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Original Article

Integrated Weed Management: A Key Component of Climate-Resilient Agriculture

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ABSTRACT:

Climate change is increasingly recognized as one of the greatest challenges facing global agriculture in the twenty-first century. Rising temperatures, altered precipitation regimes, elevated atmospheric carbon dioxide concentrations, and the increased frequency of extreme weather events are significantly affecting agricultural productivity and ecosystem stability. Among the many biotic stresses exacerbated by climate change, weeds represent one of the most persistent and economically damaging constraints to crop production. Weeds compete aggressively with crops for water, nutrients, light, and space, often causing substantial yield losses and reductions in crop quality. Climate change is expected to intensify weed problems by altering weed distribution patterns, increasing weed competitiveness, promoting biological invasions, and accelerating the evolution of herbicide resistance. In this context, Integrated Weed Management (IWM) has emerged as a sustainable and climate-resilient strategy that combines cultural, mechanical, biological, preventive, and chemical approaches to manage weed populations effectively while minimizing environmental impacts. Unlike conventional weed management systems that rely heavily on herbicides, IWM employs multiple complementary tactics to maintain weed populations below economic threshold levels and reduce the likelihood of resistance development. Furthermore, IWM contributes significantly to climate resilience by enhancing biodiversity, improving soil health, conserving water resources, reducing greenhouse gas emissions, and strengthening ecosystem services. The integration of advanced technologies such as remote sensing, artificial intelligence, precision agriculture, and decision-support systems further enhances the effectiveness of IWM under changing climatic conditions. This article reviews the relationship between climate change and weed dynamics, examines the major components of integrated weed management, and highlights its critical role in building resilient and sustainable agricultural systems capable of adapting to future environmental challenges.

Keywords: Climate change, Integrated weed management, Climate-resilient agriculture, Herbicide resistance, Sustainable weed control, Crop productivity, Precision agriculture, Agroecosystem resilience

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1. INTRODUCTION

Agriculture forms the backbone of food security and rural livelihoods across the globe. However, the sector is highly vulnerable to environmental changes, particularly those associated with climate change. According to the latest assessments of the Intergovernmental Panel on Climate Change (IPCC, 2023), global temperatures have already increased substantially compared with pre-industrial levels, and further warming is projected during the coming decades. Changes in temperature, precipitation, atmospheric carbon dioxide concentration, and the occurrence of extreme weather events are expected to profoundly influence agricultural ecosystems. Among the numerous challenges confronting agriculture under changing climatic conditions, weed infestation remains one of the most serious and underestimated threats. Weeds are undesirable plants that interfere with agricultural production by competing with crops for essential resources such as water, nutrients, sunlight, and growing space. They may also harbor insect pests and plant pathogens, reduce crop quality, interfere with harvesting operations, and increase production costs (Oerke, 2006). Globally, weeds are responsible for greater yield losses than either insect pests or plant diseases when effective control measures are not implemented. The impact of climate change on weed populations is becoming increasingly evident. Elevated carbon dioxide concentrations stimulate photosynthesis and biomass production in many weed species, particularly C3 weeds, enhancing their competitive ability against crops (Ziska and Dukes, 2011). Rising temperatures can facilitate the spread of invasive weeds into new geographical regions, while altered rainfall patterns may favor drought-tolerant and stress-adapted weed species. Moreover, climate change can affect the efficacy of herbicides, making conventional weed management approaches less reliable.

Historically, weed management has relied heavily on chemical herbicides because of their effectiveness, convenience, and relatively low labor requirements. However, excessive herbicide dependence has resulted in serious environmental concerns, including groundwater contamination, biodiversity loss, and the widespread development of herbicide-resistant weed populations (Heap, 2024). Consequently, there is an urgent need for more sustainable weed management strategies that can adapt to changing climatic conditions while maintaining agricultural productivity. Integrated Weed Management (IWM) represents a holistic and ecologically based approach to weed control that combines multiple management tactics to reduce weed pressure and minimize reliance on any single control method. By integrating preventive, cultural, mechanical, biological, and chemical measures, IWM contributes significantly to the development of climate-resilient agricultural systems capable of sustaining productivity under environmental uncertainty (Swanton and Weise, 1991).

2. Climate change and weed dynamics

Climate change is fundamentally altering weed ecology, distribution, and management. Weeds often possess greater genetic diversity, reproductive capacity, and ecological plasticity than cultivated crops, enabling them to adapt rapidly to changing environmental conditions. Consequently, many weed species are expected to benefit from climate change, potentially increasing their impact on agricultural production systems. One of the most important drivers of weed response to climate change is elevated atmospheric carbon dioxide concentration. Carbon dioxide is a critical substrate for photosynthesis, and increased concentrations generally stimulate plant growth. Studies have shown that many C3 weed species exhibit stronger growth responses to elevated CO_2 than many crop species. For example, weeds such as *Chenopodium album*, *Parthenium hysterophorus*, and *Cirsium arvense* often demonstrate enhanced biomass accumulation, increased seed production, and improved water-use efficiency under elevated CO_2 conditions (Ziska et al., 2011). Such responses may intensify crop–weed competition and reduce crop yields.

Temperature increases also play a significant role in weed proliferation. Rising temperatures can accelerate weed germination, growth, flowering, and seed production. Many tropical and subtropical weeds are expanding their geographic ranges into temperate regions as climatic barriers diminish. Species such as *Amaranthus palmeri*, *Parthenium hysterophorus*, and *Striga* spp. have demonstrated remarkable adaptability to changing climatic conditions and are becoming increasingly problematic in new agricultural landscapes (Paini et al., 2016). Changes in precipitation patterns further complicate weed management. Increased drought frequency may favor drought-tolerant weed species with deep root systems and efficient water-use strategies. Conversely, excessive rainfall and flooding can promote the establishment of aquatic and semi-aquatic weeds that interfere with crop production. Climate-induced variability in rainfall patterns can also alter weed emergence timing, making control measures more difficult to implement effectively. Another major concern is the impact of climate change on herbicide performance. Environmental conditions influence herbicide absorption, translocation, metabolism, and degradation (Table 1.). High temperatures and water stress can reduce herbicide efficacy, while altered weed physiology under elevated CO_2 may reduce herbicide sensitivity. These factors, combined with continued herbicide selection pressure, contribute to the evolution and spread of herbicide-resistant weed populations worldwide (Norsworthy et al., 2012).

Table 1. Major climate change factors affecting weed ecology.

Climate Factor	**Effect on Weeds**	**Agricultural Consequence**
Elevated CO_2	Increased growth and seed production	Greater crop competition
Rising temperature	Faster life cycles and wider distribution	Increased infestation
Drought	Favoring drought-adapted weeds	Reduced crop competitiveness
Flooding	Promotion of aquatic weeds	Increased weed diversity
Extreme weather events	Enhanced seed dispersal	Rapid spread of invasive weeds
Mild winters	Improved weed survival	Early-season infestations

3. Principles and components of integrated weed management

Integrated Weed Management (IWM) is a holistic, ecologically based approach that combines multiple weed control methods to maintain weed populations below economically damaging levels while minimizing adverse environmental impacts and preserving agricultural sustainability. Unlike conventional weed management systems that rely primarily on herbicides, IWM integrates preventive, cultural, mechanical, biological, and chemical practices in a coordinated manner to exploit weaknesses in weed life cycles and reduce their competitive ability (Swanton and Weise, 1991). The fundamental principle of IWM is that no single weed control method is sufficient to provide long-term, sustainable weed suppression. Instead, combining multiple complementary tactics enhances weed control efficacy, reduces the risk of herbicide resistance, and improves agroecosystem resilience under changing climatic conditions (Norsworthy et al., 2012). One of the core principles of IWM is the prevention of weed establishment and spread. Preventive measures aim to stop weeds from entering agricultural fields or producing seeds that contribute to the soil seedbank. The use of certified weed-free seed, sanitation of farm machinery, proper management of irrigation channels, and control of weeds along field boundaries are important preventive strategies. Prevention is often considered the most economical and environmentally sound component of weed management because it reduces future infestations and minimizes the need for intensive control measures (Liebman et al., 2001). Effective prevention can significantly lower weed seedbank density, which is critical because many weed seeds remain viable in the soil for several years or even decades.

Cultural weed management forms another important component of IWM and involves modifying agronomic practices to favor crop growth while suppressing weed development. Crop rotation is among the most effective cultural practices because it disrupts weed life cycles and prevents the dominance of weed species adapted to a particular crop. Diverse crop rotations expose weeds to varying planting dates, cultivation methods, and resource environments, thereby reducing weed population growth (Chauhan, 2020). Similarly, cover crops such as rye (*Secale cereale*), clover (*Trifolium* spp.), and hairy vetch (*Vicia villosa*) suppress weeds by shading the soil surface, competing for water and nutrients, and releasing allelopathic compounds that inhibit weed germination and growth (Teasdale, 1996). Other cultural practices include the use of competitive crop cultivars, optimum planting density, narrow row spacing, stale seedbed techniques, and mulching, all of which enhance crop competitiveness and reduce opportunities for weed establishment. Mechanical and physical weed control methods constitute another essential component of IWM. These methods physically remove, damage, or destroy weeds and have been used for centuries in agricultural systems. Common mechanical methods include hand weeding, hoeing, tillage, cultivation, mowing, and mechanical uprooting. Physical methods such as flaming, solarization, and flooding may also be used depending on crop and environmental conditions (Bond and Grundy, 2001). Mechanical control is particularly important in organic farming systems where herbicide use is restricted. However, excessive tillage may contribute to soil erosion, organic matter loss, and greenhouse gas emissions; therefore, modern IWM programs often integrate reduced tillage systems with other weed management practices to balance weed suppression and soil conservation objectives (Lal, 2015). Biological weed control involves the use of living organisms to suppress weed populations. Biological control agents include insects, pathogens, nematodes, fish, and grazing animals that naturally attack target weed species. This approach is particularly valuable for managing invasive weeds over large areas where conventional control methods are impractical or uneconomical. Successful examples include the use of *Zygogramma bicolorata* for the management of *Parthenium hysterophorus*, *Cyrtobagous salviniae* for controlling *Salvinia molesta*, and *Cactoblastis cactorum* for suppressing invasive prickly pear cacti (*Opuntia* spp.) (Julien et al., 2012). Biological control offers long-term and environmentally friendly weed suppression and contributes to biodiversity conservation by reducing reliance on chemical herbicides. Chemical weed control remains an important component of IWM but is employed strategically and in combination with non-chemical approaches. Herbicides provide rapid and effective weed control; however, their overuse has led to the widespread development of herbicide-resistant weed populations. To address this issue, IWM promotes herbicide stewardship through the rotation of herbicide modes of action, use of herbicide mixtures, application at recommended doses, and integration with cultural and mechanical control methods (Norsworthy et al., 2012). Precision herbicide application technologies, including sensor-based sprayers and site-specific weed management systems, further improve herbicide efficiency while reducing environmental contamination and production costs.

A critical principle underlying all components of IWM is the management of the weed seedbank. The soil seedbank serves as the primary source of future weed infestations. Strategies such as preventing seed production, harvesting weed seeds during crop harvest, stimulating weed germination before planting (stale seedbed technique), and promoting seed predation by insects and birds can substantially reduce seedbank size over time (Shrestha, 2019). Long-term seedbank management is considered one of the most sustainable approaches for reducing weed pressure and improving agricultural productivity. Integrated Weed Management also emphasizes continuous monitoring and decision-making based on economic thresholds. Regular field scouting enables farmers to identify weed species, assess infestation levels, and determine the most appropriate management strategies. By targeting control measures only, when necessary, farmers can optimize resource use, reduce costs, and minimize environmental impacts (Mortensen et al., 2012). This adaptive and knowledge-based approach makes IWM particularly suitable for climate-resilient agriculture, where changing environmental conditions require flexible and responsive management strategies. Overall, the success of Integrated Weed Management lies in its ability to combine multiple complementary control tactics into a unified system that suppresses weeds effectively while maintaining ecological balance. By integrating preventive, cultural, mechanical, biological, and chemical approaches, IWM provides sustainable weed management solutions that enhance crop productivity, reduce herbicide dependence, conserve natural resources, and strengthen the resilience of agricultural systems to climate change (Swanton and Weise, 1991; Chauhan, 2020).

4. Role of Integrated Weed Management in climate-resilient agriculture

Climate-resilient agriculture aims to sustain crop productivity while enhancing the capacity of agricultural systems to adapt to climate change and mitigate its impacts (FAO, 2017). Integrated Weed Management (IWM) contributes directly to these objectives by promoting ecological stability, reducing environmental degradation, and improving the adaptive capacity of farming systems. As climate change intensifies weed-related challenges, IWM provides a flexible and sustainable framework for maintaining agricultural productivity under uncertain environmental conditions. One of the most important contributions of IWM to climate resilience is its ability to enhance agroecosystem biodiversity. Agricultural systems that rely heavily on herbicides often experience reductions in plant diversity, beneficial insects, pollinators, and soil microorganisms. In contrast, diversified weed management systems support a broader range of organisms that contribute to ecosystem functioning. Crop rotations, cover crops, intercropping, and biological control strategies create more complex habitats that support natural enemies of pests and promote ecological balance (Altieri and Nicholls, 2017). Biodiversity is widely recognized as a key component of resilience because diverse ecosystems are generally more capable of withstanding environmental disturbances and recovering from climatic shocks. Another critical benefit of IWM is the improvement of soil health. Soil health plays a central role in climate resilience because healthy soils possess greater water-holding capacity, improved nutrient cycling, enhanced biological activity, and greater resistance to erosion. Practices commonly associated with IWM, such as cover cropping, residue retention, reduced tillage, and mulching, contribute to increased soil organic matter and improved soil structure (Lal, 2015). These improvements help crops withstand drought stress, heavy rainfall events, and temperature extremes, which are becoming increasingly common under climate change.

Water conservation is another major advantage of integrated weed management. Weeds often consume significant quantities of water that would otherwise be available for crops. Effective weed suppression improves water-use efficiency and enhances crop performance under water-limited conditions. Mulches and cover crops reduce soil evaporation, while improved soil structure increases water infiltration and retention. Such practices are particularly valuable in regions experiencing increasing drought frequency and water scarcity. Integrated weed management also contributes to climate change mitigation. Excessive herbicide use, repeated tillage operations, and intensive agricultural inputs contribute to greenhouse gas emissions. By reducing dependence on chemical inputs and promoting conservation agriculture practices, IWM helps decrease fossil fuel consumption and carbon emissions. Furthermore, practices such as cover cropping and residue retention enhance carbon sequestration in agricultural soils, contributing to long-term climate change mitigation efforts (Lal, 2015). Perhaps one of the most significant contributions of IWM is its role in managing herbicide resistance. Herbicide-resistant weeds have become a major global challenge, threatening crop productivity and increasing management costs. According to Heap (2024), more than 530 unique cases of herbicide-resistant weeds have been documented worldwide. Climate change may further accelerate resistance development by altering weed biology and herbicide performance. Integrated approaches that combine chemical and non-chemical control methods reduce selection pressure and slow the evolution of resistant weed populations, thereby preserving herbicide effectiveness for future generations.

Table 2. Contribution of integrated weed management to climate-resilient agriculture.

IWM Practice	Adaptation Benefit	Mitigation Benefit
Crop rotation	Reduces weed adaptation to climate variability	Improves soil carbon storage
Cover crops	Conserves moisture and suppresses weeds	Sequesters atmospheric carbon
Mulching	Reduces evaporation losses	Enhances soil organic matter
Biological control	Provides stable weed suppression	Reduces pesticide use
Precision herbicide application	Improves control under variable conditions	Lowers fuel and chemical consumption
Reduced tillage	Improves annual weed management	Reduces greenhouse gas emissions
Intercropping	Enhances ecosystem resilience	Promotes efficient resource utilization

5. Emerging technologies and future perspectives in integrated weed management

Rapid advances in agricultural technology are transforming weed management practices and creating new opportunities for climate-smart agriculture. The integration of digital technologies, artificial intelligence, and precision agriculture tools is expected to play a crucial role in the future of integrated weed management. Precision weed management represents one of the most promising innovations. Traditional herbicide applications often involve uniform treatment of entire fields regardless of weed distribution. In contrast, precision agriculture technologies enable site-specific weed management based on real-time information. Global Positioning Systems (GPS), Geographic Information Systems (GIS), drones, and remote sensing technologies can identify weed-infested areas and facilitate targeted interventions. Such approaches reduce herbicide use, lower production costs, and minimize environmental impacts (Chauhan, 2020). Artificial intelligence and machine learning are increasingly being incorporated into weed detection systems. Advanced image recognition algorithms can distinguish weeds from crop plants with remarkable accuracy. Autonomous robots equipped with cameras and sensors can identify and mechanically remove weeds or apply herbicides precisely where needed. These technologies reduce labor requirements and improve weed management efficiency while supporting sustainable agricultural practices.

Remote sensing technologies provide additional opportunities for monitoring weed populations across large areas. Satellite imagery and drone-based platforms can detect weed infestations, assess weed density, and track changes in weed distribution over time. Such information is particularly valuable under climate change scenarios, where weed populations may shift rapidly in response to environmental conditions. Decision-support systems are another important innovation.

These systems integrate weather forecasts, soil information, crop growth models, and weed emergence predictions to guide management decisions. By helping farmers optimize the timing and selection of control measures, decision-support systems enhance the effectiveness of IWM while reducing unnecessary interventions. Future weed management strategies will increasingly emphasize ecological intensification, which seeks to maximize ecosystem services while minimizing external inputs. Ecological intensification involves the strategic use of biodiversity, crop diversification, biological control agents, and ecosystem processes to regulate weed populations naturally. Such approaches align closely with climate-resilient agriculture objectives and offer sustainable alternatives to conventional input-intensive systems (Altieri and Nicholls, 2017).

6. Challenges and opportunities

Despite its numerous benefits, the widespread adoption of integrated weed management faces several challenges. One major constraint is the complexity of implementation. IWM requires detailed knowledge of weed biology, crop management, ecological interactions, and local environmental conditions. Farmers often need specialized training and technical support to implement integrated strategies effectively. Economic considerations also influence adoption. While IWM can reduce long-term costs, some practices require higher initial investments in equipment, labor, or technology. Smallholder farmers may face difficulties accessing precision agriculture technologies or biological control agents. Policy support, extension services, and incentive programs are therefore essential for promoting wider adoption. Climate change itself introduces additional uncertainties. Rapid shifts in weed distributions, emergence of new invasive species, and changing environmental conditions may require continuous adaptation of management strategies. Consequently, future weed management programs must remain flexible and responsive to evolving challenges. Nevertheless, significant opportunities exist. Increasing awareness of environmental sustainability, advances in digital agriculture, and growing concerns about herbicide resistance are driving interest in integrated approaches. Investments in research, education, and technology development can accelerate the transition toward climate-resilient weed management systems (Ziska and Dukes, 2011).

7. CONCLUSION

Climate change is reshaping agricultural ecosystems and creating unprecedented challenges for weed management. Elevated atmospheric carbon dioxide concentrations, rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events are expected to intensify weed infestations, enhance weed competitiveness, expand invasive species distributions, and complicate existing management strategies. Traditional herbicide-dependent approaches are increasingly inadequate due to environmental concerns and the widespread emergence of herbicide-resistant weeds. Integrated Weed Management offers a scientifically sound and sustainable solution to these challenges. By combining preventive, cultural, mechanical, biological, and chemical control methods, IWM provides effective weed suppression while promoting environmental stewardship and agricultural sustainability. Beyond weed control, IWM contributes substantially to climate resilience by enhancing biodiversity, improving soil health, conserving water resources, reducing greenhouse gas emissions, and strengthening ecosystem services. The future of climate-resilient agriculture will depend on the successful integration of ecological principles with emerging technologies such as artificial intelligence, precision agriculture, remote sensing, and decision-support systems. These innovations can improve the efficiency and adaptability of weed management strategies while reducing dependence on chemical inputs. As climate change continues to alter agricultural landscapes, the adoption of integrated weed management will become increasingly important for ensuring food security, protecting natural resources, and supporting sustainable agricultural development worldwide.

REFERENCES

Altieri, M.A. and Nicholls, C.I., 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change*, 140(1), pp.33–45.

Bajwa, A.A., Mahajan, G. and Chauhan, B.S., 2015. Nonconventional weed management strategies for modern agriculture. *Weed Science*, 63(4), pp.723–747.

Bond, W. and Grundy, A.C., 2001. Non-chemical weed management in organic farming systems. *Weed Research*, 41(5), pp.383–405.

Chauhan, B.S., 2020. Grand challenges in weed management. *Frontiers in Agronomy*, 1, pp.1–4.

FAO, 2017. *Climate-Smart Agriculture Sourcebook*. Rome: Food and Agriculture Organization of the United Nations.

Heap, I., 2024. *The International Herbicide-Resistant Weed Database*. Available at: http://www.weedscience.org [Accessed 12 June 2026].

IPCC, 2023. *Climate Change 2023: Synthesis Report*. Geneva: Intergovernmental Panel on Climate Change.

Julien, M.H., McFadyen, R.E. and Cullen, J.M., 2012. *Biological Control of Weeds in Australia*. Melbourne: CSIRO Publishing.

Lal, R., 2015. Restoring soil quality to mitigate soil degradation. *Sustainability*, 7(5), pp.5875–5895.

Liebman, M., Mohler, C.L. and Staver, C.P., 2001. *Ecological Management of Agricultural Weeds*. Cambridge: Cambridge University Press.

Mortensen, D.A., Egan, J.F., Maxwell, B.D., Ryan, M.R. and Smith, R.G., 2012. Navigating a critical juncture for sustainable weed management. *BioScience*, 62(1), pp.75–84.

Norsworthy, J.K., Ward, S.M., Shaw, D.R., Llewellyn, R.S., Nichols, R.L., Webster, T.M., Bradley, K.W., Frisvold, G., Powles, S.B., Burgos, N.R., Witt, W.W. and Barrett, M., 2012. Reducing the risks of herbicide resistance: Best management practices and recommendations. *Weed Science*, 60(sp1), pp.31–62.

Oerke, E.C., 2006. Crop losses to pests. *Journal of Agricultural Science*, 144(1), pp.31–43.

Paini, D.R., Sheppard, A.W., Cook, D.C., De Barro, P.J., Worner, S.P. and Thomas, M.B., 2016. Global threat to agriculture from invasive species. *Proceedings of the National Academy of Sciences*, 113(27), pp.7575–7579.

Patterson, D.T., Westbrook, J.K., Joyce, R.J.V., Lingren, P.D. and Rogasik, J., 1999. Weeds, insects and diseases. *Climatic Change*, 43(4), pp.711–727.

Pretty, J., 2018. Intensification for redesigned and sustainable agricultural systems. *Science*, 362(6417), eaav0294.

Ryan, M.R., Smith, R.G., Mirsky, S.B., Mortensen, D.A. and Seidel, R., 2010. Management filters and species traits. *Weed Science*, 58(3), pp.265–277.

Shrestha, A., 2019. Integrated Weed Management in Sustainable Agriculture. Cham: Springer.

Singh, R.P., Singh, V.P. and Bhan, V.M., 2018. *Weed Management in Climate Smart Agriculture*. New Delhi: ICAR Publications.

Swanton, C.J. and Weise, S.F., 1991. Integrated weed management: The rationale and approach. *Weed Technology*, 5(3), pp.657–663.

Teasdale, J.R., 1996. Contribution of cover crops to weed management in sustainable agricultural systems. *Journal of Production Agriculture*, 9(4), pp.475–479.

Ziska, L.H. and Dukes, J.S. (eds.), 2011. *Weed Biology and Climate Change*. Ames, Iowa: Wiley-Blackwell.

Ziska, L.H., Blumenthal, D.M., Runion, G.B., Hunt, E.R. and Diaz-Soltero, H., 2011. Invasive species and climate change: An agronomic perspective. *Climatic Change*, 105(1–2), pp.13–42.