillage is known to influence the dispersion of weed seeds and propagules through the soil profile and in a rainfed pigeon pea + finger millet cropping system, a considerable reduction in weed density is reported by Vijamahantesh *et al.* 2013. Kujur *et al.* 2018, reported hoeing twice between rows significantly reduced the density and dry matter of weeds in finger millet. Hand weeding which is costlier than chemical weeding is found to be effective in suppressing annual weeds but not perennial weeds (Thanmai *et al.* 2018, Gowda and Dhanjaya 2000).

Chemical weed management

Weed control using herbicides found to be simplest way and cost effective yet environmental issues need to be taken care. However information on weed control in small millets is limited because scarcity of herbicides in millets (Vanderlip *et al.* 1998). Atrazine is found to be successful pre-emergence herbicide in millets (Ramesh *et al.* 2019) and Vinothini and Arthanari (2017) also reported Isoproturon, a pre-emergent controlled the weed density in Kodo millet. Integrated weed management of herbicides spray in combination with one hand weeding found to be effective in weed control in millets for example in Sorghum, Pearl millet and Kodo millet (Deshveer and Deshveer 2005, Girase *et al.* 2017, Lekhana *et al.* 2021 and Thambi *et al.* 2021).

Management of weeds in millets under climate change

Climate variation on weed growth

In the beginning of global warming, scientists were very enthusiastic feeling that the higher levels of CO_2 in the atmosphere (termed as CO_2 fertilization) can act as a fertilizer and increase plant growth because most of the crop plants are C_3. Similarly, they thought there will be an advantage for C_3 crops to compete better with weeds, since most of the weeds are C_4. The studies conducted to manage weeds in millet fields are summarized as below. Pre-emergence application of Atrazine at 0.5 kg/ha + one hand weeding at 35 days after sowing and the post-emergence application of atrazine 0.4 kg/ha +one hand weeding at 35 days of sowing gave best control in pearl millet (Girase *et al.* 2017). In case of Kodo millet, research revealed that post-emergence herbicide application of bispyribac sodium 20 g/ha on 20 days after transplant had controlled weeds of all kinds in transplanted kodo millet Jawahar *et al.* (2020).

In *Kharif* (2018), in a transplanted finger millet, an experiment was conducted to evaluate the weed control in the field. The results showed that the pre-emergence application of biosulfuran-methyl 0.6G at 60 g/ha + pertilachlor 6G at 600 g/ha followed by early post-emergent application of bispyribac-sodium 10SC at 25 g/ha had the lower total weed density, total weed dry weight and greater Weed Control Efficiency. Ramadevi *et al.* (2021), reported greater grain production was obtained by applying 20 g/ha of phenoxsulam post-emergence (PoE) in transplanted finger millet. Applying isoprotaron 750 kg/ha prior to emergence and manual weeding 40 days post-sowing resulted in weed density & dry weight below the economic threshold (Vinothini and Arthanari 2017).

Elevated CO_2 and temperature

Climate change is the result of both increased CO_2 concentration and increased temperature. Weeds being C_4 plants have better adaptation to heat stress, due to high water use efficiency (Osmond *et al.* 1982, Long 1999, Morgan *et al.* 2001). Differential impacts of climate change variability such as temperature regimes, CO_2 and temperature levels on weeds and crops allows weeds to compete well and thrive even in unpredictable environments (Hartfield 2011). It is also reported that higher temperature enhances mineralization processes that increase the nutrient availability to plants (Beier 2004, Schmidt *et al.* 2002). Prolonged drought leads to dehydration of roots and reduced soil nutrient mobility impede root activity and nutrients uptake (Hinsinger *et al.* 2009). Dynamics of nutrients between crop and weeds is also influenced by elevated CO_2 (Zeng *et al.* 2011).

Weeds are managed by several ways. Of these, herbicides application for weed management is cost-effective and more reliable method. But, under climate-change scenario, elevated levels of CO_2 high temperature, precipitation, Relative humidity and solar radiation are the factors that alter the herbicide efficacy. High CO_2 and high temperature have contrast effect on herbicide entry through the leaf and translocation to the weed plants. Under high CO_2 more biomass produced by weeds may cause dilution effect and lower the efficacy of herbicide. Similarly roots grow deeper into soil layers preventing the uptake of herbicides which are present in the surface and top layer of soil (Manea *et al.* 2011). Whereas, under high temperature enhances the root uptake of herbicides due to a decrease in soil organic matter and high evaporation rates (Miraglia *et al.* 2009)

Reduction in stomatal conductance (around 50% in some plants) and leaf thickening which causes stomatal closing and increase in leaf starch concentration due to elevated CO_2 in weeds helps them to survive from post-emergence herbicides (Ziska 2008, Jackson *et al*. 2011). On the other hand, high temperatures are known to alter and lower the viscosity of cuticular lipids which in turn influences the permeability and diffusion of herbicides through the cuticles. Other temperature dependent processes such as phloem translocation, respiration and protoplasm streaming in plants will affect the efficiency of herbicides under high temperature. Not only above ground temperature, even high soil temperature causes decrease in permeability, increasing volatility and microbial breakdown affecting the efficacy of herbicides. For example at high soil temperature (25^{o}C), triallate volatilization increased from 14 to 60% in sandy and 41 % in loamy soils (Atienza *et al*. 2001). These studies suggest that increased dose or number of applications of herbicides may become the order of the day in the future under climate change scenarios.

Precipitation and relative humidity

Global climate change influences precipitation patterns and Relative humidity. These two parameters accompanied by warmer temperature leads to extreme drought and as well flooding (Clements *et al*. 2014). Intense rainfall immediately after herbicide application may dilute the concentration by washing off spray droplets and reduce herbicide retention on leaf and uptake. On the other hand lower precipitation will enhance uptake by rewetting the dried spray droplets on the leaf surface (Olesen and Kudsk 1987) and lower the translocation and decreased transpiration within the plant lowers herbicide efficacy (Zanatta 2008, Keikothaile 2011). All pre-emergence herbicides require optimum moisture in the soil for active absorption of herbicides (Olson *et al*. 2000). Dry conditions increase the adsorption of herbicides on soil particles, which will be eventually washed off due to heavy rainfall leading to heavy loss due to leaching (Soukup *et al.* 2004).

Though optimum relative humidity is desirable at the time of spraying, at high relative humidity stomatoes remain open and helps in better uptake of herbicides into the leaf (Kudsk *et al*. 1990). Studies have shown that relative humidity could exert greater influence on the uptake of foliar sprayed herbicides than temperature (Devine *et al*. 1993, Anderson *et al.* 1993). Most of the studies suggest that high temperature accompanied with high relative humidity is beneficial for weed control by most herbicides (Stopps *et al.* 2013).

Solar radiation

Solar radiation is an important determinant, it is not only critical for plant growth and development but also important for herbicide efficacy, since it facilitates the entry of herbicide through stomata and translocation of herbicides within the plant and target sites for actions. Several herbicides such as Bentazon, Clethodim and Talkoxydim showed higher efficacy of herbicides (Hatterman-valenti *et al.* 2011). In some cases, solar radiation may directly affect the chemical properties of herbicides through photodegradation. For contact herbicides light is crucial for activation of herbicides and to increase efficacy (Wright *et al.* 1995) For example paraquat (contact herbicide) efficiency decreased as UV radiation increased. This may be due to increased wax content as a mechanism by plants to prevent UV damage resulting in lower absorption and efficacy (Wang *et al.* 2006).

In the crop-weed competition enhancing the high interception by crop and thereby reducing the amount of the light reaching the land surface is one of the approaches, which can be manipulated by crop orientation (Borger *et al*. 2015, Holt 1995).

Millets being photo-insensitive, they can adapt to different environmental conditions, hence they are resilient to climate change. But, millets are having slow growth initially, they can't suppress weeds unless they adequately grow to shade the weeds (Mishra 2015). Hence optimising spacing between rows is very crucial, since large rows results in higher penetration of light to the soil surface favouring weed growth. Some findings suggested narrow row spacing results in higher productivity of finger millet by suppressing weeds (Fufa and Mariam 2016, Chavan *et al.* 2017).

Another cultural practice could be growing intercrops which facilitates better utilization of natural resources by crops and reducing the availability to weeds. Similar results can be obtained by increasing the seed rate, so that the crop can dominate over the weeds because of a higher population (Vishalini *et al.* 2020, Kumar *et al.*2019, Dubey *et al*. 2023, Hozayn *et al.* 2012). Any management practices that lead to faster canopy cover of the crop will substantially decrease weed germination (Locke *et al*. 2002). Vishalini *et al.* (2020) reported that intercropping of finger millet with onion increased weed control efficiency and yield and the same results found in intercropping of pearl millet and blackgram (Mathukia *et al*. 2015) and also with legume intercropping such as mungbean, cowpea, soybean and groundnut. Yet another option is mulching, which reduces light penetration to the soil surface and exerts a smothering effect on weeds (Teasdale and Mohler 2000, Kaur and Singh 2006).

Climate change is known to enhance the intensity of both flooding and drought globally (Bannayan *et al*. 2011; Challinor *et al*. 2014). To manage these situations which vary depending on the location and types of cultivation (Etana *et al*. 2022), shifting (pre or postponing) sowing date is also a type of management (Liu *et al*. 2020) strategy to prevent synchronization of crop critical growth stages (Mulla *et al*. 2019).

Weed competitive cultivars

The crop varieties selected to compete with weeds should possess competitive potential traits, which can grow faster, have canopy structure, ability to acquire and efficiently use light, moisture and nutrients better than weeds or release allelochemicals to prevent the germination of weeds (Peerzada *et al*. 2017, Buhler 2002; Stahlman and Wicks 2000; Gholami *et al*. 2013, Mishra *et al*. 2015). For example, CSH-16 sorghum hybrid known to suppress weed (Mishra *et al.* 2015). Several striga-resistant varieties/lines are developed by ICRISAT for Africa and Asia, S1561, S1477, S1511, IS 6961, IS 7777, IS 7739, IS 14825, IS 14928, Framida and P 967083. The mechanism here is to prevent attachment of striga to the plant through reducing stimulant production.

In addition to these interventions to control weeds in the future, attempts are made to develop herbicide resistant millet cultivar. In China, attempts are being made to develop novel herbicide-resistant millet varieties/hybrids by millet breeders (Darmency *et al*. 2017). But it is time consuming and laborious. The alternative would be to employ biotechnological/ molecular breeding approaches to develop herbicide-resistant cultivars. Already canola, soybean varieties and corn hybrids which are resistant to herbicides are developed. At the same time, it is important to follow herbicide rotation to prevent weeds developing resistant to a particular herbicide. It may not be an immediately feasible approach since the Indian Government is yet to permit growing of genetically modified crops. Till that time, one can explore gene editing and CRISPR-cas9 technologies to develop herbicide resistant cultivar (Rich *et al*. 2004; Haussmann 2004; Makaza *et al*. 2023).

Conclusion

Global climate change has already resulted in several uncertainties in agriculture production. More or less precipitation and increased temperature are certain and order of the day in future. These events are going to be much more frequent and intensive in the future that questions the capability of sustaining food production for ever increasing global population. Weed management also seems to be more crucial in days to come under climate change scenarios to sustain food production because increased CO_2 and high temperature tend to favor growth of weeds (C_4) compared to crops (C_3). This scenario is not different either with the production of millets, which are suggested to be substitutes for cereals. Because millets were hitherto considered as poor man's crops not given as much attention as in the case of cereals in managing and attaining higher productivity. In recent years, they are paid attention not only to sustain hunger but also to meet nutritional requirements since they are richer in protein (pearl millet), minerals, vitamins and antioxidants than cereals. Millets are C_4 similar to weeds, hence they can compete and thrive under climate change scenarios better than C_3 cereals. They are considered an alternative crop for the climate change condition. In fact many farmers in India already switched over to short duration, less water requiring and climate change resistant millet crops over rice, wheat and corn. Limited information suggests the herbicide application is crucial to manage weeds even in millets notwithstanding the environmental impact. Task before scientists is not only to develop herbicide resistant crops but also avoiding development of resistance in weeds. A comprehensive research program is required to understand the biology and distribution of weeds under climate change and the efficacy of herbicides to control weeds in millet crops and it is very crucial to sustain the future grain for human population.

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REVIEW ARTICLE

Climate change effect on the efficacy of biological control agents of terrestrial and aquatic invasive weeds

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ABSTRACT

Climate change may affect the weed biology and ability to thrive well in adverse situations in comparison to biocontrol agents used to manage these weeds though biological control methods. The complex interactions between invasive terrestrial and aquatic weeds and their biocontrol agents have challenges under climate change scenarios. Increased climatic parameters like temperature, CO_2 and rainfall have been documented well for increasing the fitness of terrestrial and aquatic weeds in different areas. Some studies have also pointed out the effect of elevated temperature, CO_2 and rainfall on the insect life-cycle and their performance to manage the invasive weeds by the biocontrol agents. Many prediction models based on climatic parameters have been developed in context to the distribution and range expansion of terrestrial and aquatic weeds and also suitability of their biocontrol agents to manage them. In this review, we synthesize and discuss studies describing the potential of biocontrol agents for the management of invasive terrestrial and aquatic weeds under climate change in context to India and the world as well. We also discuss potential methodologies of prediction models that can be used for the fast establishment of biocontrol agents against the invasive weeds under climate change.

Keywords: Aquatic weeds, Biocontrol agents, Biological control, Climate change, CO_2, Invasive weeds, Weed biology

INTRODUCTION

Alein invasive weeds are plant species when introduced to new environments, rapidly multiply and replace native species, causing ecological, economic, and social damage due to unbeatable attributes like rapid growth, high seed production, and environmental adaptability. Species like *Cirsium arvense, Lantana camara, Parthenium hysterophor*us, *Eichhornia crassipes, Pistia stratiotes, Salvinia molesta etc.* exemplify this disturbance. *Lantana camara* forms dense thickets that displace native plants and alter fire regimes in tropical forest areas. *Parthenium hysterophorus*, once a weed of non-cropped areas, has become a major weed of cropped areas (Sushilkumar 2014) while *Cirsium arvense* competes with crops and native species for resources in temperate zones. Water hyienth in water bodies develops dense mats on water surfaces, blocking sunlight and oxygen, severely impacting aquatic ecosystems, fisheries, and recreational activities besides being a cause of several drowning cases of men and animals in India and elsewhere (Dar *et al.* 2019, Yigermal and Assefa 2019, Sushilkumar 2011, 2012, 2022). These invasive weed species reduce biodiversity, degrade habitats, and disrupt ecosystem functions in both terrestrial and aquatic environments globally.

Methods like manual or mechanical removal and herbicides are expensive, environmentally harmful and often ineffective on a large scale. Biological control has gained popularity as a more sustainable and eco-friendly solution for managing invasive weeds. Introduction of coevolved natural enemies from an invasive species' home range (classical biological control) has been one of the key methods for suppressing invasive species (McFadyen 1998, Moran *et al.* 2005, Messing and Wright 2006). Biological control uses natural enemies like insects, pathogens, competitive plant species, nematodes or herbivores to manage invasive species through eating, killing or competition. Host specific biocontrol agents are carefully chosen from the native range of weeds to introduce in other countries where that type of weeds has become a menace or to introduce known and proven bioagents from other countries to target invasive weed without harming native plants, animals, or ecosystems (Sushilkumar 2015). Biological control has effectively managed invasive species such as *Opuntia* (prickly pear cactus) from India and many other counties (Sushilkumar 2015) including from South Africa, where *Dactylopius opuntiae*

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(cochineal insect), controlled its spread (Kudakwashe 2021). For aquatic weeds like *Eichhornia crassipes*, bioagent *Neochetina eichhorniae* targets the plant's stems and roots, reducing its growth and expansion. Similarly, *Cyrtobagous salviniae* have been introduced to control *Salvinia molesta* in regions like Southeast Asia including India and Australia, feeding on its fronds to limit its spread (Sushilkumar 2015). These examples highlight the success of biocontrol agents in managing invasive species world over by targeting their specific weaknesses. Success stories of weed biological control in India have been dealt by Sushilkumar (2022).

Biological control offers several advantages over traditional methods, including long-term, self-regulating management of invasive weed species. Once established, biocontrol agents can maintain populations in response to changes in weed numbers, reducing the need for continuous intervention and minimizing environmental risks from chemicals or mechanical methods. It is also more cost-effective for large-scale weed control, especially in resource-limited countries. However, the success of biological control depends on environmental factors, including climate conditions, which affect the survival, reproduction, and efficacy of biocontrol agents. Therefore, climate change may significantly impact the effectiveness of biological control strategies.

Climate change significantly impacts the spread, distribution, growth and ecological impact of invasive weeds in general and alien invasive weeds in particular. Rising temperatures, changed rainfall patterns and increased atmospheric CO_2 can increase the invasiveness of weed species, which in turn disrupt ecosystems, threaten native biodiversity, and cause economic losses in cropped, non-cropped and forest areas. There is prediction of increase of global temperatures which may exceed 1.5°C during 2021 to 2040, particularly under high-emission scenarios (Bacchin *et al.* 2023, IPCC 2023). It has been projected that CO_2 concentrations may increase two to four times higher than those observed in the last 0.8 million years without significant mitigation efforts. This may lead unprecedented climatic changes (Raviraja 2023). According to the Intergovernmental Panel on Climate Change (IPCC), the global atmospheric CO_2 concentration may rise to 730-1000 µmol/mol by the end of the 21st century (Varanasi *et al.* 2015). Further, if emissions remain unchecked, global temperatures could rise by 3.6 to 4.4°C by the end of the 21st century (Adak *et al.* 2023), which may cause severe consequences for, food security, human health and water availability.

Simberloff (2012) opined that climate change may also influence weeds and natural enemy's species interactions, and biological control agents effectiveness by causing changes in their life-cycle and distribution. Climate change can shift interactions of invasive weeds and biocontrol agents which may cause risks to non-target species (Simberloff 2012).

With the growing concern of climate change and weed invasions, there has been an increase in studies on climate change effects on biocontrol agents, however, our understanding of the response of these plant-herbivore interactions to the full complement of climate-driven changes are still elementary. The aim of this paper is to review the available information of climate change effects on weed biocontrol agents apart from some insight on effect on invasive weeds.

Climate change impacts on terrestrial invasive weeds

Clements and Ditommaso (2011) interpreted those rising temperatures, altered precipitation patterns, and an increase in extreme weather events will likely to facilitate the spread and proliferation of invasive weeds, allowing them to expand into new regions and become more abundant and harmful to the existing ecosystems. Rising temperatures increase growing seasons, accelerating growth and seed production, while enabling weeds to colonize in higher altitudes that were previously unfavorable (Clements and Jones 2021). *Parthenium hysterophorus*, an invasive species in Asia, Africa, and Australia, thrives in disturbed soils and regions with low rainfall. The increase in temperatures and atmospheric CO_2 levels has enhanced its germination and spread, particularly in the cooler regions, where it poses a significant threat to agriculture and public health due to its toxic nature and allergenic pollen (Mao *et al.* 2021).

Chromolaena odorata, native to America, has also spread into parts of Africa and Asia as a result of climate-induced changes in temperature and precipitation (Adhikari *et al.* 2023). This weed has been reported to increase its spread from South India to Central and North India through Chhattisgarh and Madhya Pradesh (Sushilkumar 2015). Likewise, *Mikania micrantha* was never encountered in Central India, but its recent occurrence in Sarni village of Betul district of Madhya Pradesh and near Talpuri lake of Durg district of Chhattisgarh is an indication of its expanding range due to climate change (Sushikkumar, personal observations).

Lantana camara, native to Central and South America, has become a major invasive species in tropical and subtropical regions, forming dense thickets that displace native vegetation and alter fire regimes. Rising temperatures and changing rainfall patterns have accelerated its spread in Africa, Asia, and Australia, complicating biocontrol efforts by increasing its density and resilience (Dar *et al.* 2019). *Carduus nutans*, an invasive weed, has become more aggressive due to warmer temperatures and higher CO_2 levels. These conditions enhance its growth and seed production, increasing competition with native plants and crops, and complicating biocontrol efforts by agents like the *Rhinocyllus conicus* weevil (Keller 2019).

With the increase in temperatures, many invasive weeds may extend their growing seasons and expand their geographic ranges, moving into areas that were previously too cold. For example, earlier *Ageratina adenophora* (Crofton weed) and *Lantana camara* (Lantana) were observed to invade higher altitudes and new temperate zones but hot temperatures now support their growth and reproduction. This tendency has caused the invasion of Lantana for cooler and temperate reasons world over. Such shifts enable these species to invade new habitats and outcompete native flora adapted to cooler climates (Bradley *et al.* 2010, Hulme, 2016).

Increased CO_2 can increase the growth rate, biomass, and reproductive output of species like *Bidens pilosa* (black jack) and *Ipomoea purpurea* (morning glory), allowing them to replace native plants (Ziska and George 2004). Climate change in the form of droughts can benefit drought-tolerant invasive terrestrial weeds like *Chromolaena odorata* and *Parthenium hysterophorus* at the expense of native species that may not be resilient as of them (Sushilkumar 2015).

Climate change has contributed to increased fire frequencies. Lantana has been found responsible for many forest fires in India. This accelerated the spread of Lantana after forest fires in the barren land devoid of other native vegetation. Weeds like *Parthenium hysterophorus* are becoming more difficult to manage in crop fields as climate change extends their growing seasons throughout the year and enhances their resilience. These factors affect crop yields and increase the costs associated with weed management, such as herbicide applications and labor (Sushilkumar and Varshney 2009). Ziska and George (2004) opined that although some aspects of climate change may be viewed as advantageous, the rise in atmospheric CO_2 is not selective as it stimulates the growth of both wanted and unwanted plants.

Effects of climate change in aquatic invasive weeds

Aquatic invasive weeds spread and establishment in new areas may be altered by flood or increased drought. Rahel and Olden (2008) reported that *Cabomba caroliniana* (Carolina fanwort) and *Typha angustifolia* (narrow leaf cattail) benefitted from altered water regimes, allowing them to spread in new or expanded waterways. Similarly, *Salvinia molesta* has expanded its range from its native areas into regions such as India, Southeast Asia, and Australia, driven by rising temperatures and fluctuating water levels. This invasive fern forms dense mats on water surfaces, blocking sunlight and oxygen, which disrupts aquatic ecosystems and outcompetes native plants Expanding range of *Salvinia molesta* in water bodies from South India to central and North India is an alarming indications of climate change on the thriving abilities of this weed (Sushilkumar 2022, 2024).

Rising temperatures and changing rainfall patterns create favorable conditions for invasive aquatic weeds like water hyacinth, alligator weed, water fern to grow faster and spread more widely. *Eichhornia crassipes* (water hyacinth) thrives in warmer temperatures, which allows it to proliferate across all over the world including India. Warmer winters reduce natural die-back, enabling it to form dense mats that obstruct waterways, hinder fishing, and disrupt ecosystems (Patel 2012, Datta and Palit 2021, Sushilkumar 2022). For example, water hyacinth thrives more in South India during winter than the North India where its growing points are killed due to die-back symptoms, which reduced its growth drastically. *Najas* spp. and other submerged weeds have been benefited from warmer temperatures allowing it to invade new regions and persist longer in water bodies. (Sharma *et al.* 2020, Sushilkumar 2022).

Water hyacinth and *Salvinia molesta* (giant salvinia) respond positively to elevated CO_2 leading to rapid biomass accumulation (Gupta *et al.* 2020). *Azolla pinnata* (mosquito fern), a highly CO_2 -responsive species, showed increased biomass production in elevated CO_2 environments. This proliferation enables it to rapidly cover the surface of ponds and canals, significantly reducing oxygen levels and blocking sunlight, which impacts the photosynthesis of submerged plants (Gupta *et al.* 2021). *Potamogeton crispus* (curly-leaf pondweed) demonstrates accelerated growth and larger plant mass with higher CO_2 levels (Rajan and Mathew 2019).

Climate-induced droughts can lower water levels in rivers, lakes, and reservoirs, creating shallow, warm waters ideal for invasive submerged weeds like *Hydrilla verticillata, Potamogeton* spp., *Vallisneria* spp. *etc*. Increase and heavy rainfall lead to flooding, which aids the quick dispersal of floating invasive weeds like water hyacinth, *Pistia stratiotes*, and *Alternanthera philoxeroides* (alligator weed) through broken weed fragments and seeds over larger areas, accelerating the colonization of new water bodies and flooded plains. This spread affects agriculture, as these weeds often invade rice paddies and irrigation canals, leading to reduced crop yields and higher management costs (Singh *et al*. 2016). *Salvinia molesta* fast spread and invasion was reported in the rice field in the Bhandara district of Maharashtra state of India with the flood water of Wainganga River during rainy season of 2022 (Sushilkumar, personal observation). Farmers and Agricultural department were worried due to invasion of this aquatic weed in the rice fields.

Current biocontrol scenario of terrestrial and aquatic weeds in India

In India, biological agents, mainly insects have provided excellent biological control of prickly pear *Opuntia elatior* and *O. vulgaris* by *Dactylopius ceylonicus* and *D. opuntiae*; *Salvinia molesta* by weevil, *Cyrtobagous salviniae*; water hyacinth by weevils *Neochetina bruchi, N. eichhorniae* and mite *Orthogalumna terebrantis*; and *Parthenium hysterophorus* by chrysomelid beetle *Zygogramma bicolorata*. Some introduced bioagents did not prove success but providing partial control like of Lantana by agromyzid seed fly, *Ophiomyia Lantanae*, tingid lace bug, *Teleonemia scrupulosa* out of 9 introduced bioagents; *Chromolaena odorata* by *Pareuchaetes pseudoinsulata* and *Cecidochares connexa*; *Ageratina adenophora* by gallfly *Procecidochares utilis*; submerged aquatic weeds such as *Vallisneria* spp. and *Hydrilla verticillata* in fish ponds by grass carp (Sushilkumar 2024).

A tropical American rust fungus (*Puccinia spegazzinii*), collected in Trinidad, was released in India in Assam and Kerala in 2005. Initial symptoms of attack were noticed but it did not prove potential bioagent so far. Despite the rust failing to persist in the field in India and China, the potential of *P. spegazzinii* is recognized by Taiwan, Fiji where it has established and causing significant damage to *Mikania micrantha* (Sushilkumar 2024).

Currently in India, about 32 exotic biological control agents have been introduced against weeds, of which six could not be released in the field, 3 could not be recovered after release while 23 were recovered and established. Based on established results of biological control agents, 7 are providing excellent control, 4 substantial control and 10 partial controls (Sushilkumar 2024). Maximum degree of success by classical biological control agents in India has been reported by Singh (2004) by aquatic weeds (55.5%) followed by homopterous insect pests, a type of sucking insect class (46.7%) and again terrestrial weeds (23.8%).

Effect of climate change on physiology and nutritional status of weeds vis-a-vis their natural enemies

It has been documented that biological invasions will be favoured under this new atmospheric regime (Reeves 2017), as exotic weed species are more adapted to take up and use available resources at a faster rate than native communities. Bale *et al*. (2002) examined the direct effects of climate change on insect herbivores and identified temperature as the dominant abiotic factor, which affects development, survival, range and abundance. Photoperiod is the dominant cue for the seasonal synchrony of temperate insects, but their thermal requirements may differ at different times of year. Many studies have shown that increased CO_2 levels in the atmosphere cause significant impacts on photosynthesis, plant productivity (Reeves 2015, Gufu *et al*. 2018) and plant-insect interactions (Cornelissen 2011). Feeding habits of insects may get affected due to changes in nutritional parameters of weeds under high CO_2 (Casteel *et al*. 2012). Study showed that plants including weeds grown under elevated CO_2 inclined to have increased rates of photosynthesis, reduced photorespiration, high C:N which cause overall decrease in plant quality with lower nutritive ratios (Zavala *et al*. 2013, Reeves 2017, Kumar *et al*. 2021). Climate change significantly affects the dynamics between invasive weeds and their biological control agents, with far-reaching implications for ecosystem management (Pyšek and Richardson 2010). In addition to altering weed distribution, climate change can also impact the physiological traits of plants, such as nutrient content and the production of chemical defenses, which make these invasive species more resilient and reduce the effectiveness of biocontrol agents (Finch *et al*. 2021). Increased carbon assimilation may reduce nutrient levels like nitrogen and phosphorus, which are responsible for reducing biocontrol effectiveness (Grutters *et al*. 2016). Increased CO_2 levels can boost the production of defensive compounds in invasive weeds, such as alkaloids and tannins, making them more resistant to biocontrol agents (Kaur *et al*. 2022). For example, *Carduus nutans* increase lignin and carbon-based compounds under elevated CO_2 making it tougher and less palatable to herbivores like the *Rhinocyllus conicus* weevil. This reduces the weevil's feeding efficiency and limits its impact on the weed population (Crawley and Ross 1990). Zhang *et al*. (2016) mentioned that elevated CO_2 levels can alter the biochemical composition of invasive weeds, affecting their nutrient content and chemical defenses.

Climate change can alter water temperature and chemistry, affecting *Salvinia molesta* nutritional content and increasing secondary metabolites. This makes the plant less palatable to biocontrol agents like *Cyrtobagous salviniae*, reducing their feeding rates and effectiveness in controlling the weed (Wahl *et al*. 2021). Higher CO_2 levels can boost secondary metabolite production, such as tannins, lignins, and alkaloids, making plants more resistant to herbivores and biocontrol agents. For example, Parthenium shows increased allelopathic chemicals under elevated CO_2 reducing biocontrol agents' effectiveness (Mao *et al*. 2021).

Effects of climate change on biocontrol agents of terrestrial weeds

With the increase in spread and abundance of an invasive weed species into new regions, the effectiveness of biological control becomes increasingly ambiguous. In some cases, the height and growth of invasive plants may overwhelm the capacity of biocontrol agents to reduce weed populations effectively. Initially, it was found that *Zygogramma bicolorata*, a bioagent of Parthenium was suited to a moderate climate and may not establish in areas experiencing temperature below 15°C and above 35°C (Jayanth and Bali 1993). However, Sushilkumar (2012, 2014, 2015, 2022, 2024) found the effectiveness of these bioagents in many parts of India under extreme climatic conditions. Omkar *et al*. (2008) found that development was fastest with maximum survival at 27°C. They also showed that a lower temperature threshold (lowest average temperature in which, life cycle can sustain well) of 18.5°C and thermal constant (K) of 480.8 degree-day were required to complete the development.

While there are a number of studies predicting the effects of increased CO_2 on plant ecology (Reeves 2017), increased temperature under the same conditions has not received noteworthy attention, especially within the terrestrial environment. It is of utmost importance to ensure constant effectiveness of biological control in the light of climate change as it would be detrimental to the environment and the economy of the country to re-employ previous control measures like the use of chemicals and mechanical and manual removal to manage the weeds. Therefore, it is essential to perceive and predict precisely the response of invasive weeds and their biological control agents to climate change (Reeves 2017).

Terrestrial weed *Parthenium hysterophorus* has invaded about 35 million hectares of land in India (Sushilkumar and Varshney 2009). It has been considered a biggest threat for loss of crop productivity, biodiversity and many health problems in human beings. In spite of thr invincible attributes of Parthenium, its biological control by bioagent *Zygogramma bicolorata,* introduced from Mexico during the 1980s caused huge reduction of the weed and helped in restoration of the biodiversity. Although, it is claimed by the non-believer of biocontrol that the bioagent has done nothing to reduce the intensity of Parthenium. However, in a conservative estimate Sushilkumar (2022) estimated that *Z. bicolorata* has spread and established well in about 25 million hectares out of 35 million infested area of India, which amounts to be about 71% area. The bioagent effectiveness was recorded from low to high temperature regimes from different regions of India. This bioagent controls Parthenium at varied levels from nil to 100% during the rainy season only. Taking only 10% complete control (100%) of the weed, the saving of about Rs. 6.0 billion every year was estimated in terms of herbicides required to control it.

Climate change may indirectly affect biocontrol of weeds by the way of its direct influence on the reproduction, survival, distribution and behavior of bioagents especially insects (Sujayan and and Karuppaiah 2016). Successfully adapted and established bioagents may also get affected due to climate change. For example, feeding efficiency of *Zygogramma bicolorata* on Parthenium was reportedly decreased at the optimal temperatures above 27-30^{0}C (Kumar *et al*. 2021). Changed quality of parthenium weed leaves in elevated CO_2 and temperature levels resulted in the increase of consumption, slower food conversion rates, increase in developmental period with reduced reproduction efficiency of *Z. bicolorata* (Kumar *et al*. 2021). Their findings indicated that the reproduction efficiency of *Z. bicolorata* is likely to be reduced as the climate changes, despite increased feeding rates exhibited by grubs and adult beetles on parthenium weed foliage. Sushilkumar *et al*. (2018) studied the effect of elevated CO_2 and temperature in combination and separately on the efficacy of *Z. bicolorata* on

Parthenium amidst the blackgram crop in open top chambers (OTC). They found low nitrogen content in elevated CO_2 foliage while carbon content was higher in elevated CO_2 foliage. C: N ratio was considerably higher in elevated CO_2 foliage. Elevated CO_2 foliage had higher polyphenol content too, compared to ambient CO_2. Mean population counts revealed maximum population (adults/plant) of *Z. bicolorata* during 6th and 7th weeks in the chambers having elevated CO_2 alone or elevated temperature alone while it was high during 7th to 8th week in the chambers having both elevated CO_2 and elevated temperature, but in ambient chamber, population increased in 8th to 9th weeks. This showed that alone high temperature and high CO_2 induced high egg laying and early development while under combination of temperature and CO_2, population increased was delayed.

Chidawanyika *et al.* (2017) studied heat tolerance in biocontrol agent *Z. bicolorata* through multiple experiments. The results showed the effects of heat waves on the performance and survival of biocontrol agent, which may influence its effectiveness on *Z. bicolorata*. The authors also emphasized the importance of different methodologies when studying heat tolerance. In contrast, the sap-sucking bug *Dactylopius opuntiae* Cockerell (Dactylopiidae) had reduced fitness under elevated CO_2 which resulted in the target weed, *Opuntia stricta* Haw. (Haw.) (Cactaceae), taking on average three weeks longer to die than plants exposed to the same initial density of the agent at current CO_2 concentration (Venter *et al*. 2022). The efficacy of biocontrol of *O. stricta* in South Africa may therefore be reduced in future (Venter *et al*. 2022). The physiological impacts of agents under different climate change scenarios could have important management implications and is an understudied area of research where more effort is warranted.

The effectiveness of *Cactoblastis cactorum* (moth) as a biocontrol agent for *Opuntia* spp. depends heavily on temperature. Warmer temperatures can enhance the insect's life-cycle speed, potentially increasing its population. However, extreme heat may disrupt its reproduction and reduce survival rates, decreasing overall efficacy (Sutherst *et al.* 2007) whereas *Dactylopius ceylonicus* (cochineal insect) also exhibits temperature-dependent development. Climate-driven temperature increase can either improve its efficacy by increasing feeding rates or hinder it if temperatures exceed tolerance levels, impacting the spread and density control of *Opuntia dillenii*. The bioagent *Zygogramma bicolorata*, is an effective biological control agent of *Parthenium hysterophorus* in India and Australia and many other countries. Adult beetles diapause in soil during December to May. As a result, there is delay in its effectiveness on the plant that reaches to flowering and seed production by the time the beetle is able to build up its population after emerging from diapause. Sushilkumar and Ray (2010) conducted a study to explore possibilities of diapause aversion by temperature regulation. They found that exposure of newly emerged adults to heat treatment of 35°C and to low temperature of 10°C could reduce diapause in *Z. bicolorata*. It was suggested to use low temperature as a medium for the storage of the mass reared beetles for a long time without having negative effect on their longevity and fecundity.

Zygogramma bicolorata (Mexican beetle) performs best in moderately dry conditions, and heavy rainfall can limit its effectiveness by reducing its activity and survival rates. Climate change-induced rainfall variability may lead to fluctuations in beetle populations, affecting its capacity to control *Parthenium* effectively (McFadyen 1992). In the Assam state of India, senior author released many thousand adults of *Zygogramma bicolorata* during 2015 to 2017, but only mild establishment of the bioagent was observed in Guwahati and no establishment was found yet (Sushilkumar 2014, 2022). Excessive rainfall and moisture were considered one of the limiting factors in this case.

Higher CO_2 levels may increase the growth rate of *Chromolaena odorata,* making it more challenging for *Pareuchaetes pseudoinsulata* (moth) and *Cecidochares connexa* (gall fly) to keep pace with its growth. Enhanced plant biomass under elevated CO_2 could demand higher agent populations to achieve similar control effects as before, reducing the per capita impact of the agents (Stiling and Cornelissen 2007). *Procecidochares utilis* (gall fly), which is used for biocontrol of *Ageratina adenophora,* may experience altered reproductive cycles under climate change. Rising temperatures may accelerate its development, potentially increasing its population in the short term but potentially leading to fewer generations over the year as reproductive timing is disrupted (Wang *et al.* 2013).

These examples illustrate the ways, climate change affects biocontrol efficacy, including shifts in temperature, water availability, and CO_2 levels. Adaptation strategies in biocontrol may need to account for these men-driven challenges to maintain effective control over invasive weed species in India and elsewhere.

Effects of climate change on biocontrol agents of aquatic weeds

Reproduction and development of *Cyrtobagous salviniae*, a bio-control agent of *Salvinia molesta* may get affected due to rising temperature (Allen *et al.* 2014). Decreased plant palatability of alligator weed (*Alternanthera philoxeroides*) under drought has reportedly caused reduction in population growth of its bio-agent *Agasicles hygrophila* suggesting that drought can reduce the biological control of alligator weed indirectly by interrupting plant–insect interaction (Wei *et al.* 2015). Climate change may shift interactions of invasive plants, herbivorous insects and native plants, potentially affecting biological control effcacy and non-target effects on native species.

Lu *et al.* (2015) showed how climate warming affects the impacts of a multivoltine introduced biocontrol beetle *Agasicles hygrophila*, an effective biocontrol agent of aquatic and terrestrial weed *Alternanthera philoxeroides* on the non-target native plant *Alternanthera sessilis* in China. In field surveys across a latitudinal gradient covering their full distributions, they found beetle damage on *A. sessilis* increased with rising temperature and plant life history changed from perennial to annual. Experiments showed that elevated temperature changed plant life history and increased insect overwintering, damage and impacts on seedling recruitment. These results suggest that warming can shift phenologies, increase non-target effect magnitude and increase non-target effect occurrence by beetle range expansion to additional areas where *A. sessilis* occurs. This study highlights the importance of understanding how climate change affects species interactions for future biological control of invasive species and conservation of native species. Further, they interpreted that because *A. philoxeroides* will also expand its range further North China in response to warming, and the plant tolerates cold better than *A. hygrophila*, the overall effect of biocontrol may be weak in higher latitude.

Henriksen *et al*. (2018) studied effects of elevated CO_2 on the invasive weed *Alternanthera philoxeroides* and the biocontrol beetle *Agasicles hygrophila*. The authors explored the impacts of elevated CO_2 on the interactions of a plant invader and its biocontrol beetle in terrestrial and flooded conditions. The results suggested that elevated CO_2 will have minor effects on the efficacy of this biocontrol agent

In one of the studies, Reddy *et al.* (2019) compared four biotypes of the weevil, *Neochetina eichhorniae* Warner (Coleoptera: Curculionidae), a biocontrol agent of water hyacinth (*Eichhornia crassipes*) and found variation in tolerance to cold among populations. They suggested that the introduction of *N. eichhorniae* from Australia into northern California would result in climate matching between source and release environments and increase the distribution and densities of weevils, and by this improve biocontrol efficacy.

Spread of water hyacinth bioagent namely *Neochetina bruchi, N. eichhorniae* and mite *Orthogalumna terebrantis* has been found in water bodies all over India infested with the water hyacinth from their first release sites of Bangaluru (Karnataka state) during 1980s. This has happened due to their movement through flood water from one river to another river and water channels. Now these bioagents are common along with the water hyacinth, however, their impacts vary region to region and water bodies to water bodies under different climatic conditions (Sushilkumar 2011, 2020). Water hyacinth has become the worst aquatic weed all over India, but under North-East and Kerala situation, water hyacinth has assumed a serious problem worth to consider. Many scientists opined that bioagent *Neochetina* spp. are not effective to control the weed. However, there are spectacular success stories of biological control of water hycienth from all over India like Karnataka, Madhya Pradesh, Manipur, Uttar Pradesh, Bihar, Andhra Pradesh, Tamil Nadu states, *etc*. experiencing warmer to extreme temperature regimes (Sushilkumar, 2011, 2024). It has been proved that for successful biological control of water hyacinth, perennial nature of water bodies is essential. Biological control of water hycienth cannot be expected in rivers and running water channels where, population build-up of bioagent is impossible owing to washing away of the existing population along with weed during flood in the rainy season. This is the reason that bioagents is not effective against water hyacinth in the water channels and rivers. Intentional systematic release of the bioagents in appropriate numbers in suitable water bodies can bring spectacular success (Sushilkumar 2024).

Reductions in light may cause oxygen depletion beneath floating invasive macrophyte mats alter submerged plant, plankton, invertebrate, and vertebrate communities (Coetzee *et al.* 2014). For example, severe invasion of *Salvinia molesta* in 900-hectare reservoir in Sarni village of Betul district of Madhya Pradesh in India caused depletion of earlier dominated submerged weed *Hydrilla verticillata* and other flora and fauna especially fishes, which subsequently lead unemployment to inhabiting fisheries communities around the reservoir (Bhagitath 2024, Sushilkumar 2024). Similarly, Paper *et al.*

(2023) investigated the role of current (400 ppm) and projected (800 ppm) CO_2 concentration on another free-floating aquatic weed, *P. crassipes*, growth with and without two of its biocontrol agents, the leaf-chewing *Cornops aquaticum* Brüner (Orthoptera: Acrididae) and the phloem-feeding *Megamelus scutellaris* Berg (Hemiptera: Delphacidae). The study showed that herbivory by *C. aquaticum* was consistent across CO_2 conditions, but the feeding by *M. scutellaris* increased at the elevated CO_2 level suggesting that, at predicted elevated CO_2 concentrations, the successful biocontrol of *P. crassipes* might rely on phloem-feeding insects (Paper *et al.* 2023).

Baso *et al.* (2021) conducted a study to investigate the effects of elevated atmospheric CO_2 (800 ppm) on the biological control of four invasive aquatic weeds (*Azolla filiculoides, Salvinia molesta, Pistia stratiotes* and *Myriophyllum aquaticum* and their respective biological control agents *Stenopelmus rufinasus, Cyrtobagous salviniae, Neohydronomus affinis,* and *Lysathia* sp. in South Africa. They found an overall increase in biomass production and C:N across all species at elevated CO_2, both in the presence or absence of biological control, although C:N of *M. aquaticum* and biomass of *A. filiculoides* with herbivory were not consistant with this trend. Insect feeding damage was reduced by elevated CO_2, except for *S. molesta*. Thus, they found different responses to CO_2 increase, but the general trend suggested that these species will become more challenging to manage through biological control in future.

Cyrtobagous salviniae (*Salvinia* weevil) depends on specific water conditions to effectively manage *Salvinia*. Drought conditions resulting from climate change can reduce water levels, causing habitat desiccation that negatively impacts weevil survival and reduces efficacy in weed control. Conversely, if water bodies become overly flooded, weevil populations may disperse more widely but may not be concentrated enough to control the weed effectively (Julien *et al.* 1999). Sushilkumar (2024) emphasized that for effectiveness of biocontrol agent of water hyacinth *Neochetina* spp., perennial water bodies are one of the important factors after release of bioagents. Water bodies which are dried during summer seasons may affect the pupation process of *Neochetina* spp., because pupation of weevils occur amidst the roots and if roots are anchored in the soil during drought conditions, life cycle will be hampered hence, no success in biological control of water hyacinth may be achieved.

The efficacy of *Neochetina eichhorniae* and *Neochetina bruchi* (water hyacinth weevils) is affected by climate-induced shifts in seasonal patterns. Warmer winter temperatures could disrupt weevil diapause (hibernation period), leading to fewer weevils being ready to control *Eichhornia crassipes* in spring. Moreover, warmer conditions might accelerate the growth of water hyacinth, requiring higher weevil densities to achieve similar levels of control (Tipping *et al.* 2014).

Prediction model to assess effectiveness of bioagent over the weeds in their expanding range

Van and Pichancourt (2015) used matrix models to explore the effects of a biocontrol agent *Evippe* spp. on an invasive shrub *Prosopis* spp. under different climatic conditions. The results showed that plant population dynamics are sensitive to rainfall due to changes in the longevity of the agent adults. Both biocontrol herbivory and changing climate have a strong influence on the invasive shrub and need to be

Dhileepan and Senaratne (2009) mapped the widespread distribution of *P. hysterophorus* and *Z. bicolorata* using CLIMEX modelling and suggested that besides India and Pakistan, this biocontrol agent may be released to *P. hysterophorus* invaded areas of the countries including Bangladesh, Sri Lanka and parts of Nepal. Despite extensive research on *P. hysterophorus and Z. bicolorata* in India, Australia, Africa, Pakistan, *etc*. no serious effort through modelling, other than CLIMEX (Dhileepan and Senaratne 2009, King 2008) has been made to describe the suitable climatic conditions for establishment of *Z. bicolorata* for the management of *P. hysterophorus*. These models have predicted the whole South India including Kerala, coastal areas of Odisha (20.95°N, 85.10°E), West Bengal and whole North-East region of India climatically highly suitable for the establishment of *Z. bicolorata*. However, during ground survey, *Z. bicolorata* was not even recovered from Thrissur, Kerala (10.53°N, 76.21°E); Mohanpur, West Bengal (23.66°N, 88.23°E) and Jorhat, Assam (26.75°N, 94.20°E) in spite of several releases made during 2001–2017 by Sushilkumar (2015, 2022). So far, we have recovered only negligible to moderate establishment of *Z. bicolorata* in Kozhinjampara, Kerala (10.74°N, 76.83°E); Birbhum (West Bengal) and Guwahati (Assam) through ground survey. To predict suitable sites for the establishment of *Z. bicolorata*, an attempt was made by Gharde (2019) to develop statistical models based on ground information so that favorable release sites may be identified. Models were developed using data on climatic variables like temperature, rainfall and relative humidity of the rainy season (July to October) instead of annual mean, when the *Z. bicolorata* remains most active and influences establishment in the subsequent mild season (February to March) and next rainy season. In contrary to CLIMEX Model of King (2008) and Dhileepan and Senaratne (2009), Gharde *et al* (2019) models predict only negligible to moderate establishment of *Z. bicolorata* in Kerala, coastal areas of Odisha, West Bengal and north-east region of India. CLIMEX model on the basis of lower EI values (11–30 and 30–50) predicted Central and North India less suitable while Gharde *et al*. (2019) model predicted these areas moderately to highly suitable for establishment of *Z. bicolorata*. It was understood from the results that although rainfall and relative humidity do not play a significant role if taken individually but their interaction with minimum temperature play a substantial part to predict the establishment. The incorporating of four months climatic data of temperature, rainfall and relative humidity in this model, provide more precise information about the possible establishment of *Z. bicolorata*. Gharde *et al.* (2019) concluded that a site experiencing climate with indices values of average minimum temperature ranging 24.2–26.2°C and rainfall between 191.2–257.3 mm during July to October would be highly suitable for setting up the *Z. bicolor*ata population in the region. It was inferred from the results that sites with very high weighted average rainfall (>514 mm indices value) with MMIN are not suitable for establishment of *Z. bicolorata*. Gaharde *et al.* (2019) models might be useful to decide the most suitable sites for release and establishment of *Z. bicolorata* in India as well as in other parts of the world with similar climatic conditions. The comparative evaluation of these two prediction model based on climate variables clearly reflected that many times, for a particular biocontrol agent, annual mean climatic parameters are not suitable to fit in the predetermined climatic software to predict the suitable areas for the establishment of biocontrol agents. Prediction models for the suitable establishment of bioagent should always be tested with ground verification.

Iris pseudacorus originally from Europe has historically invaded North America, China and Japan, and more recently spread through Argentina, South Africa and Australia, where it is now a target for biological control. In this regard, climatic suitability can be used to model the potential distributions of weeds and their candidate agents, both in space and time, thus allowing to identify areas at risk of invasion and predict where agents will be able to establish long-term. Minuti *et al* (2023) modelled the present and future (2040–2060) climatic suitability of *I. pseudacorus* and its candidate agents using the software MaxEnt. They predicted North America and eastern Asia, climatically suitable for *I. pseudacorus* but found very low suitability of its bioagent across these regions, further decreasing under future climatic conditions.

Sun (2017) studied climatic suitability like elevated temperature, CO_2 and high rainfall on biological control candidates for ragweed management in Europe. This modelling study compared the suitability of six biocontrol candidates with regard to their expected range overlap with the plant invader in the introduced range. The authors advocated this approach as a first cost effective pre-release assessment before more elaborate and time consuming experiments.

Future of biological control in India in context to climate change

In spite of failure of many bioagents, we should be optimistic and enthusiastic to do more introduction of known effective bioagent, which have shown promising results in suppression of weeds like water hyacinth, alligator weed, *Pistia, Parthenium, Mikania, Chromolaena etc*. in the countries of their introduction. Many of such bioagents have not been introduced yet in India, which need immediate attention. Some of these like *Listronotus setosipennis, Stobaero concinna, Buccalatrix parthenica, Epiblema strenuana, Puccinia abrupt* on *Parthenium;* a flea beetle *Agasicles hygrophila* for alligator weed *Alternanthera philoxeroides; Sameodes albiguttalis Warren (Lepidoptera: Pyralidae)* on water hyacinth, *Neohydronomous affinis (Hustache)* on *Pistia stratiotes, Heteropsylla spinulosa* (Homoptera: Psyllidae) on *Mimosa diplotricha* have been effective in controlling growth of the weed in many areas in USA and Australia (Sushilkumar 2024). Some of the suggestions are listed below:

1. In India, relatively little work has been done on new introduction of bioagents against weeds after 1980s. Therefore, there is a great scope of introduction of natural enemies against invasive weeds of terrestrial and aquatic situations.
2. Weeds like C. *odorata, A. adenoforum, M. micrantha* and *Mimosa diplotricha* have assumed serious status in forestry plantations and now spreading their tentacles to agricultural and wastelands. There is urgent need to explore the introduction of new bioagent against these weeds.
3. In India, there is great scope of introduction of some well proven exotic insect enemies like dipterous leaf minor *Coteomvze lanatanae* from Australia and noctuid *Neogulea esula* from Hawaii against *Lantana.*

4. Many alien weeds are great problems in protected forests. The problem may be reduced by release of proven bioagents under classical biological control. The authorities of protected areas such as National Parks do not give permission to release bioagents in the pretext of ban to introduce exotics in PA, while the bioagent has been introduced in the country by due permission of Government. It is also true that in due course, an introduced bioagent will reach on its suitable host inside the protected areas, without man's efforts. This need retrospection by the forest authorities to hasten the biological control process.
5. There are known bioagent, which have shown promising results in suppression of weeds like water hyacinth, alligator weed, *Pistia etc*. in the country of their introduction. Many of such bioagents have not been introduced yet in India, which need immediate attention. Some of these are : *Listronotus setosipennis, Smicronyx lutulentus, Stobaero concinna, Buccalatrix parthenica Epiblema strenuana Puccinia abrupta* on Parthenium; alligator weed flea beetle *Agasicles hygrophila* for alligator weed *Alternanthera philoxeroides*; *Sameodes albiguttalis* Warren (Lepidoptera: Pyralidae) on water hyacinth, *Neohydronomous affinis* (Hustache), *Pistia stratiotes* , *Heteropsylla spinulosa* (Homoptera: Psyllidae) on *M. diplotricha* has been effective in controlling aquatic growth of the weed in many areas in USA.

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