

International Journal of Plant & Soil Science

Volume 38, Issue 11, Page 492-522, 2026; Article no.IJPSS.170346
ISSN: 2320-7035

Weed Flora and Management Practices in Cereal Crops: A Critical Review of Weed Composition, Herbicide Resistance and Integrated Control

R. Naseeruddin [a++*], K. Satish Babu [b++], K. Arun Kumar [b++], K. Ashok Kumar [b#] and G. Narayana Swamy [a†]

[a] ARS, Ananthapuramu, India.
[b] RARS, Nandyal, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i116444

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/170346

Review Article

Received: 25/09/2026
Accepted: 16/11/2026
Published: 21/11/2026

Abstract

Background: Weeds cause the largest potential yield loss of any pest group in the major cereals, and weed control in wheat, rice and maize has become heavily dependent on herbicides. Widespread herbicide resistance, changes in crop establishment and tillage, and pressure to reduce pesticide use have made the composition of cereal weed floras and the effectiveness of alternative management practices central questions for cereal production.
Purpose and Scope: This critical narrative review examines how cereal weed floras are assembled and why they shift, how reliably weed-induced yield losses have been estimated, how herbicide resistance has evolved and should be managed, and what evidence supports preventive, cultural, physical, biological, diversification-based and precision tactics in wheat, rice, maize and, where evidence allows, barley, sorghum and millets.

[++] Scientist (Agronomy); [#] Principal Scientist (Agronomy); [†] Principal Scientist (Agronomy) & Head;
**Corresponding Email(s): r.naseeruddin@angrau.ac.in;*

Contact Email(s): r.naseeruddin@angrau.ac.in;

Cite as: *Naseeruddin, R., Babu, K. S., Kumar, K. A., Kumar, K. A., & Swamy, G. N. (2026). Weed Flora and Management Practices in Cereal Crops: A Critical Review of Weed Composition, Herbicide Resistance and Integrated Control. International Journal of Plant & Soil Science, 38(11), 492–522. https://doi.org/10.9734/ijpss/2026/v38i116444*

Approach: Literature published between 2000 and 2026 was identified through searches of multidisciplinary, life-science and open-access indexes, supplemented by citation tracking and inclusion of seminal earlier work. Studies were appraised for experimental realism, strength of inference, quality of measurement and generalisability.
Principal Findings: Management filters, particularly crop sowing season, crop sequence, tillage and herbicide use, explain more variation in cereal weed communities than soil or climate at field scale. Potential yield losses from uncontrolled weeds are large but are estimated with methods that inflate their generality. Resistance in grass weeds of cereals is now frequently multiple and metabolism-based, which weakens strategies built on rotating herbicide groups. Higher crop density, spatially uniform sowing, competitive cultivars, diversified rotations, cover crops and harvest weed seed control reduce weed populations with reasonable consistency, but their effects are partial, context dependent and rarely tested in combination over long periods.
Implications: Effective cereal weed management requires several partially effective tactics that reduce seedbank inputs and selection pressure together, supported by economic and institutional conditions that make adoption rational for farmers.
Conclusion: Long-term, multi-site systems experiments, standardised loss assessment and research on adoption are needed more urgently than further single-tactic efficacy trials.

Keywords: *Arable weed communities; herbicide resistance; integrated weed management; crop competitiveness; harvest weed seed control; direct-seeded rice; conservation agriculture; crop diversification.*

1. Introduction

Wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.) and maize (*Zea mays* L.) are the principal staple cereals, and weeds are, on average, the most damaging group of pests in the major field crops. An analysis of crop losses for 2001–2003 estimated that weeds produced a potential loss of 34% across major crops, higher than that caused by animal pests or pathogens, although weed control was also more efficient than control of other pests because it could be achieved by both mechanical and chemical means (Oerke, 2006). Regional assessments point in the same direction. Uncontrolled weeds reduced maize yield by an average of 50% across the United States and Canada (Soltani *et al.*, 2016) and winter wheat yield by a production-weighted 23.4% (Flessner *et al.*, 2021), while on-farm trials across 18 Indian states recorded potential losses of 15–66% in direct-seeded rice and 18–65% in maize (Gharde *et al.*, 2018). The weed problem in cereals is therefore not marginal, and its management absorbs a large share of the labour, chemical inputs and decision-making effort of cereal farmers.

The term weed flora is used here for the assemblage of non-crop plant species that establish and reproduce in a cropped field, and weed management for the set of preventive, cultural, physical, biological and chemical actions that reduce the impact of that assemblage on crop production. Over the past half-century these two components have co-evolved. Intensified fertiliser and herbicide use reduced the diversity of arable floras in Europe and favoured a smaller set of competitive, nitrophilous and herbicide-tolerant species (Storkey *et al.*, 2012, 2010), while the replacement of hand weeding by herbicides as rural labour became scarce has spread the same transition to Asia and is beginning in sub-Saharan Africa (Gianessi, 2013; Haggblade *et al.*, 2017). Changes in crop establishment have reshaped floras further. The move from puddled transplanting to direct seeding of rice in Asia removed the head start that transplanted seedlings and standing water had given the crop (Chauhan, 2012; Kumar & Ladha, 2011), and the adoption of zero tillage in rice–wheat systems of the Indo-Gangetic Plains altered the vertical distribution of weed seeds and the relative importance of grass and broad-leaved species (R. S. Chhokar *et al.*, 2007; Kumar *et al.*, 2013).

In a long-term winter wheat study, reduced tillage was associated with higher weed abundance but only small changes in weed diversity, while residue removal had no clear effect on the weed flora (Lacroix *et al.*, 2024).

Herbicide resistance has become the most visible consequence of this co-evolution. More than 400 unique cases of resistance had been documented by 2014, with acetolactate synthase (ALS) inhibitor resistance particularly troublesome in rice and cereals and resistance to acetyl-coenzyme A carboxylase (ACCase) inhibitors in species of *Avena*, *Lolium*, *Phalaris*, *Setaria* and *Alopecurus* infesting more than 25 million hectares of cereals (Heap, 2014). Cases of greatest concern now involve resistance to several modes of action under polygenic control, often based on enhanced herbicide metabolism (Délye *et al.*, 2013; Yu & Powles, 2014). No herbicide with a commercially significant new mode of action reached the market for several decades (Duke, 2012; Selby *et al.*, 2023), so the chemical options available to cereal farmers have narrowed even as dependence on them has grown (Peterson *et al.*, 2018).

A regional survey of annual ryegrass in south-eastern Australia identified spatially clustered patterns of resistance to multiple herbicides, illustrating the heterogeneity of resistance across agricultural landscapes (Paril *et al.*, 2025).

The response of weed science has been to advocate integrated weed management (IWM), which combines several control methods so that no single tactic carries the full burden of weed control (Harker & O'Donovan, 2013; Riemens *et al.*, 2022). The evidence base for IWM in cereals is extensive but uneven. Reviews have examined crop competitiveness (Andrew *et al.*, 2015; Lemerle *et al.*, 2001), weed dynamics in wheat (Jabran *et al.*, 2017), conservation agriculture (Chauhan *et al.*, 2012; Nichols *et al.*, 2015), direct-seeded rice (Matloob *et al.*, 2015; Rao *et al.*, 2007), rice-based systems in Africa (Rodenburg & Johnson, 2009), harvest weed seed control (Walsh *et al.*, 2018), allelopathy (Jabran *et al.*, 2015), site-specific weed management (Gerhards *et al.*, 2022) and climate change (Peters *et al.*, 2014), usually in isolation. A field study of maize reported lower weed infestation under a maize–wheat–soybean rotation integrated with herbicide treatments than under continuous maize in the conditions examined (Simić *et al.*, 2025). In zero-till wheat, another study found that combining rice-residue mulch, increased seeding rate and pre-emergence herbicide mixtures improved weed suppression under its experimental conditions (Sindhu *et al.*, 2026). Several features of this literature limit the confidence that can be placed in its practical recommendations. Yield-loss estimates are derived largely from small-plot comparisons of weedy and weed-free treatments that may not represent losses on farms. Many non-chemical tactics have been tested for one or two seasons at one site, whereas their value lies in effects on the seedbank that accumulate over years.

Evidence on resistance management rests partly on modelling and partly on national-scale correlative data that can disagree with each other (Comont *et al.*, 2020; Hicks *et al.*, 2018). The adoption of IWM by farmers has remained limited, and herbicide use has rarely fallen where IWM has been promoted (Moss, 2019). Existing reviews have seldom brought weed community ecology, yield-loss assessment, resistance evolution, non-chemical tactics and adoption into a single appraisal for cereals, and fewer still have asked which conclusions rest on strong evidence and which on extrapolation from limited designs.

1.1 Scope, Research Gap and Objectives

This review addresses weed floras and their management in the major cereals, namely wheat, rice and maize, with barley, oats, sorghum and millets considered where their evidence adds to the argument. It covers temperate and tropical production systems, mechanised and smallholder farming, and conventional, conservation and organic management. Parasitic weeds are included because they constrain cereal production in sub-Saharan Africa, and weedy rice is included because it is both a weed and a conspecific relative of the crop. Weeds of non-cereal crops, rangeland and non-crop land, aquatic weeds outside rice fields, and the toxicology and environmental fate of herbicides are excluded except where they bear directly on cereal weed management decisions.

The knowledge gap addressed is the absence of a cross-cereal synthesis that connects the processes shaping weed floras with the evidence for each management option and that distinguishes well-supported conclusions from those resting on short-term, single-site or modelled evidence. Five objectives follow from this gap. The first is to characterise the dominant weed floras of cereal systems and the management and environmental filters that determine their composition and change. The second is to evaluate how weed-induced yield losses have been quantified and what the estimates can legitimately be used for. The third is to appraise the evolution and management of herbicide resistance in cereal weeds, including contested questions about herbicide doses, mixtures and rotations. The fourth is to assess the strength and consistency of evidence for preventive, cultural, physical, biological, diversification-based and precision tactics. The fifth is to examine why integrated approaches remain under-adopted and to identify the research designs most likely to improve cereal weed management. The intended contribution is an evidence-graded framework that links weed community processes to management choices, together with a prioritised research agenda.

2. Methods for Literature Selection

2.1 Review Design and Rationale

A critical narrative review was chosen because the question spans plant community ecology, agronomy, evolutionary biology, agricultural engineering and agricultural economics, and the relevant studies differ too much in design, scale and outcome for meaningful statistical pooling. The evidence ranges from national weed surveys and long-term rotation experiments to dose–response assays, molecular studies of resistance mechanisms, simulation models and farmer surveys, and its outcomes include weed density, biomass, seedbank size, species richness, resistance frequency, crop yield and profitability. A systematic review with meta-analysis would require a narrow comparable outcome that this literature does not provide, and a scoping review would map the field without appraising the strength of its inferences. Narrative synthesis is appropriate where interpretation and theory building across heterogeneous evidence are the aims, provided that the search, selection and appraisal are reported transparently (Greenhalgh *et al.*, 2018). The quality criteria of the Scale for the Assessment of Narrative Review Articles, namely justification of the article's importance, statement of concrete aims, description of the literature search, referencing, scientific reasoning and appropriate presentation of data, were used to structure the review (Baethge *et al.*, 2019). The narrative design does not remove the need for transparency or critical appraisal, and both are described below.

2.2 Information Sources

Searches were conducted in PubMed, Europe PMC, OpenAIRE, Crossref and the Directory of Open Access Journals, together with Google Scholar and Semantic Scholar. Europe PMC was used as the principal life-science index because its coverage extends beyond biomedical journals to agricultural and plant science records, and Crossref was used both for bibliographic searching of agronomy and weed science journals and for verifying records. Database searching was supplemented by backward citation searching of recent reviews and key primary studies, forward citation searching of seminal papers, related-article searching and checks for published corrections, expressions of concern and retractions using Crossref update metadata. Bibliographic details and Digital Object Identifiers were confirmed against Crossref records and, where available, PubMed, Europe PMC or publisher landing pages.

2.3 Search Strategy and Search Period

The search was organised around a weed block and a crop block that were combined in every query, to which thematic blocks were added. The weed block captured weeds, weed flora, weed communities, weed seedbanks and named problem species. The crop block captured wheat, rice, maize, corn, barley, oats, sorghum, millets and cereals. Thematic blocks addressed yield loss and competition, herbicides and resistance, cultural and physical tactics, tillage and crop establishment, diversification and biological control, precision technologies, climate change, and adoption and economics. Additional targeted searches were made for named species, mechanisms, technologies and controversies identified during reading.

The core search syntax, as applied in Europe PMC, was TITLE_ABS:(weed *OR "weed flora" OR "weed community" OR "weed seedbank") AND TITLE_ABS:(wheat OR rice OR maize OR corn OR barley OR sorghum OR millet* OR cereal*) AND TITLE_ABS:(management OR control OR herbicide* OR resistance OR tillage OR competition OR "yield loss*") AND PUB_YEAR:[2000 TO 2026]. Equivalent strings were adapted for the other platforms. In PubMed the title and abstract field tag*

[tiab] and publication-date limits replaced the Europe PMC field codes; Crossref was queried with bibliographic free-text strings restricted to journal articles and to the same publication period, mainly to locate and verify specific records; and OpenAIRE, the Directory of Open Access Journals, Google Scholar and Semantic Scholar were searched with simplified keyword combinations drawn from the same blocks because these platforms do not support identical field tagging. The query blocks and the evidence domains they were designed to interrogate are recorded in Table 1.

The search period ran from 1 January 2000 to 14 September 2026. The search end date and the last search date were the same, and minor literature refinements were made during the review and revision stage. The starting year corresponds to the period in which multiple herbicide resistance in grass weeds of cereals became widespread, direct seeding of rice and zero tillage expanded across Asia, and herbicide-tolerant cereal technologies entered commercial use. Earlier publications were included when they were historically or conceptually indispensable, such as the hyperbolic yield-loss model, the first synthesis of rotation and intercropping effects on weeds and the first report of herbicide resistance in *Phalaris minor* Retz. in India. Eligibility by date was determined by the first public journal publication date, meaning the online-first or version-of-record date where available, rather than the later date of issue assignment.

Studies were appraised with a qualitative rubric of four domains. Realism and scale distinguished multi-site, multi-season field studies, long-term experiments and national surveys from single-site trials, pot experiments and controlled-environment studies. Strength of inference ranked replicated field experiments with appropriate weedy and weed-free or untreated controls, long-term systems comparisons, confirmed resistance assays combined with mechanistic analysis, and meta-analyses above uncontrolled comparisons, anecdotal reports and untested model predictions. Quality of measurement considered whether weed density, biomass, seed production, seedbank, resistance status and crop yield were measured directly and with adequate replication. Generalisability considered the number of crops, sites, seasons and production systems examined and whether findings had been independently reproduced. Evidence was described as strong when supported by consistent results from several independent field studies or meta-analyses, moderate when supported by well-designed but geographically or temporally limited studies, and limited when it rested on single studies, simplified systems or modelling alone.

Table 1. Search architecture: query blocks used for evidence discovery and the principal evidence domains they were intended to interrogate

Query block	Concept captured	Representative terms and operators	Principal evidence domains interrogated	Sections informed
A. Weeds and weed flora	Non-crop plants in cereal fields	weed *OR "weed flora" OR "weed communit*" OR "weed seedbank" OR "weedy rice" OR named species (*Phalaris minor*, *Lolium rigidum*, *Alopecurus myosuroides*, *Echinochloa*, *Avena*, *Amaranthus*, *Striga*)	Species composition, functional traits, community shifts	3
B. Cereal crops	Crop context	wheat OR rice OR maize OR corn OR barley OR oat *OR sorghum OR millet* OR cereal	Restriction of all queries to cereal systems	3–10
C1. Competition and yield loss	Impact of weeds on yield	"yield loss*" OR competition OR interference OR "critical period" OR threshold*	Magnitude, mechanisms and timing of weed-induced losses	4
C2. Herbicides and resistance	Chemical control and its evolutionary consequences	herbicide *AND (resistance OR "cross-resistance" OR metabolism OR mixture* OR rotation *OR "mode of action" OR tolerant)*	Resistance frequency, mechanisms, management strategies, new chemistry	5
C3. Preventive, cultural and physical tactics	Non-chemical control in the crop	"seeding rate" OR "row spacing" OR "competitive cultivar*" OR tillage OR "conservation agriculture" OR "direct-seeded rice" OR mulch OR harrow* OR hoeing OR "harvest weed seed control" OR "seed predation"	Efficacy and consistency of crop competition, tillage, establishment and physical methods	6
C4. Diversification and biological approaches	System-level and biological suppression	"crop rotation" OR "cover crop*" OR intercrop* OR allelopath OR bioherbicide* OR "push–pull"	Rotational, spatial and biological suppression, parasitic weed control	7
C5. Technology and change	Precision tools and climate	"site-specific" OR "spot spraying" OR "machine vision" OR "deep learning" OR "climate change" OR "elevated CO2" OR invasive	Herbicide savings, detection accuracy, range shifts, herbicide efficacy	8, 9
D. Adoption, economics and controversies	Human dimensions and contested findings	"integrated weed management" AND (adoption OR farmer *OR economic* OR survey) OR "economic threshold" OR "low dose"	Adoption barriers, profitability, contested evidence	5, 10, 11

Note. Blocks A and B were combined in all core searches; blocks C1–D were added to A and B to target specific themes. Asterisks denote truncation. Database-specific record counts are not reported because they are not required for a critical narrative review and would not reflect the iterative citation searching used alongside database queries. CO_2, carbon dioxide

Table 1 records the architecture of the search rather than database-specific yields. The weed and crop blocks formed the core of every query, and each thematic block can be traced to the sections of the review it principally informed. The final block was used deliberately to retrieve evidence on adoption, economics and contested findings, which are under-represented when searches are framed only around agronomic efficacy.

2.4 Eligibility Criteria

Eligible publications were peer-reviewed original research articles, reviews, meta-analyses and modelling studies published in English that addressed the composition or dynamics of weed floras in cereal crops, the impact of weeds on cereal yield, or any chemical, cultural, physical, biological, diversification-based or technological method of managing weeds in cereals. Studies of mixed cropping systems were eligible when cereals formed a major component and the weed outcomes could be attributed to the cereal phase or the cropping system as a whole. Studies of herbicide resistance mechanisms were included when the species concerned was an important weed of cereals or when the mechanism had demonstrated relevance to cereal weed management. Studies on farmer adoption, economics and policy were included when they concerned weed management in arable or cereal-based systems. No geographical restriction was applied, and evidence from smallholder systems in Asia and Africa was sought deliberately. Excluded were studies confined to non-cereal crops, pastures, plantations or non-crop land; laboratory screening of plant extracts or microorganisms without whole-plant or field validation; conference abstracts, theses, preprints, trade literature and non-peer-reviewed reports; and any record whose bibliographic details could not be verified.

2.5 Screening, Duplicate Handling and Study Selection

Titles and abstracts retrieved from each source were screened for relevance to the scope, and potentially relevant records were then assessed in full text or, where the full text was inaccessible, on the basis of the abstract and publisher metadata. A source was cited only for claims that could be verified from accessible content. Duplicates arising from overlapping database coverage were identified by matching Digital Object Identifiers and normalised titles and were retained once. The language restriction to English was applied at the screening stage. Records with incomplete or inconsistent metadata were checked against Crossref and publisher pages and were excluded if the inconsistency could not be resolved. A critical narrative review does not require the procedures that are mandatory for a systematic review, such as record-level screening counts, deduplication counts, dual independent screening or formal reviewer agreement statistics, and none is reported here; selection was instead bounded by the eligibility and appraisal criteria described in this section.

2.6 Critical Appraisal and Evidence Synthesis

Selected studies were appraised using the rubric described in Section 2.3, with particular attention to experimental scale and duration, the presence of appropriate controls, the confirmation of resistance by dose–response testing, the direct measurement of seedbank and seed production, and the degree of independent replication across sites and seasons. Influential studies were identified through a combination of conceptual importance, methodological contribution and sustained use in subsequent work rather than citation counts alone, and conflicting or negative findings were sought deliberately. Themes were developed iteratively, beginning with weed community composition and yield loss and then extending to resistance, non-chemical tactics, system diversification, technology, climate change and adoption. Where studies disagreed, the disagreement was interpreted in relation to differences in crop, weed species, environment, management history, spatial and temporal scale and the outcome measured, and the review states explicitly when a disagreement could not be resolved from the available evidence. No formal risk-of-bias tool was applied because no recognised instrument covers the range of experimental, observational and modelling designs involved.

3. Weed Flora of Cereal Systems: Composition, Drivers and Shifts

3.1 Dominant Weed Floras of the Major Cereals

Cereal weed floras are taxonomically diverse but functionally convergent. Across production systems, the species that dominate are annuals with high seed output, a degree of seed dormancy, emergence that is synchronised with crop sowing and, increasingly, tolerance or resistance to the herbicides most commonly used in that crop. Grass weeds that share the life cycle and much of the physiology of the crop are disproportionately important because selective control is difficult and because many of them have evolved resistance to graminicides (Heap, 2014).

In autumn-sown wheat and barley of north-western Europe, *Alopecurus myosuroides* Huds. is the most damaging grass weed, and its densities in the United Kingdom are now correlated with the frequency of evolved herbicide resistance at a national scale (Hicks *et al.*, 2018). Annual ryegrass (*Lolium rigidum* Gaudin) occupies a similar position in the dryland wheat systems of southern Australia (M. J. Owen *et al.*, 2014), and wild oats (*Avena fatua* L. and *A. sterilis* L.) are important grass weeds of wheat in temperate and subtropical production systems (Beckie *et al.*, 2012; Mahajan & Chauhan, 2021). Broad-leaved weeds in temperate cereals are dominated by a recurring set of species. In Swedish cereals, *Capsella bursa-pastoris* (L.) Medik. and *Matricaria perforata* Mérat were among the most detrimental species in autumn-sown crops (Milberg & Hallgren, 2004), and five successive surveys of Finnish spring cereals have recorded *Chenopodium album* L., *Viola arvensis* Murray and *Stellaria media* (L.) Vill. as the most frequent species, with the perennial grass *Elymus repens* (L.) Gould producing roughly a quarter to a third of total weed biomass (Salonen *et al.*, 2011, 2023).

In the rice–wheat systems of the Indo-Gangetic Plains, *Phalaris minor* is the principal grass weed of wheat. Its tolerance of anaerobic conditions during the rice phase, its morphological similarity to wheat until flowering, its shedding of seed before wheat

harvest and its emergence in successive flushes all favour its persistence in this rotation (P. K. Chhokar *et al.*, 2025). The broad-leaved *Rumex dentatus* L. becomes more prominent when wheat is sown without tillage (R. S. Chhokar *et al.*, 2007). Rice floras are dominated by grasses of the genus *Echinochloa*, particularly *E. crus-galli* (L.) P. Beauv. and *E. colona* (L.) Link, together with sedges and broad-leaved species (Bajwa *et al.*, 2015; Rao *et al.*, 2015). Ninety-eight weed species were recorded in rice in the Indian state of Karnataka alone (Rao *et al.*, 2015), and about 90 species have been reported to compete with aerobic rice (Jabran & Chauhan, 2015). Under aerobic conditions in the Philippines the dominant species were *Rottboellia cochinchinensis* (Lour.) Clayton, *Digitaria ciliaris* (Retz.) Koeler, *E. colona* and *Eleusine indica* (L.) Gaertn. (Chauhan & Johnson, 2011). Weedy rice, a conspecific form of *O. sativa*, has become one of the most serious problems wherever direct seeding has replaced transplanting, because no selective herbicide distinguishes it from conventional rice cultivars (Chauhan, 2013; Ziska *et al.*, 2015).

Maize floras are dominated by summer-emerging annuals. A survey of 1,460 German maize fields found *Chenopodium* spp., *E. crus-galli* and *Solanum nigrum* L. at high densities and frequencies, with site conditions and crop sequence determining their occurrence (de Mol *et al.*, 2015). In the southern United States, *Amaranthus palmeri* S. Watson showed one of the greatest increases in importance in maize between the mid-1990s and the late 2000s, the period in which glyphosate-resistant crops were adopted (Webster & Nichols, 2012). This species is highly competitive in maize and produced between 140,000 and 514,000 seeds m^{-2} when it emerged with the crop at densities of 0.5–8 plants per metre of row (Massinga *et al.*, 2001), and it is now spreading into European and Mediterranean agriculture (Matzrafi *et al.*, 2025). In sub-Saharan Africa, maize, sorghum, millets and upland rice are additionally constrained by obligate root-parasitic witchweeds, chiefly *Striga hermonthica* (Delile) Benth. and *S. asiatica* (L.) Kuntze, obligate root parasites that damage the host before conventional control measures can be applied (Kanampiu *et al.*, 2003; Spallek *et al.*, 2013). In African rice, parasitic weeds were estimated to cause losses of at least US$111 million per year, most likely about US$200 million, increasing by about US$30 million annually (Rodenburg *et al.*, 2016).

3.2 Management Filters and Trait-Based Assembly

The composition of a field's weed community can be understood as the outcome of filters that admit or exclude species according to their traits. Large surveys consistently show that management filters dominate at field scale. In about 700 arable fields in France, the main gradients of weed species composition were associated with the current crop and the preceding crop, producing three broad communities associated with winter-, spring- and summer-sown crops, while soil pH and texture formed only the third most important gradient (Fried *et al.*, 2008). In 561 French fields, crop sowing date was strongly related to many weed traits (Gunton *et al.*, 2011), and a comparison of winter wheat surveys from the 1970s and 2000s showed that tillage intensity and other management practices filtered weeds according to identifiable traits (Fried *et al.*, 2012). In the United Kingdom, a trait analysis of common and rare arable species combined with long-term data from the Broadbalk experiment indicated that the species that declined under intensification shared an adverse combination of plant height, seed weight and flowering time under high fertiliser and herbicide inputs (Moss *et al.*, 2004; Storkey *et al.*, 2010). At the continental scale, the number of rare, threatened or extinct arable plants in 29 European countries increased with national wheat yield, and fertiliser use explained more of the variation in threat status than herbicide use (Storkey *et al.*, 2012).

Weed floras respond to these filters over decades as well as between fields. Danish surveys found that overall weed frequency increased between 1987–1989 and 2001–2004 (Andreasen & Stryhn, 2008), whereas the Finnish surveys showed broadly stable frequencies of common broad-leaved species but a substantial increase in *Poa annua* L. in conventional spring cereals between 2007–2009 and 2020–2022 (Salonen *et al.*, 2023). Production system has a large and consistent effect. Organic fields in Finland supported on average 21 species compared with 12 in conventional fields in both survey periods, and weed density in the more recent survey was 384 plants m^{-2} in organic fields compared with 147 plants m^{-2} in sprayed conventional fields (Salonen *et al.*, 2011, 2023). A meta-analysis confirmed that organic practices increase weed density, diversity and evenness relative to conventional practices (Mwangi *et al.*, 2024). Landscape context adds a further filter, since weed species richness in 123 winter wheat fields increased with landscape heterogeneity measured within a 200 m radius (Gaba *et al.*, 2010).

The main limitation of this survey-based evidence is its geographical concentration. Most trait-based and long-term survey studies come from France, the United Kingdom, Germany and the Nordic countries, whereas comparable repeated surveys are rare for the rice–wheat systems of South Asia, the maize systems of sub-Saharan Africa and the rice systems of South-East Asia. Survey methods also differ in timing, plot size and the treatment of herbicide-treated fields, which limits comparison across countries and periods. The trait-based framework is nevertheless general, and it explains why simplified management, in which the same crop is sown at the same time with the same herbicides year after year, repeatedly selects a few well-adapted species.

3.3 Tillage and Crop Establishment as Agents of Floristic Change

Tillage alters the vertical distribution of the seedbank, the conditions for germination and the mortality of perennial propagules, so changes in tillage are among the strongest drivers of floristic change in cereals. Under no-till, seeds accumulate near the soil surface, where germination is more likely but mortality from predation and weather is also greater, and weed communities tend to shift from annual dicots towards grasses and perennials (Nichols *et al.*, 2015). Long-term experiments in Norwegian spring cereals found that perennial species such as *Cirsium arvense* (L.) Scop. and *E. repens* and overwintering species increased under reduced tillage, so that glyphosate became necessary in addition to post-emergence herbicides (Tørresen *et al.*, 2003). In an Italian experiment, tillage affected seedbank size and composition far more than crop rotation after 12 years (Bàrberi & Lo Cascio, 2001).

Table 2. Characteristic weed floras of major cereal systems, their principal drivers and implications for management

Cereal system	Characteristic dominant taxa	Principal drivers of composition and change	Implications for management	Supporting references
Autumn-sown wheat and barley, north-western Europe	*Alopecurus myosuroides*, *Lolium* spp., *Avena* spp., *Capsella bursa-pastoris*, *Matricaria perforata*, *Stellaria media*	Autumn sowing, non-inversion tillage, short rotations, intensive herbicide use selecting resistant grass weeds	Spring cropping, delayed drilling and ploughing reduce grass weeds but conflict with other objectives	Fried *et al.*, 2008; Hicks *et al.*, 2018; Lutman *et al.*, 2013; Milberg & Hallgren, 2004; Storkey *et al.*, 2010
Spring cereals, northern Europe	*Chenopodium album*, *Viola arvensis*, *Stellaria media*, *Galium spurium*, *Elymus repens*, *Poa annua*	Production system (organic versus conventional), herbicide use, perennial grass control	Organic systems carry more species and higher densities; perennial and annual grasses require specific attention	Andreasen & Stryhn, 2008; Hyvönen *et al.*, 2003; Salonen *et al.*, 2011, 2023
Dryland wheat, southern Australia	*Lolium rigidum*, *Avena* spp., *Bromus* spp., *Raphanus raphanistrum*	Continuous cropping, reduced tillage and reliance on few herbicide modes of action	Multiple resistance makes non-chemical seed-focused tactics necessary	Beckie *et al.*, 2012; Mahajan & Chauhan, 2021; M. J. Owen *et al.*, 2014; Walsh & Powles, 2014
Rice–wheat systems, Indo-Gangetic Plains	Wheat: *Phalaris minor*, *Rumex dentatus*, *Avena sterilis* ssp. *ludoviciana*; rice: *Echinochloa* spp. and sedges	Rice–wheat monocropping, puddling versus zero tillage, herbicides with the same mode of action, late wheat sowing	Tillage and establishment choices redistribute the seedbank and change the dominant species	P. K. Chhokar *et al.*, 2025; R. S. Chhokar *et al.*, 2007; Lowry *et al.*, 2021; Malik & Singh, 1995; Mishra *et al.*, 2022
Direct-seeded and aerobic rice, Asia	*Echinochloa crus-galli*, *E. colona*, *Digitaria ciliaris*, *Eleusine indica*, *Rottboellia cochinchinensis*, sedges, weedy rice	Loss of flooding and of the crop size advantage at establishment; tillage system	Weed control becomes the main constraint to adoption; weedy rice requires preventive measures	Chauhan, 2012, 2013; Chauhan & Johnson, 2011; Jabran & Chauhan, 2015; Matloob *et al.*, 2015; Ziska *et al.*, 2015
Maize, Europe and North America	*Chenopodium* spp., *Echinochloa crus-galli*, *Solanum nigrum*, *Amaranthus palmeri*	Site and crop sequence; glyphosate-based systems; range expansion of invasive species	Summer annuals with high seed output require early control; surveillance of invaders	de Mol *et al.*, 2015; Massinga *et al.*, 2001; Matzrafi *et al.*, 2025; Webster & Nichols, 2012
Maize, sorghum and rice, sub-Saharan Africa	Annual grasses and broad-leaved weeds, *Imperata cylindrica* after fallow, *Striga hermonthica*, *S. asiatica*, *Rhamphicarpa fistulosa*	Shortening of fallows, low soil fertility, limited labour for hand weeding, parasitic weeds	Low-cost combinations of competition, diversification and parasitic weed control are required	Chikoye *et al.*, 2004; Johnson & Kent, 2002; Mhlanga *et al.*, 2022; Rodenburg *et al.*, 2016; Spallek *et al.*, 2013

Note. The table summarises representative evidence and is not an exhaustive inventory of species. Taxa are listed as reported in the supporting studies; dominance varies among fields, seasons and management histories

The evidence is not uniform. A 23-year experiment in Mediterranean dryland cereals found no large differences in weed diversity among no-tillage, minimum tillage and conventional tillage (Plaza *et al.*, 2011), and an 18-year Canadian study found that seedbank richness, evenness and diversity varied little among tillage systems (Légère *et al.*, 2011), whereas a functional analysis showed that reduced tillage changed both the composition and the functional attributes of weed communities (Armengot *et al.*, 2016). These discrepancies probably reflect differences in herbicide programmes, residue management, climate and duration, and also whether the outcome measured was the emerged flora, the germinable seedbank or a diversity index that can remain stable while composition changes. A Michigan systems experiment illustrates the importance of the whole management package: seedbanks under conventional and no-till management with full herbicide inputs diverged from those under reduced-input and organic management, which included mechanical weed control and a legume cover (Davis *et al.*, 2005).

The rice–wheat systems of South Asia provide the clearest examples of establishment-driven change. Under zero-till wheat, *R. dentatus* densities were 12.1 plants m^{-2} compared with 1.9 plants m^{-2} under conventional tillage, whereas *P. minor* biomass was lower under zero tillage, a contrast attributed to the redistribution of seeds by puddling for transplanted rice (R. S. Chhokar *et al.*, 2007). In the eastern Indo-Gangetic Plains, the composition of germinable seedbanks was examined in relation to zero tillage, soil properties and landscape position (Lowry *et al.*, 2021), and a long-term experiment in Bihar found that zero tillage in all three crops of a rice–wheat–mungbean rotation reduced weed density and the soil seedbank while maintaining system productivity (Mishra *et al.*, 2022). The shift from puddled transplanting to dry direct seeding of rice has had a larger effect. Direct seeding removes both the size advantage of transplanted seedlings and the suppression of weed emergence by standing water (Chauhan, 2012), and aerobic direct-seeded rice on raised beds experienced the greatest weed pressure of the establishment methods compared in one multi-year study (S. Singh *et al.*, 2008). Early flooding can still suppress weeds in direct-seeded systems, but it hinders rice establishment and is ineffective against weeds such as *Echinochloa* species that are adapted to germinate under flooded conditions (Ismail *et al.*, 2012). Weedy rice has spread with direct seeding for the same reasons (Chauhan, 2013).

3.4 Weed Diversity: Problem or Resource?

The decline of arable weed diversity has been treated as a conservation problem by some researchers and as an irrelevance, or even a success, by others concerned with yield. Weeds support invertebrates and birds within crop fields, and changes in the British weed flora over the past century, including declines in the seedbank, have accompanied the shift to winter-sown crops and broad-spectrum herbicide combinations (Marshall *et al.*, 2003). It has been argued that more diverse weed communities may also be agronomically preferable because they are likely to be less competitive and less prone to dominance by a few highly adapted, herbicide-resistant species (Storkey & Neve, 2018).

Empirical support for this hypothesis is emerging but remains limited. In three years of observations in 54 zones of winter cereals, only four of six weed communities generated significant yield losses, ranging from 19% to 56%, and weed biomass decreased by 83% while crop productivity increased by 23% along a gradient of increasing community evenness (Adeux *et al.*, 2019). Conservation agriculture practices in southern Africa were associated with more diverse weed communities and higher maize grain yield (Mhlanga *et al.*, 2022), and in Zimbabwe maize–pigeon pea strip cropping gave the best weed suppression while supporting the highest weed species diversity (Masamba *et al.*, 2026). These studies are consistent with the diversity hypothesis, but they are observational or confounded with other management changes, and their causal direction is uncertain. Evenness may reduce yield loss because competitive dominants are absent, or both outcomes may result from management that suppresses dominant species. Until experiments manipulate weed community composition independently of management, weed diversity is best regarded as a promising indicator of a well-regulated system rather than a demonstrated management lever.

The patterns described in this section are summarised in Table 2, which links the characteristic floras of the major cereal systems to their principal drivers and to the management responses that follow. The table shows that, although the dominant species differ among regions, the drivers are strikingly similar: repeated sowing at the same season, simplified rotations, changes in tillage or establishment and heavy reliance on herbicides with few modes of action. It also shows that the evidence base is densest for temperate winter cereals and weakest for African cereals other than rice, where parasitic weeds, low fertility and labour constraints interact.

4. Crop–Weed Competition and Yield Loss: What the Estimates Show and What They Do Not

4.1 Magnitude of Weed-Induced Losses

Estimates of weed-induced yield loss are frequently cited to justify research and control expenditure, but they differ widely in design and meaning. The most widely cited global analysis distinguished potential losses, which would occur without crop protection, from actual losses after current control practices, and estimated that weeds produced the highest potential loss of any pest group at 34% across major crops (Oerke, 2006). National estimates are derived mainly from replicated small-plot experiments comparing weedy and weed-free treatments. Using this approach, uncontrolled weeds reduced maize yield in the United States and Canada by an average of 50% over 2007–2013, equivalent to 148 million tonnes of grain valued at more than US$26.7 billion annually (Soltani *et al.*, 2016). For winter wheat over 2007–2017, losses ranged from 2.9% to 34.4% among states and provinces, with production-weighted averages of 25.6% for the United States and 2.9% for Canada (Flessner *et al.*, 2021). In India, 1,581 on-farm trials conducted between 2003 and 2014 recorded potential losses of 15–66% in direct-seeded rice and 18–65% in maize, and location, crop and soil type significantly explained the variation in actual losses (Gharde *et al.*, 2018). Reviews of aerobic rice report yield reductions of 23–100% when weeds are not controlled (Jabran & Chauhan, 2015).

These figures establish that weed control is valuable, but they should not be read as measures of losses currently suffered by farmers. Potential-loss estimates assume no control, and their aggregation to national values multiplies plot-scale percentages by total production, which implicitly assumes that every hectare would carry the weed pressure of a research plot. Research-station weed communities may be denser or more uniform than those on farms, and weedy checks maintained season-long represent an extreme that rarely occurs in practice. The relationship between weed losses and production level also differs from that of other pests. In experiments that manipulated injuries across lowland rice production situations in tropical Asia, losses from weed infestation remained stable as attainable yield increased, whereas losses from sheath blight increased and those from rice tungro disease decreased (Savary *et al.*, 2000). Large-scale variability is considerable even within one country, as shown by the ranking of weed species from benign to highly detrimental across Swedish cereal fields (Milberg & Hallgren, 2004). The weed community itself matters. Across 54 zones of winter cereals, two of six weed communities caused no significant yield loss while the other four caused losses of 19–56% (Adeux *et al.*, 2019), which indicates that weed abundance alone is a poor predictor of damage.

A further category of loss arises from resistance. By combining national density and resistance data for *A. myosuroides* with yield maps and an economic model, the annual cost of resistance in England was estimated at £0.4 billion in lost gross profit and 0.8 million tonnes of wheat, and complete loss of herbicide control would cost £1 billion and 3.4 million tonnes annually (Varah *et al.*, 2020). Estimates of this kind are among the few that address losses under realistic management, but they depend on modelled relationships between density and yield. Losses from parasitic weeds are more poorly quantified still because their incidence data are scant (Rodenburg *et al.*, 2016).

4.2 Mechanisms of Interference

Weed interference has traditionally been explained by competition for light, water and nutrients (Kaur *et al.*, 2018). Nutrient competition is particularly relevant to fertiliser management, because many weeds respond to nitrogen as strongly as or more strongly than cereals. In a controlled-environment comparison of 23 weed species, 15 showed a greater increase in shoot biomass with added nitrogen than wheat (Blackshaw *et al.*, 2003). Nitrogen supply also shifts the timing of competition. In dryland maize, applying 120 kg N ha^{-1} delayed the beginning and, at most site-years, hastened the end of the critical period for weed control relative to lower rates, implying that reduced nitrogen use may require more intensive weed management (S. P. Evans *et al.*, 2003).

This resource-based view has been challenged. A re-evaluation of physiological evidence proposed that crops perceive neighbouring weeds through changes in light quality and other signals before resources become limiting, and that the resulting shift in crop development reduces yield even when weeds are subsequently removed (Horvath *et al.*, 2023). Field evidence from maize shows that damage begins very early: across three locations the critical period began on average between the third and fifth leaf-tip stages, and yield then declined by 0.5–1.6% per day, mainly through fewer kernels per plant. Plant-to-plant variability in dry matter increased as control was delayed but contributed little to the overall yield loss (Page *et al.*, 2012). A rebuttal argued that competition for resources cannot be set aside as the main mechanism of yield loss (Colbach *et al.*, 2023). The disagreement is not merely academic. If early perception is important, effective control must begin earlier than resource-based models suggest, and crop cultivars with reduced sensitivity to neighbour signals could limit losses. The evidence for perception-driven loss comes largely from controlled environments and a small number of field sites, so its quantitative importance under farm conditions remains unresolved.

4.3 Timing of Control and Decision Thresholds

The critical period for weed control is the interval in the crop cycle during which weeds must be controlled to prevent unacceptable yield loss, and its determination by fitting logistic and Gompertz functions to sequential weed-removal and weed-addition treatments has been standardised (Knezevic *et al.*, 2002). Critical periods vary with environment, crop management and the acceptable loss level chosen. In aerobic rice in Malaysia, maintaining 95% of weed-free yield required control from 7 to 49 days after seeding in the off-season and from 7 to 53 days in the main season (Anwar *et al.*, 2012). Crop spatial arrangement shortens the period of vulnerability. In Zimbabwe, maize sown in 60 cm rows intercepted more radiation than maize in 75 cm or 90 cm rows, and the weed-free period required for maximum yield was three weeks shorter (Mashingaidze *et al.*, 2009). In aerobic rice, 30 cm rows supported more weed biomass and produced less grain than 15 cm or paired rows (Chauhan & Johnson, 2011). The relative time of emergence of crop and weeds is often more important than weed density. For *A. palmeri* in irrigated maize, yield loss depended more on emergence time than on density (Massinga *et al.*, 2001).

Yield-loss models based on the rectangular hyperbola provided the quantitative foundation for economic thresholds (Cousens, 1985), and thresholds have been used to decide whether herbicide application is needed at all (O'Donovan *et al.*, 2007). Threshold-based management has two important limitations in cereals. First, the threshold depends on the competitiveness of the crop, which is itself manipulated by seeding rate, cultivar and fertiliser placement (O'Donovan *et al.*, 2007). Second, single-season thresholds ignore the seed produced by surviving weeds and the selection imposed on the population. For this reason, guidance on herbicide resistance has recommended moving away from single-year economic thresholds towards preventing additions to the seedbank (Norsworthy *et al.*, 2012). The critical period is similarly a single-season concept that identifies when yield protection is needed but not how to limit the long-term growth of weed populations.

The estimates discussed in this section are compared in Table 3, together with the design features that constrain their interpretation. The table shows that the most frequently cited figures are potential losses from research plots, that on-farm estimates are fewer but reveal wide spatial variation, and that losses from resistance and parasitic weeds rely on modelling or sparse incidence data. None of these designs measures the actual losses experienced by farmers under their own weed management, which is the quantity most relevant to setting research and policy priorities.

Table 3. Representative estimates of weed-induced yield loss in cereals and the methodological constraints on their interpretation

Crop and region	Design and scale	Reported loss	Principal constraint on interpretation	Supporting references
Major field crops including wheat, rice and maize, global	Regional synthesis for 2001–2003 across 19 regions	Weeds: highest potential loss of any pest group, 34% across crops	Potential losses assume no control; compiled from heterogeneous sources	Oerke, 2006
Maize, United States and Canada	Replicated small-plot comparisons of non-treated and >95% weed control, 2007–2013	Mean 50%; 148 million tonnes; >US$26.7 billion yr^{-1}	National value assumes no control on every hectare	Soltani *et al.*, 2016
Winter wheat, United States and Canada	Weedy versus >90% control in replicated trials, 2007–2017	2.9–34.4% among regions; weighted mean 23.4%	Research-plot weed pressure may exceed farm conditions	Flessner *et al.*, 2021
Direct-seeded rice and maize, India	1,581 on-farm trials in 18 states, 2003–2014	Potential loss 15–66% (rice) and 18–65% (maize)	Large spatial variation explained by location, crop and soil type	Gharde *et al.*, 2018
Aerobic rice, several countries	Literature review	23–100% without weed control	Heterogeneous studies and weed pressures	Jabran & Chauhan, 2015
Lowland rice, tropical Asia	445 plots with manipulated injuries and production factors	Weed losses stable across attainable yields of 2–11 t ha^{-1}	Experimental injury levels	Savary *et al.*, 2000
Winter wheat and barley	Three years of observations in 54 zones	19–56% for four of six weed communities; no significant loss for two	Observational; community composition confounded with management	Adeux *et al.*, 2019
Winter wheat, England (herbicide-resistant *Alopecurus myosuroides*)	National density and resistance data, yield maps and economic model	0.8 million tonnes and £0.4 billion yr^{-1} attributable to resistance	Depends on modelled density–yield relationships	Varah *et al.*, 2020
Rice, Africa (parasitic weeds)	Herbarium records and literature	At least US$111 million, most likely about US$200 million yr^{-1}	Sparse incidence and loss data	Rodenburg *et al.*, 2016

Note. Potential loss refers to loss in the absence of weed control. Values are reported as in the supporting studies and are not directly comparable because of differences in design, definition of weed-free conditions and aggregation methods

5. Herbicide-Based Management and the Evolution of Resistance

5.1 Why Herbicides Dominate Cereal Weed Control

Herbicides account for about 60% of pesticide use by volume worldwide (Dayan, 2019), and their dominance in cereals has economic and demographic roots. As rural workers move to cities, the labour required for hand weeding becomes scarce and expensive, and herbicides become cheaper and more reliable than manual control. This transition occurred earlier in the United States, Germany, Japan and South Korea, and it is now under way in India, China and Bangladesh and is expected in sub-Saharan Africa (Gianessi, 2013; Haggblade *et al.*, 2017). Herbicide use intensity increased over 25 years in maize, rice and wheat in the United States, and increases were more rapid in crops without genetically engineered herbicide tolerance than in those with it, although chronic and acute toxicity per unit of use declined in several crops (Kniss, 2017). Wheat and rice have remained outside the genetically engineered herbicide-tolerant crop systems that transformed weed management in North American maize and soybean (M. D. K. Owen *et al.*, 2015). Increasing dependence on herbicides as the agricultural labour force declines has been identified as the principal driver of the rise in multiple resistance worldwide (Peterson *et al.*, 2018).

Herbicide performance on farms frequently falls short of that in experiments. A survey of 320 farmers practising dry-seeded rice in Punjab found that inappropriate nozzles, timing and spray volumes led 42% of farmers to undertake additional hand weeding because of poor weed control (Mahajan *et al.*, 2013). In Haryana, a survey of 300 wheat farmers found that some applied three to four times the recommended dose of graminicides and still obtained only about 70% control of *P. minor*, and that resistance was associated not only with repeated use of herbicides with the same mode of action but also with cultural variables such as rotation and the use of rotary tillers for wheat sowing (R. Singh *et al.*, 2021). These findings indicate that application quality and farm practice, rather than herbicide chemistry alone, determine much of the realised efficacy and selection pressure.

5.2 Status of Resistance in Cereal Weeds

Resistance has evolved to all major herbicide modes of action despite resistance management strategies introduced in the 1990s (Délye *et al.*, 2013). By 2014, 220 weed species and 404 unique species-by-site-of-action cases had been documented; ALS inhibitors accounted for about a third of cases and were especially troublesome in rice and cereals (Heap, 2014). Glyphosate resistance, first identified in *L. rigidum* in an Australian orchard in 1996, had been reported in 38 weed species in 37 countries by 2018, including cereal and fallow situations (Heap & Duke, 2018).

Cereal systems provide the most advanced examples of multiple resistance. A random survey of 466 cropping fields in Western Australia in 2010 found that 96% of *L. rigidum* populations contained plants resistant to diclofop-methyl, 98% to sulfometuron and 65% to clethodim (M. J. Owen *et al.*, 2014). In India, *P. minor* resistant to isoproturon was reported in the early 1990s and was more prevalent in rice–wheat areas (Malik & Singh, 1995). The alternative graminicides introduced in response (R. S. Chhokar & Malik, 2002) were followed by resistance across three modes of action, with clodinafop resistance up to 11.7-fold and cross-resistance to fenoxaprop (R. S. Chhokar & Sharma, 2008). In the United Kingdom, *A. myosuroides* populations resistant to one herbicide were likely to be resistant to several classes, and loss of control through resistance could double the economic cost of the weed (Hicks *et al.*, 2018). In rice, *Echinochloa phyllopogon* in California and *E. crus-galli* var. *formosensis* in dry-seeded rice in Japan have evolved resistance to ALS and ACCase inhibitors (Iwakami *et al.*, 2014, 2015). Weedy rice has acquired resistance to imidazolinone herbicides where imidazolinone-tolerant rice is grown (Sudianto *et al.*, 2013; Turra *et al.*, 2026).

5.3 Target-Site and Non-Target-Site Mechanisms

Target-site resistance arises from mutations in the gene encoding the herbicide target that reduce herbicide binding, or from increased expression or duplication of the target gene, whereas non-target-site resistance limits the amount of active herbicide reaching the target, most importantly through enhanced metabolism (Gaines *et al.*, 2020; Powles & Yu, 2010). Early cases were largely herbicide-specific and monogenic, while the cases of greatest current concern involve multiple modes of action, polygenic control and pre-existing stress-response pathways (Délye *et al.*, 2013). Metabolic resistance was first evident in the 1980s in *L. rigidum* in Australia and *A. myosuroides* in the United Kingdom, and it often confers resistance to herbicides of different chemical groups and modes of action, including herbicides to which the population has never been exposed (Yu & Powles, 2014).

The molecular basis of metabolic resistance in cereal weeds is now partly resolved. Increased expression of a phi-class glutathione transferase, AmGSTF1, is associated with multiple resistance in both *A. myosuroides* and *L. rigidum* (Cummins *et al.*, 2013). A single cytochrome P450 gene, CYP81A10v7, from *L. rigidum* conferred resistance to herbicides from at least five modes of action when expressed in rice (Han *et al.*, 2021), and CYP81A enzymes in *E. phyllopogon* metabolise both ALS and ACCase inhibitors, producing concomitant cross-resistance (Iwakami *et al.*, 2014, 2019). Target-site and non-target-site mechanisms frequently co-occur in the same population (Kaundun, 2010). A global review concluded that cross-resistance patterns within the herbicide groups of the Herbicide Resistance Action Committee are usually far more complex than the classification implies (Riechers *et al.*, 2024).

These findings have a direct practical consequence. Resistance management advice has long relied on rotating or mixing herbicides from different groups on the assumption that all active ingredients within a group are affected similarly. Where resistance is metabolic and broad-spectrum, rotating groups may not avoid cross-resistance, and the effective number of independent herbicide options is smaller than the number of groups registered for a crop.

5.4 Contested Questions in Resistance Management

Three questions remain contested. The first concerns herbicide dose. Recurrent selection of an initially susceptible *L. rigidum* population with 10% of the recommended rate of diclofop-methyl produced, after three cycles, a line whose median lethal dose was 56-fold that of the original population and which showed cross-resistance to four other herbicides (Neve & Powles, 2005). Subsequent genetic analysis indicated polygenic control by at least three genes enriched from standing variation (Busi, Neve, & Powles, 2013). These experiments demonstrate that reduced doses can select for quantitative, metabolism-based resistance, but they were conducted with pot-grown plants under controlled selection, and the extent to which sublethal exposure on farms, through underdosing, poor coverage or application at late growth stages, drives resistance has not been quantified in the field.

The second concerns mixtures and rotations. In a four-year field experiment in western Canada, the proportion of ALS-inhibitor-resistant field pennycress (*Thlaspi arvense* L.) in the seedbank rose from 29% after one application to 85% after four applications in rotation sequences, whereas the mixture treatment kept resistance at the level of the untreated control (Beckie & Reboud, 2009). Across 105 Illinois farms with more than 500 site-years of application records, mixing herbicide modes of action at application reduced the likelihood of glyphosate-resistant *Amaranthus tuberculatus* (Moq.) J.D. Sauer, whereas a high annual turnover of modes of action was associated with greater occurrence of resistance (J. A. Evans *et al.*, 2016). A national-scale study of *A. myosuroides* in the United Kingdom, however, found that greater use of mixtures was associated with lower levels of target-site resistance but higher levels of a generalist metabolic mechanism (Comont *et al.*, 2020). Mixtures therefore appear to delay specialist resistance at the cost of selecting for broad-spectrum resistance, which is particularly damaging in cereal grass weeds already prone to metabolism-based resistance. These studies are correlative or confined to single species and regions, and none followed the long-term consequences of a mixture strategy for the full spectrum of available herbicides.

The third concerns the contribution of cultural practices. Modelling and recommendations emphasise diversification of control methods, prevention of seed spread and elimination of seed additions to the seedbank (Norsworthy *et al.*, 2012), and experienced practitioners in the northern Great Plains ranked crop diversity as the most important resistance management practice (Beckie & Harker, 2017). Yet in the national-scale study of *A. myosuroides*, resistance was correlated with the historical frequency of herbicide applications but was not directly related to other cultural techniques (Hicks *et al.*, 2018). This apparent contradiction may reflect the coarse recording of cultural practices in farm surveys, the long time lags between cultural change and its effect on resistant populations, or a genuine dominance of herbicide selection intensity. Resolving it requires long-term experiments in which cultural diversification is imposed and resistance is monitored directly.

5.5 Herbicide-Tolerant Cereals and the Search for New Chemistry

Herbicide-tolerant cereals produced by conventional mutagenesis have provided selective control of weeds that are otherwise impossible to separate from the crop. Imidazolinone-tolerant rice produced the cleanest rice fields in the southern United States by controlling weedy rice, but imidazolinone-resistant weedy rice outcrosses became abundant in some countries, negating the utility of the technology, and herbicide carryover to rotational crops remained a concern (Sudianto *et al.*, 2013). Field experiments in Korea and China confirmed gene flow from cultivated rice to weedy and wild relatives (Chen *et al.*, 2004). In Brazil, nearly two decades of imidazolinone-tolerant rice have produced a landscape of ALS resistance in weedy rice shaped mainly by repeated crop-to-weed gene flow but also by independent mutations, including a Trp574Leu substitution that confers broad cross-resistance to ALS inhibitors (Turra *et al.*, 2026). Gene editing has been added to mutagenesis and transformation as a route to herbicide-tolerant rice (Luo & Liu, 2025), but the experience with imidazolinone-tolerant rice shows that the durability of such traits depends more on stewardship and on the presence of sexually compatible weeds than on the method used to create them. A contrasting use of herbicide tolerance is the coating of imazapyr onto seed of ALS-resistant maize, which gave season-long control of *Striga* and three- to four-fold yield increases under high infestation in 93 farmers' fields and three research stations in four African countries (Kanampiu *et al.*, 2003).

Herbicides with genuinely new modes of action would relieve some of the pressure on existing chemistry. Between the early 1950s and the mid-1980s, a new mode of action was introduced on average every two years, but discovery slowed markedly after the introduction of glyphosate-resistant crops (Dayan, 2019; Duke, 2012). Reasons proposed include the reduced market for new herbicides once glyphosate-tolerant crops were widely adopted, industry consolidation and competition from generic products (Duke, 2012). Recent discoveries include an aryl pyrrolidinone anilide that inhibits dihydroorotate dehydrogenase in pyrimidine biosynthesis and combines strong grass weed control with safety in rice (Selby *et al.*, 2023), and analyses of how new modes of action have originated identify several distinct discovery routes, from competitor-inspired chemistry to natural products (Sparks *et al.*, 2025). New chemistry will take years to reach smallholder systems, will be exposed to existing metabolic resistance mechanisms and will face increasingly stringent regulation. Desk studies of a potential glyphosate ban in the European Union concluded that no-tillage and conservation agriculture would face severe problems without glyphosate and that fundamental and costly changes in farming practice would be required (Kudsk & Mathiassen, 2020). With few new modes of action in prospect and often no economical alternatives to herbicides in large-area crops (Westwood *et al.*, 2018), the central challenge has been framed as the development of alternatives to the almost exclusive reliance on herbicides (Busi, Vila-Aiub, *et al.*, 2013). Herbicide discovery is therefore best regarded as a necessary complement to, not a substitute for, reduced reliance on herbicides.

Table 4 brings together the resistance evidence for the cereal weeds of greatest concern. It shows that the best-characterised cases combine high resistance frequencies with metabolic mechanisms that undermine the logic of rotating herbicide groups, and that the management responses with the strongest support act on weed seed production and population size rather than on the choice of herbicide alone. It also shows that, for *P. minor* in India, extensive documentation of resistance is not matched by equivalent molecular characterisation, a gap that limits prediction of cross-resistance to new herbicides.

Table 4. Herbicide resistance in major weeds of cereals: documented resistance, predominant mechanisms and implications for management

Weed species and system	Documented resistance	Predominant or demonstrated mechanisms	Management implications and confidence	Supporting references
Lolium rigidum, dryland wheat, Australia	96% of surveyed populations with diclofop-methyl resistance, 98% with sulfometuron resistance, 65% with clethodim resistance; glyphosate resistance	Target-site mutations and cytochrome P450-based metabolism across at least five modes of action; low-dose selection of polygenic resistance	Herbicide-only management has failed at landscape scale; strong evidence for adding seed-targeted tactics	Busi, Neve, & Powles, 2013; Han *et al.*, 2021; Heap & Duke, 2018; Neve & Powles, 2005; M. J. Owen *et al.*, 2014
Alopecurus myosuroides, winter wheat, United Kingdom	Multiple resistance at national scale; density correlated with resistance	Glutathione transferase-associated metabolism; target-site mutations; mixtures associated with generalist resistance	Strong evidence that resistance drives abundance; cultural tactics reduce populations but resistance trade-offs persist	Comont *et al.*, 2020; Cummins *et al.*, 2013; Hicks *et al.*, 2018; Moss *et al.*, 2007; Varah *et al.*, 2020
Phalaris minor, wheat, India	Isoproturon resistance from the early 1990s; later resistance to ACCase and ALS inhibitors	Mechanisms incompletely characterised; overdosing and repeated use of one mode of action reported	Moderate evidence; integrated cultural and chemical programmes required	P. K. Chhokar *et al.*, 2025; R. S. Chhokar & Malik, 2002; R. S. Chhokar & Sharma, 2008; Malik & Singh, 1995; R. Singh *et al.*, 2021
Echinochloa spp., rice, United States and Japan	Resistance to ALS inhibitors (bensulfuron-methyl, penoxsulam) and ACCase inhibitors (cyhalofop-butyl)	CYP81A-mediated metabolism conferring concomitant cross-resistance	Strong mechanistic evidence; cross-resistance may extend to herbicides not yet used	Bajwa *et al.*, 2015; Iwakami *et al.*, 2014, 2015, 2019
Weedy rice, imidazolinone-tolerant rice systems	Imidazolinone and wider ALS-inhibitor resistance	Crop-to-weed gene flow and independent target-site mutations	Strong evidence that tolerant-crop systems require strict stewardship	Chen *et al.*, 2004; Sudianto *et al.*, 2013; Turra *et al.*, 2026; Ziska *et al.*, 2015
Other grass weeds of cereals (*Avena*, *Lolium*, *Setaria* spp.)	ACCase-inhibitor resistance across more than 25 million ha of cereals	Target-site substitutions co-occurring with non-target-site mechanisms	Group-based herbicide rotation of limited value where cross-resistance is complex	Heap, 2014; Kaundun, 2010; Riechers *et al.*, 2024
Amaranthus spp., maize systems, North America	Glyphosate resistance associated with frequent glyphosate use	Not addressed in landscape analyses	Mixtures at application reduced risk but did not prevent resistance	J. A. Evans *et al.*, 2016; Heap & Duke, 2018; Webster & Nichols, 2012

Note. ACCase, acetyl-coenzyme A carboxylase; ALS, acetolactate synthase. Confidence statements refer to the strength of evidence for the management implication, assessed with the rubric in Section 2.3

6. Preventive, Cultural and Physical Tactics

6.1 Crop Density, Spatial Arrangement and Competitive Cultivars

The cheapest weed control is often a crop that occupies space and resources before weeds can. Experiments with spring wheat showed that weed suppression increases with crop density and with the spatial uniformity of sowing: across densities of 200–600 plants m^{-2}, sowing in a uniform grid rather than in rows produced 30% less weed biomass and 9% higher grain yield (Weiner *et al.*, 2001). A follow-up study found that reducing the aggregation of plants within rows, even through a random rather than a strictly uniform pattern, increased weed suppression almost as much as a uniform pattern, although the uniform pattern gave the highest yield (Olsen *et al.*, 2005). Under low rainfall in southern Australia, wheat densities of at least 200 plants m^{-2}, compared with the then-recommended 100–150 plants m^{-2}, were required to suppress *L. rigidum*, and yield loss averaged 23% at 100 plants m^{-2} compared with 17% at 200 plants m^{-2}, with cultivar differences small relative to those due to density (Lemerle *et al.*, 2004). Narrow rows have similar effects in maize and rice (Chauhan & Johnson, 2011; Mashingaidze *et al.*, 2009), and crop competition has been reviewed as a practical tool for rice, wheat and maize in India (Ramesh, Rao, & Chauhan, 2017). Higher density is not universally effective. In 52 experiments on *A. myosuroides*, increasing winter wheat density above 100 plants m^{-2} did not reduce weed plant numbers, although it reduced weed heads by 15% for every additional 100 crop plants (Lutman *et al.*, 2013).

Cultivar choice offers a second route to competitiveness, but its exploitation has been slow. Traits associated with competitive ability in cereals include plant height, early vigour, canopy architecture and the pattern of resource partitioning, and competitiveness has not traditionally been a priority in breeding or in farmers' choice of cultivar (Andrew *et al.*, 2015; Lemerle *et al.*, 2001). In New South Wales, competitive commercial wheat cultivars suppressed weeds two- to five-fold more than less competitive cultivars without significant yield penalties (Mwendwa *et al.*, 2020). In aerobic rice at the International Rice Research Institute, early vigour two weeks after seeding and weed-free yield together explained 87% of cultivar variation in yield under weed competition and 40% of variation in weed biomass, so indirect selection on these traits was predicted to be efficient (Zhao *et al.*, 2006). A comparison of 63 spring wheat landraces and modern cultivars, however, found that yield had increased over the past 150 years while weed-suppressive ability had declined slightly (Murphy *et al.*, 2008), and the lack of weed-competitive cultivars adapted to direct seeding remains a constraint in rice (Mahajan & Chauhan, 2013b). Breeding programmes have therefore sought to combine competitive and allelopathic traits (Worthington & Reberg-Horton, 2013).

Two qualifications limit the value of competitive ability as a general cultivar attribute. First, suppression of weeds and tolerance of their presence are distinct, and tolerance is less stable across seasons and locations (Andrew *et al.*, 2015). Second, weed suppression is largely an outcome of interactions among genotype, environment and management. The cultivars of wheat and maize that compete best at high density are often not those that compete best at low density, and effective suppression is achievable only at high crop density and spatial uniformity (Weiner, 2023; Weiner *et al.*, 2001). Screening of cultivars at standard seeding rates may therefore identify the wrong genotypes for systems designed around crop competition.

6.2 Sowing Date, Seedbed Preparation and Nutrient Placement

Sowing date determines which part of the weed emergence period coincides with crop establishment. A meta-analysis of field experiments on *A. myosuroides*, mostly from the United Kingdom, found that delaying drilling of winter cereals from September to the end of October reduced weed densities by about 50%, sowing wheat in spring reduced them by 88%, and mouldboard ploughing reduced them by an average of 69% compared with non-inversion tillage (Lutman *et al.*, 2013). In organic winter wheat in Denmark, delayed sowing and false seedbeds reduced weed biomass, and false seedbeds also reduced the soil seed reserve (Rasmussen, 2004). Stale seedbeds, thorough land preparation and the use of clean seed and machinery are central to the management of weedy rice in direct-seeded systems where selective herbicides are lacking (Chauhan, 2013).

The effect of sowing date is species and system specific. In the rice–wheat systems of India, late sowing of wheat is listed among the factors that increase selection pressure and the problem posed by *P. minor* (P. K. Chhokar *et al.*, 2025), whereas in north-western Europe delayed drilling is a recommended tactic against *A. myosuroides* (Lutman *et al.*, 2013). The contrast reflects the emergence ecology of the target weed, the yield penalty of late sowing in each environment and the interval available between crops. Placement of nutrients can also shift competition in favour of the crop, and strategic fertiliser placement, including sub-surface banding, together with competitive cultivars at relatively high seeding rates, reduced weed effects in spring-sown crops in western Canada (O'Donovan *et al.*, 2007). Because many weeds respond strongly to nitrogen (Blackshaw *et al.*, 2003), broadcast fertiliser applied before crop canopy closure may benefit weeds more than the crop.

6.3 Tillage, Residues and Conservation Agriculture

Conservation agriculture combines minimum soil disturbance, permanent soil cover and crop rotation, and it changes weed management fundamentally. Without tillage there is no burial of weed seeds and soil-applied herbicides are not incorporated, while crop residues can intercept a considerable proportion of pre-emergence herbicide and reduce its efficacy (Chauhan *et al.*, 2012). Conversely, surface residues lower soil temperature, delay emergence and suppress small-seeded annuals through reduced light, physical impedance and possible allelopathic effects, and germinable seedbanks under no-till decline more rapidly than under conventional tillage if new seed inputs are prevented (Nichols *et al.*, 2015). In pot experiments, sorghum residue at 6 t ha^{-1} reduced the biomass of most summer weeds by 59–94% and wheat residue at 8 t ha^{-1} reduced the biomass of winter weeds by 15–100%, although emergence of *Amaranthus retroflexus* L. and *E. colona* was unaffected (Mobli & Chauhan, 2020).

The weed outcomes of conservation agriculture depend on whether all three principles are implemented. A global meta-analysis of 5,463 paired observations found that no-till reduced yields on average, but that negative effects were minimised when no-till was

combined with residue retention and crop rotation, and that the full package increased rainfed yields in dry climates (Pittelkow *et al.*, 2015). A scoping review concluded that the evidence on conservation agriculture for smallholder farmers in sub-Saharan Africa and South Asia was too weak to support strong general conclusions about yield benefits (Brouder & Gomez-Macpherson, 2014). Weeds are repeatedly identified as a major barrier. In the rice–wheat systems of the Indo-Gangetic Plains, weed control remains a major challenge to the adoption of zero tillage and increases dependence on herbicides (Kumar *et al.*, 2013), and in dry-seeded rice, zero-till systems yielded as much as conventionally tilled systems when weeds were effectively controlled but 0.9–1.5 t ha^{-1} less when only one hand weeding was done (Chauhan & Opeña, 2012). The reliance of conservation agriculture on glyphosate for burndown and cover-crop termination makes it particularly vulnerable to regulatory restriction and to glyphosate resistance (Heap & Duke, 2018; Kudsk & Mathiassen, 2020).

Direct-seeded rice raises similar issues. Its adoption in Asia has been driven by scarcity of labour and water (Kumar & Ladha, 2011; Shekhawat *et al.*, 2020), and weed management has been reviewed repeatedly as the main constraint to its success (Matloob *et al.*, 2015; Rao *et al.*, 2007). Field experiments show that dry-seeded or aerobic rice can match puddled transplanted rice in yield and net returns when weeds are controlled, typically with a sequence of pre-emergence and post-emergence herbicides followed by one hand weeding (Mahajan & Chauhan, 2013a; S. Singh *et al.*, 2008). Intercropping with *Sesbania* for about 30 days and wheat residue mulch at 4 t ha^{-1} reduced weed pressure in dry-seeded rice (S. Singh *et al.*, 2007), and rice cultivars tolerant of anaerobic germination could allow early flooding to be used against weeds (Ismail *et al.*, 2012). Weed control practices increased aerobic rice yields by 15–307% across the studies reviewed (Jabran & Chauhan, 2015). The evidence base is nevertheless dominated by research-station experiments with herbicide-intensive programmes, and the alternative establishment methods tested in the north-western Indo-Gangetic Plains were judged to require further refinement in cultivar choice and in nutrient, water and weed management before their potential could be realised (Saharawat *et al.*, 2010).

6.4 Mechanical Weeding

Mechanical weeding by harrowing, inter-row hoeing and hand hoeing remains the main alternative to herbicides in organic cereals and in smallholder systems. European research has sought to replace hand weeding with mechanisation and to integrate physical and cultural methods (Melander *et al.*, 2005). In organic spring cereals, inter-row hoeing reduced weed biomass in spring wheat by 60–70% compared with the standard 125 mm row spacing without hoeing, and the wider rows needed for hoeing did not reduce yield or grain quality, whereas barley suppressed weeds sufficiently on its own (Melander *et al.*, 2018). In poorly competitive organic crops, increased seeding rate combined with several mechanical methods reduced weed biomass (Alba *et al.*, 2020). Mechanical weeding is not free of costs. In organic winter wheat, mechanical control reduced yield when weed pressure was low, had no effect at intermediate pressure and increased yield only when weed pressure was high (Rasmussen, 2004), and cultivars differ in their tolerance of mechanical cultivation (Murphy *et al.*, 2008). Camera-guided hoes are now robust and commercially available, but fully automated mechanical weeding remains constrained by the variability of field conditions (Machleb *et al.*, 2020).

In smallholder maize systems, hoe weeding is often delayed because it is laborious, which leads to large yield losses (Mashingaidze *et al.*, 2009). In the northern Guinea savanna of Nigeria, combinations of herbicide or a velvetbean (*Mucuna cochinchinensis* (Lour.) A. Chev.) cover crop with a medium maize density and three hoe weedings were recommended for weed management (Chikoye *et al.*, 2004). Such combinations illustrate that, where labour is the binding constraint, the value of cultural measures lies largely in reducing the number of weedings required.

6.5 Harvest Weed Seed Control and Weed Seed Predation

Most annual weeds of cereals persist through their seedbank, and tactics that prevent seed return can reduce populations regardless of herbicide resistance status. Harvest weed seed control exploits two biological weaknesses of many annual weeds, namely retention of seed on the plant at crop maturity and a short-lived seedbank, by collecting and destroying the weed-seed-bearing chaff during grain harvest through chaff carts, narrow windrow burning, baling or mechanical seed destructors (Walsh *et al.*, 2013). Across nine locations in the Western Australian wheat belt, 63% of the seed of *L. rigidum* and 79% of that of *Raphanus raphanistrum* L. was still retained above a 15 cm cutting height 28 days after the first opportunity for harvest, but only 41% for brome grass (*Bromus* spp.) and 39% for wild oat (Walsh & Powles, 2014). Simulation modelling indicated that annual, efficient harvest weed seed control protects herbicides from resistance evolution and nearly always eliminates outbreaks of multiple resistance (Somerville *et al.*, 2018). A survey of 600 Australian growers found that 43% routinely used harvest weed seed control, mostly by narrow windrow burning, and that 82% expected to use some form of it within five years (Walsh *et al.*, 2017).

The transferability of harvest weed seed control is less certain. In North America, rotations including crops such as maize that are not currently amenable to the approach, high grain moisture at harvest and untimely harvests limit its potential (Shergill *et al.*, 2020), and the first Canadian adopters of impact mills were mainly operators of large farms of more than 4,000 ha (Tidemann *et al.*, 2024). In Danish oat fields, seed retention at harvest ranged from 23.5% for *Sonchus arvensis* L. to 95.7% for *Silene noctiflora* L., so that only some species were good targets (Bitarafan & Andreasen, 2020), and the opportunities and constraints in European cropping systems have been reviewed (Akhter *et al.*, 2023). No comparable evidence exists for rice or for smallholder systems in which crops are harvested manually, where the equivalent intervention would be the removal of weed seed heads before or during harvest.

Natural seed predation provides a complementary but less controllable route to seedbank reduction. In four organic cereal fields in the Netherlands, calculated annual losses of weed seeds to predation ranged from 32% to 70% when seeds remained exposed from shedding until harvest, falling to 18–57% or 28–67% when exposure was limited to two or four weeks after shedding, and early crop sowing together with hot, dry weather increased the proportion lost (Westerman *et al.*, 2003). Molecular analysis of carabid beetle regurgitates from organic cereal fields across Central Europe showed that weed seeds formed an important part of their diet (Frei *et*

al., 2019). The contribution of predation to population regulation on conventional farms, where tillage buries seeds and insecticides may reduce predator numbers, remains poorly quantified.

7. Diversification, Allelopathy and Biological Approaches

7.1 Crop Rotation and Cropping System Diversity

Simplified rotations expose weeds repeatedly to the same conditions and the same herbicides, whereas diverse rotations impose variable filters that no single weed species is adapted to. Multispecies rotations, intercrops and cover crops may limit weed growth and regeneration through resource competition and niche disruption (Liebman & Davis, 2000). An early synthesis found that crop rotation reduced emerged weed density in 21 of 27 comparisons with monocultures, and seed density in 9 of 12 comparisons (Liebman & Dyck, 1993). A meta-analysis of 298 paired observations from 54 studies on six continents found that diversifying simple rotations reduced weed density by 49% but had no significant effect on weed biomass. Diversification that increased the variance of crop planting dates was more effective than increasing crop species richness alone, and density reductions were larger under zero tillage (65%) than with tillage (41%), regardless of whether herbicides were also used (Weisberger *et al.*, 2019).

Long-term systems experiments show that diversification can maintain weed control with fewer herbicides. In Iowa, three- and four-year rotations including small grains and forage legumes produced yields and profits similar to or greater than those of a conventional two-year maize–soybean rotation, suppressed weeds effectively and reduced freshwater toxicity by two orders of magnitude (Davis *et al.*, 2012). In 12 years of seedbank data from eight no-till rotations, systems including grazed forage phases received less herbicide yet had the lowest weed abundance and the highest weed diversity, and wheat yields were highest where crop diversity was greatest (MacLaren *et al.*, 2019). In the semi-arid Central Great Plains of the United States, an ecological approach to rotation planning allowed producers to control weeds with 50% less herbicide (Anderson, 2005). Experienced researchers and practitioners in the northern Great Plains ranked crop diversity as the foundation of herbicide resistance management (Beckie & Harker, 2017).

The absence of an effect on weed biomass in the global meta-analysis is an important caveat, since biomass rather than density determines competition and seed production in many cases (Weisberger *et al.*, 2019). Fewer but larger weeds may compensate for reductions in density. Most long-term rotation experiments are also located in North America and Europe, while the rice–wheat systems of South Asia, where monocropping is identified as a driver of *P. minor* resistance (P. K. Chhokar *et al.*, 2025), have few long-term tests of diversified rotations with weed outcomes. Rotation is ultimately constrained by markets, irrigation infrastructure and policy, which are outside the control of individual farmers.

7.2 Cover Crops, Intercrops and Companion Plants

Cover crops suppress weeds through competition during their growth and through residues after termination. A meta-analysis found that cover crops provided early-season weed suppression comparable to that achieved by chemical or mechanical methods without affecting the yield of grain crops, and that high biomass production and persistent residue mattered more than whether cover crops were grasses or broad-leaved species or were sown alone or in mixtures (Osipitan *et al.*, 2018). A second meta-analysis of 53 studies found that cover crop biomass was inversely related to weed biomass ($r^2 = 0.67$) and weed density ($r^2 = 0.64$), that grass cover crops suppressed weeds more than broad-leaved species, that autumn-sown cover crops were more suppressive than spring-sown ones and that doubling or tripling the seeding rate increased suppression (Osipitan *et al.*, 2019). In mixtures, low seeding rates of aggressive grasses such as cereal rye were sufficient for suppression, and substantial weed seed production occurred in spring in treatments without cereal rye (Baraibar *et al.*, 2018). The allelopathic potential of rye residues has been linked to benzoxazinoids, which can be released from greenhouse-grown residues at 12–20 kg ha^{-1} and have been measured in soil at 0.5–5 kg ha^{-1} (Schulz *et al.*, 2013).

Intercrops and companion plants provide spatial rather than temporal diversity. A meta-analysis of legume companion plants found no significant effect on cash crop yield but reductions in weed biomass of 56% relative to an unweeded control and 42% relative to a weeded control, with the largest yield benefit in maize (Verret *et al.*, 2017). Under conservation agriculture in Zimbabwe, maize–pigeon pea strip cropping outperformed rotations for weed management, and cropping system biomass was associated with lower weed biomass, although effects were weaker at the less fertile site (Masamba *et al.*, 2026). These results support the general principle that the amount of competitive biomass maintained over the season matters more than species identity, but they also show that suppression weakens where low fertility limits crop and cover biomass, which is precisely where many smallholders farm.

7.3 Allelopathy

Varietal differences in the allelopathic activity of crops were first recognised in the 1970s, and rice, wheat, barley and sorghum have received most attention (Belz, 2007). Allelopathy can be exploited through allelopathic cultivars, crop rotations, cover crops, mulches and plant extracts (Jabran *et al.*, 2015). The difficulty of separating allelochemical effects from competition has long made allelopathy controversial, but reverse genetics has provided direct evidence in rice. Knock-out mutants unable to synthesise momilactones lost part of their ability to suppress the growth of *E. crus-galli* (Xu *et al.*, 2012). In paddy fields, allelopathic rice cultivars combined with cultural management and low herbicide doses suffered no yield reduction, whereas a non-allelopathic cultivar lost 45–60% of its yield even with a low herbicide dose (Kong *et al.*, 2008).

Allelopathy is therefore best regarded as one trait contributing to cultivar weed suppression, which breeding programmes seek to combine with competitive ability (Worthington & Reberg-Horton, 2013), rather than as a stand-alone control method. Field effects are variable, allelochemical release depends on cultivar, development and environment (Schulz *et al.*, 2013), and much of the evidence for weed suppression by plant extracts comes from laboratory bioassays that do not reflect soil conditions.

Table 5. Non-chemical and integrated weed management tactics in cereals: representative effects, conditions for success and principal limitations

Tactic	Representative effect	Conditions favouring success	Principal limitations and evidence gaps	Supporting references
Increased crop density and spatial uniformity	Grid sowing of wheat gave 30% less weed biomass and 9% more yield; at least 200 wheat plants m^{-2} needed to suppress *Lolium rigidum*	High weed pressure; adequate water and nutrients	Cultivar × density interactions; no effec on *Alopecurus myosuroides* plant numbers above 100 crop plants m^{-2}	Lemerle *et al.*, 2004; Lutman *et al.*, 2013; Olsen *et al.*, 2005; Weiner, 2023; Weiner *et al.*, 2001
Competitive cultivars	Two- to five-fold greater weed suppression without yield penalty in wheat; early vigour explained most cultivar variation in weedy yield of aerobic rice	Early vigour, height and rapid canopy closure	Not a breeding priority; tolerance unstable across environments; few cultivars for direct-seeded rice	Andrew *et al.*, 2015; Mahajan & Chauhan, 2013b; Murphy *et al.*, 2008; Mwendwa *et al.*, 2020; Zhao *et al.*, 2006
Narrow rows and planting pattern	Weed-free period required in maize three weeks shorter at 60 cm than at wider rows; narrower rows reduced weeds in aerobic rice	Smallholder systems with limited weeding labour	Few multi-site tests	Chauhan & Johnson, 2011; Mashingaidze *et al.*, 2009
Sowing date, spring cropping and ploughing	About 50%, 88% and 69% reductions of *A. myosuroides*	Autumn-emerging grass weeds	Effects species specific; late sowing aggravates *Phalaris minor* in rice–wheat systems	P. K. Chhokar *et al.*, 2025; Lutman *et al.*, 2013; Rasmussen, 2004
Residue retention and conservation agriculture	Sorghum residue at 6 t ha^{-1} reduced biomass of most summer weeds by 59–94% in pots	Full implementation of residue retention and rotation	Interception of pre-emergence herbicides; perennial weeds; dependence on glyphosate	Chauhan *et al.*, 2012; Kudsk & Mathiassen, 2020; Mobli & Chauhan, 2020; Nichols *et al.*, 2015; Pittelkow *et al.*, 2015
Mechanical weeding	Inter-row hoeing reduced weed biomass in spring wheat by 60–70%	Wide rows, guidance systems, high weed pressure	Yield reduction at low weed pressure; crop injury; labour for hand hoeing	Machleb *et al.*, 2020; Mashingaidze *et al.*, 2009; Melander *et al.*, 2018; Rasmussen, 2004
Harvest weed seed control	Used routinely by 43% of Australian growers; 63–79% of seed of key weeds retained at harvest	Weeds retaining seed above cutting height; dry harvest conditions	Seed-shedding species; maize rotations and high grain moisture; no evidence for rice or manual harvest	Bitarafan & Andreasen, 2020; Shergill *et al.*, 2020; Somerville *et al.*, 2018; Walsh *et al.*, 2017; Walsh & Powles, 2014
Diversified rotations	Weed density reduced by 49% on average, without significant effect on biomass; weeds controlled with 50% less herbicide	Variation in planting dates; zero tillage	Market and infrastructure constraints; few long-term tropical tests	Anderson, 2005; Davis *et al.*, 2012; Liebman & Dyck, 1993; MacLaren *et al.*, 2019; Weisberger *et al.*, 2019
Cover crops, intercrops and companion plants	Early-season suppression comparable to chemical or mechanical control; legume companions reduced weed biomass by 42–56%	High biomass, autumn sowing, high seeding rates, fertile soils	Weaker at low fertility; termination often relies on herbicides	Baraibar *et al.*, 2018; Masamba *et al.*, 2026; Osipitan *et al.*, 2018, 2019; Verret *et al.*, 2017
Allelopathic cultivars	No yield loss in allelopathic rice under integrated management, compared with 45–60% loss in a non-allelopathic cultivar	Integration with cultural measures and reduced herbicide doses	Separation from competition difficult; variable release of allelochemicals	Belz, 2007; Kong *et al.*, 2008; Schulz *et al.*, 2013; Xu *et al.*, 2012
Push–pull and *Desmodium* intercropping	Reduced *Striga* and stemborer damage; mean maize yield 2.5 times higher	East African smallholder maize	Evidence largely from developer-led studies	Khan *et al.*, 2002, 2008; Midega *et al.*, 2015
Biological control and seed predation	*Fusarium oxysporum* f. sp. *strigae* increased maize yield by more than 40–50%; 32–70% annual seed losses to predators in organic cereals	Targeted host-specific agents; undisturbed soil surface after seed shed	Only 13 commercial bioherbicides; predation poorly quantified in conventional systems	Cordeau *et al.*, 2016; Frei *et al.*, 2019; Nzioki *et al.*, 2016; Westerman *et al.*, 2003

Note. Effects are those reported in the supporting studies under their specific conditions and are not additive. Most estimates derive from single tactics tested in isolation

7.4 Parasitic Weeds and Biological Control

The genus *Striga* comprises about 30 obligate root parasites, of which *S. hermonthica*, *S. asiatica* and *S. gesnerioides* (Willd.) Vatke cause the greatest losses in sub-Saharan Africa (Spallek *et al.*, 2013). Because the parasite damages the host before it emerges, control must act on the seedbank, the germination of parasite seed or the attachment process. Intercropping maize with the forage legumes *Desmodium uncinatum* (Jacq.) DC. and *D. intortum* (Mill.) Urb. dramatically reduced *S. hermonthica* infestation, more than other legumes, through a mechanism shown to be allelopathic rather than solely a result of shading or added nitrogen (Khan *et al.*, 2002). This intercrop forms part of the push–pull system, in which *Desmodium* is grown between maize rows and a fodder grass is planted around the field to manage stemborers. On-farm evaluation in western Kenya showed lower *Striga* counts and stemborer damage and higher maize yields in push–pull plots (Khan *et al.*, 2008), and a climate-adapted version using drought-tolerant companion species reduced stemborer levels six-fold and increased mean maize yields 2.5-fold (Midega *et al.*, 2015). Much of this field evidence has been generated by the research groups that developed the technology, and independent evaluation across contrasting environments would strengthen confidence in its generality.

Host resistance and biological agents offer further options. In sorghum, loss of function of the *LOW GERMINATION STIMULANT 1* gene changes the dominant strigolactone in root exudates from 5-deoxystrigol, a potent germination stimulant, to orobanchol and confers resistance to *Striga* (Gobena *et al.*, 2017). A strain of *Fusarium oxysporum* f. sp. *strigae* selected to excrete amino acids toxic to *Striga* and delivered on toothpicks increased maize yields by more than 50% in the long-rains season and by more than 40% in the short-rains season in Kenya (Nzioki *et al.*, 2016). More broadly, the development of bioherbicides has been disappointing. Only 13 bioherbicides were available on the market, representing less than 10% of all biopesticides, although they could contribute to integrated weed management by targeting the seedbank, enhancing mechanical weeding and terminating cover crops (Cordeau *et al.*, 2016).

The evidence on non-chemical and integrated tactics reviewed in Sections 6 and 7 is summarised in Table 5. The table shows that most tactics reduce weed density or biomass by roughly half or less when used alone, that their effects depend strongly on crop biomass, timing and weed species, and that the strongest evidence comes from temperate mechanised systems. It also highlights a recurring evidence gap: few studies have measured the combined and cumulative effects of several tactics on the weed seedbank and on resistance over periods long enough to capture population dynamics.

8. Precision and Digital Weed Management

Weeds in cereal fields are usually distributed in patches rather than uniformly, so uniform broadcast application treats large areas where weed density is below any economically relevant level. Site-specific weed management aims to match physical and chemical treatments to this spatial and temporal heterogeneity by combining sensing, decision algorithms and precise actuation (Gerhards *et al.*, 2022). Early systems for real-time weed detection, decision making and patch spraying were developed for maize, winter wheat and winter barley (Gerhards & Christensen, 2003). In a four-year experiment on five fields with a GPS-guided sprayer, an average of 54% of herbicides was saved, with savings of 90% for grass herbicides in winter cereals and 78% in maize, and of 60% for broad-leaved weed herbicides in winter cereals but only 11% in maize; the corresponding monetary savings were €42 ha^{-1} in maize, €32 ha^{-1} in winter wheat and €27 ha^{-1} in winter barley (Timmermann *et al.*, 2003).

Detection technologies have since moved from spectral indices to imaging from unmanned aerial vehicles and to deep learning. An object-based analysis of multispectral images from unmanned aerial vehicles produced weed maps of early-season maize (Peña *et al.*, 2013), and deep learning methods, particularly convolutional neural networks, have been reviewed extensively for weed recognition and incorporated into the design of modular spot sprayers (Allmendinger *et al.*, 2022; Darbyshire *et al.*, 2024; Hasan *et al.*, 2021). In an on-farm trial in four maize fields in south-western Germany, an automatic classifier correctly identified 94% of weed plants in aerial images, spot spraying based on these maps achieved weed control efficacy of up to 86%, equal to broadcast application, and early spot spraying saved 47% of herbicide without reducing maize yield (Allmendinger *et al.*, 2024). Sensors are also being used to guide mechanical weeders, and camera-steered hoes are now robust commercial products (Machleb *et al.*, 2020).

The evidence supports substantial herbicide savings where weeds are patchy and where detection is reliable, but it has three limitations. Most evaluations are short-term and conducted in a small number of fields in Europe and North America, and the long-term consequences of leaving low-density patches untreated for seedbank dynamics and resistance have not been measured. Herbicide savings reduce the area treated, but within treated patches the selection pressure on the weed population is unchanged, so precision application is not in itself a resistance management strategy. Adoption is also constrained by technical factors: most systems use proprietary information technology protocols that prevent the connection of sensors and implements from different manufacturers, and further on-farm research is needed to integrate these technologies into practice (Gerhards *et al.*, 2022). The relevance of these technologies to smallholder cereal systems, where fields are small and herbicides are applied with knapsack sprayers, remains largely untested.

9. Climate Change and Emerging Weed Threats

Climate change is expected to alter weed floras directly, through effects on germination, growth and reproduction, and indirectly, through the adaptations of agronomic practice that it forces. In European arable systems, thermophilous, late-emerging and some opportunistic weeds have become more abundant over recent decades, and changes in species composition and the introduction of new species are expected to be favoured under further warming (Peters *et al.*, 2014). Ecological niche modelling predicts poleward expansion of *E. indica*, a globally distributed grass weed with multiple resistance mechanisms, into key agricultural regions (Ludwig *et al.*, 2026). *A. palmeri*, introduced to Europe and the Mediterranean region possibly through contaminated animal feed

and grain shipments, spread from roadsides into nearby agricultural fields (Matzrafi *et al.*, 2025), illustrating that trade and climate act together in shaping future cereal weed floras.

Climate and rising carbon dioxide concentrations may also reduce herbicide efficacy through effects on spray coverage and field access during weather extremes and through direct effects on plant biochemistry and morphology (Ziska, 2016). The breeding of cultivars that tolerate both climate stress and weed competition has been proposed as an adaptation strategy (Korres *et al.*, 2016). The evidence base for these projections is weaker than for most other topics in this review. It relies heavily on controlled-environment experiments with single species, niche models calibrated on occurrence records and observations that coincide with simultaneous changes in management. Recent shifts in weed spectra that have been attributed to climate change therefore warrant closer examination before causal conclusions are drawn (Ramesh, Matloob, *et al.*, 2017), and research at the population and community scales, rather than only the landscape scale, is needed to inform management (Peters *et al.*, 2014).

10. Integration and Adoption: Why Integrated Weed Management Remains Under-Used

10.1 The Gap between Recommendation and Practice

Integrated weed management has been defined as a holistic approach that integrates different control methods to give the crop an advantage over weeds, with the potential to restrict weed populations to manageable levels, reduce environmental impacts and reduce selection for resistance (Harker & O'Donovan, 2013). Frameworks for its implementation have been developed for European arable systems (Riemens *et al.*, 2022), and an ecological approach that manipulates the agroecosystem to limit weed competitiveness while maintaining weed diversity has been advocated as the most sustainable route (MacLaren *et al.*, 2020). Yet research effort and practice remain dominated by herbicides. A bibliometric assessment found that publications on chemical control still eclipsed those on any other weed management method (Harker & O'Donovan, 2013), and in the United States and Canada integrated weed management has been characterised in practice as integrated herbicide management, with limited adoption of diverse tactics (M. D. K. Owen *et al.*, 2015).

Adoption studies identify consistent reasons. Compared with chemical control, the general applicability, reliability and efficacy of most cultural measures are lower and their outcomes more variable, and their combination increases system complexity and involves trade-offs (Bastiaans *et al.*, 2008). Herbicides are justifiably seen as the easier option because their convenience outweighs the complexity, cost and management time associated with non-chemical alternatives, and non-chemical methods are often adopted to compensate for reduced herbicide efficacy due to resistance rather than as alternatives to herbicides (Moss, 2019). Farmers in Ohio understood integrated weed management but did not practise it, partly because of gaps in their understanding of the human role in weed dispersal and a focus on the risks posed by weeds rather than the risks associated with management (Wilson *et al.*, 2009). Among 132 Western Australian grain growers, awareness of integrated practices was high, but herbicide-based practices were perceived as the most cost-effective, and adoption was most likely where practices offered short-term economic value to the wider farming system (Llewellyn *et al.*, 2004).

10.2 Resistance as a Collective Problem

Herbicide susceptibility in a region behaves as a common-pool resource that is depleted by the actions of individual farmers and by weed dispersal across farm boundaries, so resistance management has been described as a wicked problem with no standard template across regions (Jussaume & Ervin, 2016). Well-known socioeconomic phenomena create barriers to resistance management that biological research alone cannot remove, and overcoming them requires approaches that recognise differences among farmers and engage regulators, researchers, extension services and industry (Hurley & Frisvold, 2016). The experience of Australian grain production shows that adoption of demanding non-chemical tactics can become widespread once resistance has made herbicide-only systems unworkable, as the routine use of harvest weed seed control by 43% of growers demonstrates (M. J. Owen *et al.*, 2014; Walsh *et al.*, 2017). That adoption was reactive, however, and the national-scale analysis of black-grass in the United Kingdom concluded that an evolutionarily informed approach must be proactive rather than reactive (Hicks *et al.*, 2018).

The available evidence suggests that substantial reductions in herbicide use are possible without economic loss in many situations. In a national network of French arable farms, low pesticide use was compatible with high productivity and profitability in 59% of farms, which corresponded to an average reduction in herbicide use of 37% (Lechenet *et al.*, 2017). In Iowa, more diverse rotations met or exceeded the performance of a conventional rotation with much lower agrichemical inputs (Davis *et al.*, 2012). These studies come from high-income systems with established markets for diverse crops, and their transferability to the rice–wheat systems of South Asia or to smallholder maize in Africa, where alternative crops, machinery and advisory services may be lacking, is uncertain. In India, surveys of farmers practising dry-seeded rice and of wheat growers facing resistant *P. minor* show that deficiencies in herbicide selection, timing, dose and application are themselves major contributors to poor weed control and resistance (Mahajan *et al.*, 2013; R. Singh *et al.*, 2021).

10.3 An Evidence-Graded Framework

The relationships synthesised in this review are drawn together in Fig. 1, an original conceptual framework developed from the present synthesis rather than adapted from earlier work. It links the socioeconomic drivers of weed management choices to the filters that management imposes on weed communities and to the agronomic and evolutionary outcomes that follow, and it distinguishes relationships supported by strong evidence from those that are conditional or hypothesised. The framework emphasises two feedbacks. The first is the evolutionary feedback in which reliance on herbicides selects for resistance, reduces herbicide efficacy and prompts further, often reactive, changes in management (Hicks *et al.*, 2018; Moss, 2019). The second is the

ecological feedback in which diversified management lowers weed seedbank inputs and the dominance of competitive species, which may in turn reduce both yield loss and selection pressure (Adeux *et al.*, 2019; Weisberger *et al.*, 2019). The first feedback is well documented; the second is supported for weed density but remains conditional for yield and resistance outcomes because few long-term studies have measured them together.

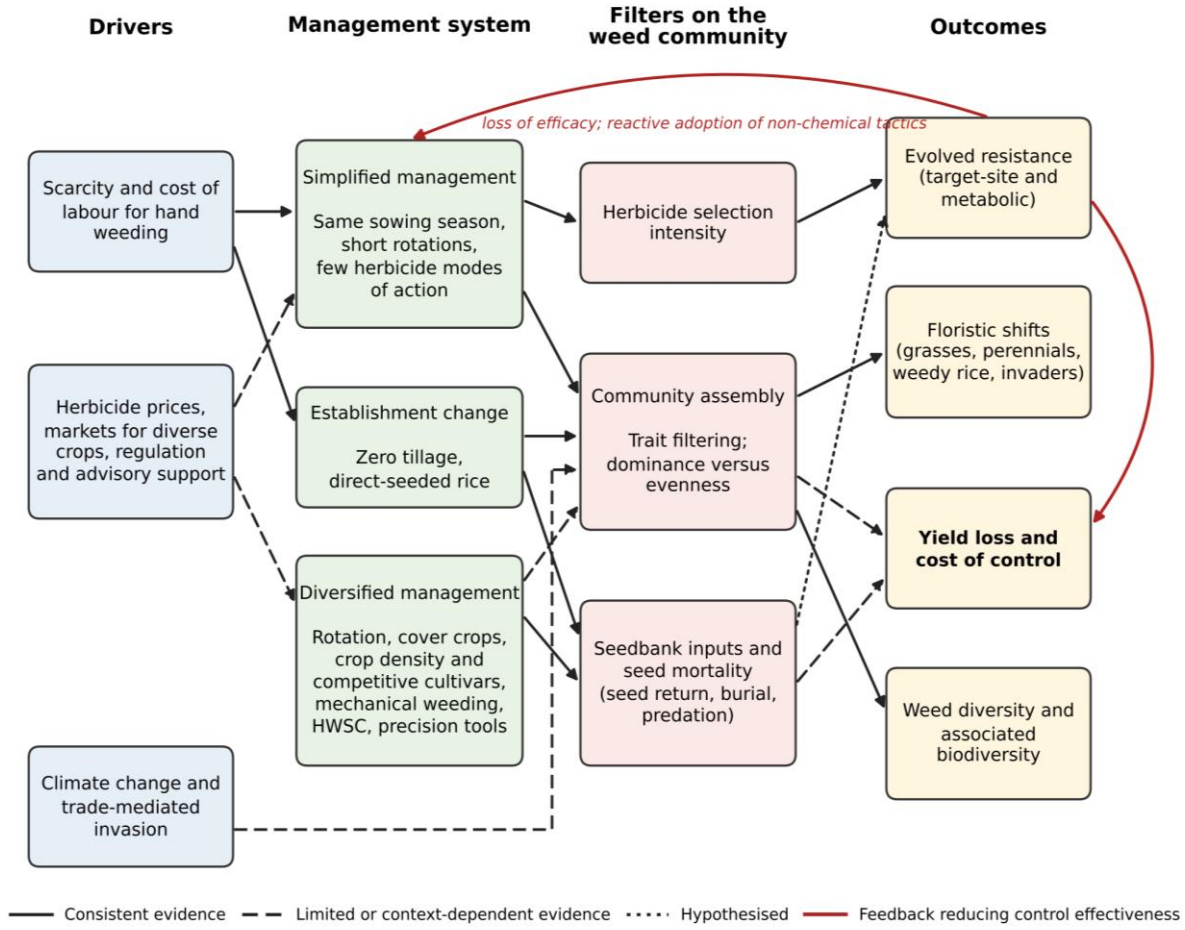


Fig. 1. Evidence-graded conceptual framework linking drivers of weed management, management filters, weed community responses and outcomes in cereal systems, developed from the present synthesis. Solid arrows denote relationships supported by consistent evidence from multiple independent field studies, meta-analyses or national-scale analyses; dashed arrows denote relationships supported by limited or context-dependent evidence; dotted arrows denote hypothesised relationships not yet tested directly; red arrows denote feedbacks that reduce the effectiveness of weed control. HWSC, harvest weed seed control; MOA, mode of action

11. Future Directions

The most urgent research need is long-term, multi-site testing of combinations of tactics rather than further short-term efficacy trials of single tactics. Current evidence shows that crop density, competitive cultivars, rotation, cover crops, mechanical weeding and harvest weed seed control each reduce weed populations partially and inconsistently, and that their value lies in cumulative effects on the seedbank that are rarely measured. Diversified rotations reduce weed density but not, on average, weed biomass (Weisberger *et al.*, 2019), and the weed-suppressive potential of rotations of four or more years has been identified as a research gap (Nichols *et al.*, 2015). The appropriate design is a systems experiment of at least eight to ten years, replicated across contrasting environments and including the rice–wheat systems of South Asia and the maize systems of sub-Saharan Africa, in which combinations of tactics are compared with herbicide-intensive controls. Outcome measures should include seed production, seedbank density and composition, resistance frequency confirmed by dose–response testing, crop yield, labour requirement, profitability and herbicide use. Such experiments would replace extrapolation from single-tactic trials with direct evidence on whether integrated systems deliver durable control, and they would provide the quantitative insight into efficacy, variability and trade-offs that has long been called for (Bastiaans *et al.*, 2008).

Table 6. Prioritised research agenda for weed management in cereal crops

Priority and timescale	Unresolved problem	Recommended design and scale	Key outcome measures	Supporting references
1. Long-term integrated systems experiments (immediate)	Single tactics are partial and short-term trials do not capture seedbank dynamics	Multi-site systems experiments of at least eight to ten years, including South Asian and African cereal systems	Seed production, seedbank, resistance frequency, yield, labour, profitability, herbicide use	Bastiaans *et al.*, 2008; Nichols *et al.*, 2015; Weisberger *et al.*, 2019
2. Actual losses under farm conditions (immediate)	National estimates measure potential losses in research plots	On-farm trial networks comparing farmer practice with weed-free and improved treatments	Actual and attainable yield loss; weed community composition	Adeux *et al.*, 2019; Flessner *et al.*, 2021; Gharde *et al.*, 2018; Rodenburg *et al.*, 2016; Soltani *et al.*, 2016
3. Resistance in Asian and African cereal weeds (immediate)	Mechanisms in *Phalaris minor*, *Echinochloa* spp. and weedy rice poorly characterised; mixture versus rotation debate unresolved	Representative surveys with molecular diagnostics; multi-generation field comparisons of resistance strategies	Target-site and metabolic resistance frequencies; cross-resistance spectra	P. K. Chhokar *et al.*, 2025; Comont *et al.*, 2020; Iwakami *et al.*, 2015; Riechers *et al.*, 2024; Turra *et al.*, 2026
4. Breeding for weed suppression (medium term)	Competitiveness rankings depend on density; few cultivars for direct-seeded rice	Multi-environment trials at high density and uniform sowing; trait-based and genomic selection	Weed biomass and seed production, yield under competition, early vigour	Horvath *et al.*, 2023; Mahajan & Chauhan, 2013b; Weiner, 2023; Zhao *et al.*, 2006
5. Seed-focused tactics in new contexts (medium term)	Harvest weed seed control untested in rice and smallholder systems; predation unquantified in conventional fields	On-farm adaptation trials; predation exclusion experiments	Seed retention, seed destruction, seedbank change	Akhter *et al.*, 2023; Bitarafan & Andreasen, 2020; Shergill *et al.*, 2020; Westerman *et al.*, 2003
6. Precision technologies (medium term)	Effects on populations and resistance unknown; limited interoperability; untested in small fields	Multi-year on-farm comparisons of spot spraying and guided weeding	Herbicide use, weed density trajectory, resistance, cost	Allmendinger *et al.*, 2024; Gerhards *et al.*, 2022; Machleb *et al.*, 2020
7. Adoption and institutions (immediate to medium term)	Integrated weed management under-adopted despite evidence of profitable herbicide reduction	Randomised or quasi-experimental evaluation of incentives, advisory and area-wide approaches	Practice change, herbicide use, weed control, farm income	Hurley & Frisvold, 2016; Jussaume & Ervin, 2016; Lechenet *et al.*, 2017; Moss, 2019
8. Surveillance of floristic change (longer term)	Climate-driven and invasion-driven shifts cannot be separated from management effects	Repeated standardised national surveys in Asian and African cereal regions	Species frequency and density, trait composition, new invasions	Ludwig *et al.*, 2026; Matzrafi *et al.*, 2025; Peters *et al.*, 2014; Salonen *et al.*, 2023

Note. Timescales indicate the order in which work is most needed rather than the duration of individual projects

A second immediate priority is the assessment of actual weed-induced losses under farm conditions. Existing national estimates measure potential losses in research plots (Flessner *et al.*, 2021; Soltani *et al.*, 2016), whereas on-farm trials reveal large spatial variation driven by location, crop and soil (Gharde *et al.*, 2018). Networks of on-farm trials in which the farmer's own weed management is compared with weed-free and improved treatments, combined with standardised protocols and statistical models that account for weed community composition (Adeux *et al.*, 2019), would allow research and policy priorities to be based on attainable gains rather than on theoretical maxima. These networks should also quantify losses from parasitic weeds, for which data remain scant (Rodenburg *et al.*, 2016).

The third priority concerns resistance in the cereal weeds of Asia and Africa. Resistance in *P. minor* is well documented phenotypically but poorly characterised at the molecular level (P. K. Chhokar *et al.*, 2025; R. S. Chhokar & Sharma, 2008), and resistance in *Echinochloa* species and weedy rice is expanding with direct seeding and herbicide-tolerant rice (Iwakami *et al.*, 2015; Turra *et al.*, 2026). Molecular diagnostics that distinguish target-site from metabolic resistance, combined with surveys designed for statistical representativeness, are needed to predict cross-resistance to new herbicides. Because mixtures may trade specialist for generalist resistance (Comont *et al.*, 2020) and cross-resistance within herbicide groups is complex (Riechers *et al.*, 2024), field experiments that compare mixtures, rotations and non-chemical diversification while monitoring both resistance types over several generations would resolve one of the main contested questions in this field.

In the medium term, breeding for weed suppression should be redirected towards the conditions in which suppression is effective. Cultivar rankings for competitiveness change with crop density (Weiner, 2023), and indirect selection on early vigour and weed-free yield appears efficient in aerobic rice (Zhao *et al.*, 2006), yet cultivars adapted to direct seeding remain scarce (Mahajan & Chauhan, 2013b). Breeding trials should evaluate candidate lines at high density and with uniform sowing, include traits related to allelopathy and to the perception of neighbours (Horvath *et al.*, 2023; Xu *et al.*, 2012), and report weed seed production as well as yield. Seed-focused tactics also need to be adapted to new contexts. Harvest weed seed control has not been evaluated in rice or in manually harvested smallholder crops, and its constraints in North American and European systems have been identified but not overcome (Akhter *et al.*, 2023; Shergill *et al.*, 2020). The contribution of seed predators to weed regulation in conventional cereals also requires field quantification (Westerman *et al.*, 2003).

Precision technologies require long-term evaluation of their effects on weed populations and resistance, not only on herbicide savings, together with work on interoperability and on low-cost versions suited to small fields (Allmendinger *et al.*, 2024; Gerhards *et al.*, 2022). Research on adoption should be treated as a core component of weed science rather than an afterthought. The reasons why farmers do not adopt integrated weed management are increasingly well described (Llewellyn *et al.*, 2004; Moss, 2019), but evaluations of interventions designed to change practice, including area-wide management of resistance as a common-pool problem (Jussaume & Ervin, 2016), incentives and advisory approaches, are largely absent. Randomised or quasi-experimental evaluations of such interventions, with herbicide use, weed control and farm income as outcomes, would show which policies can turn the evidence that herbicide use can often be reduced without loss of profitability (Lechenet *et al.*, 2017) into practice. Finally, as a longer-term need, repeated standardised weed surveys modelled on the long-running Finnish series (Salonen *et al.*, 2023) should be established in the major cereal regions of Asia and Africa, so that shifts in floras caused by climate change, invasion and changes in management can be detected and distinguished (Ludwig *et al.*, 2026; Peters *et al.*, 2014).

These priorities are summarised in Table 6, which distinguishes immediate from longer-term needs and specifies for each the problem, the recommended design and the outcomes that would make the results useful for management and policy. The common thread is a shift in emphasis from short-term efficacy of individual tactics towards long-term population, evolutionary and economic outcomes of management systems.

12. Conclusions

The weed floras of cereal crops are shaped above all by management. Sowing season, crop sequence, tillage, crop establishment and the intensity and diversity of herbicide use act as filters that select a small number of well-adapted species, particularly grass weeds that resemble the crop and broad-leaved annuals with high seed output. Where management has been simplified, weed communities have become less diverse and more dominated by competitive, herbicide-resistant species, and the transition from transplanted to direct-seeded rice and from tillage to zero tillage has reorganised floras within a few seasons. These conclusions are supported by large surveys and long-term experiments, although they rest disproportionately on European evidence.

Weeds remain capable of causing very large yield losses in all major cereals, but the most widely cited estimates are potential losses measured in research plots and should be interpreted as the value of weed control rather than as losses suffered by farmers. Losses depend on the composition of the weed community and on the relative timing of crop and weed emergence as much as on weed density, and early, possibly partly resource-independent interference makes the timing of control critical. Whether perception-driven interference is quantitatively important in the field remains unresolved.

Herbicide resistance in the principal grass weeds of cereals is now widespread, often multiple and increasingly metabolic. This is the most strongly supported and most consequential conclusion of the review, because it undermines resistance management based on rotating herbicide groups and limits the protection that new modes of action can offer. Whether herbicide mixtures delay or redirect resistance evolution is contested, and herbicide-tolerant cereals, although valuable, have shown that resistance traits can move into weedy relatives where stewardship is weak.

Non-chemical tactics are individually partial. Higher crop density with uniform sowing, competitive cultivars, narrow rows, appropriate sowing dates, residue retention, mechanical weeding, harvest weed seed control, diversified rotations, cover crops and

intercrops each reduce weed populations, but rarely by more than about half, and their effects vary with environment, crop biomass and weed species. The evidence is strongest for tactics that reduce seed return to the seedbank and for system diversification in temperate mechanised agriculture, and weakest for combinations of tactics over long periods and for smallholder systems in Asia and Africa. Allelopathy, biological control and precision technologies add useful options but do not yet provide stand-alone solutions.

The central problem is therefore not a shortage of tactics but the difficulty of combining them into systems that farmers can and will adopt. Herbicides remain easier and, in the short term, often cheaper than the alternatives, and integrated approaches are typically adopted only after resistance has made herbicide-only systems fail. Durable cereal weed management will depend on diversified management that limits both seedbank inputs and selection pressure, on research designed to measure long-term population, evolutionary and economic outcomes, and on institutional arrangements that recognise herbicide susceptibility as a shared resource.

13. Limitations

The first limitation is intrinsic to the narrative review design. Although the search strategy, eligibility criteria and appraisal rubric were reported transparently, the selection and interpretation of studies involved judgement, and selection and interpretive bias cannot be excluded. A narrative review does not require the procedures of a systematic review, such as record-level screening counts, deduplication counts or independent dual screening with reviewer agreement statistics, and these were not undertaken, so the completeness of the evidence base cannot be quantified.

The search relied on open and freely accessible bibliographic sources, and subscription-based citation indexes were not used. Some relevant studies may therefore have been missed, particularly those in regional journals that are poorly indexed in international databases. Only English-language publications were included, which probably under-represents research published in Chinese, Japanese, Korean, Portuguese, Spanish and other languages on rice and maize weed management. For a small number of studies the full text was not accessible, and their use was restricted to claims verifiable from abstracts and publisher metadata.

The evidence base is heterogeneous in design, scale, duration and outcome, ranging from controlled-environment experiments to national surveys and simulation models, and this heterogeneity precluded quantitative synthesis. The geographical distribution of evidence is uneven, with long-term experiments, trait-based analyses and resistance mechanism studies concentrated in Europe, North America and Australia, while evidence from South and South-East Asia and sub-Saharan Africa is dominated by short-term field trials. Much of the evidence on weed community drivers, resistance management and adoption is observational, which limits causal inference, and publication bias may favour reports of effective tactics over null results. Finally, fields such as gene editing, machine vision and herbicide discovery are developing rapidly, so some conclusions about emerging technologies may be overtaken by new evidence.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Adeux, G., Vieren, E., Carlesi, S., Bàrberi, P., Munier-Jolain, N., & Cordeau, S. (2019). Mitigating crop yield losses through weed diversity. *Nature Sustainability*, *2*(11), 1018–1026. https://doi.org/10.1038/s41893-019-0415-y

Akhter, M. J., Sønderskov, M., Loddo, D., Ulber, L., Hull, R., & Kudsk, P. (2023). Opportunities and challenges for harvest weed seed control in European cropping systems. *European Journal of Agronomy*, *142*, Article 126639. https://doi.org/10.1016/j.eja.2022.126639

Alba, O. S., Syrovy, L. D., Duddu, H. S. N., & Shirtliffe, S. J. (2020). Increased seeding rate and multiple methods of mechanical weed control reduce weed biomass in a poorly competitive organic crop. *Field Crops Research*, *245*, Article 107648. https://doi.org/10.1016/j.fcr.2019.107648

Allmendinger, A., Spaeth, M., Saile, M., Peteinatos, G. G., & Gerhards, R. (2022). Precision chemical weed management strategies: A review and a design of a new CNN-based modular spot sprayer. *Agronomy*, *12*(7), Article 1620. https://doi.org/10.3390/agronomy12071620

Allmendinger, A., Spaeth, M., Saile, M., Peteinatos, G. G., & Gerhards, R. (2024). Agronomic and technical evaluation of herbicide spot spraying in maize based on high-resolution aerial weed maps: An on-farm trial. *Plants*, *13*(15), Article 2164. https://doi.org/10.3390/plants13152164

Anderson, R. L. (2005). A multi-tactic approach to manage weed population dynamics in crop rotations. *Agronomy Journal*, *97*(6), 1579–1583. https://doi.org/10.2134/agronj2005.0194

Andreasen, C., & Stryhn, H. (2008). Increasing weed flora in Danish arable fields and its importance for biodiversity. *Weed Research*, *48*(1), 1–9. https://doi.org/10.1111/j.1365-3180.2008.00603.x

Andrew, I. K. S., Storkey, J., & Sparkes, D. L. (2015). A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Research*, *55*(3), 239–248. https://doi.org/10.1111/wre.12137

Anwar, M. P., Juraimi, A. S., Samedani, B., Puteh, A., & Man, A. (2012). Critical period of weed control in aerobic rice. *The Scientific World Journal*, *2012*, Article 603043. https://doi.org/10.1100/2012/603043

Armengot, L., Blanco-Moreno, J. M., Bàrberi, P., Bocci, G., Carlesi, S., Aendekerk, R., Berner, A., Celette, F., Grosse, M., Huiting, H., Kranzler, A., Luik, A., Mäder, P., Peigné, J., Stoll, E., Delfosse, P., Sukkel, W., Surböck, A., Westaway, S., & Sans, F. X. (2016). Tillage as a driver of change in weed communities: A functional perspective. *Agriculture, Ecosystems & Environment*, *222*, 276–285. https://doi.org/10.1016/j.agee.2016.02.021

Baethge, C., Goldbeck-Wood, S., & Mertens, S. (2019). SANRA: A scale for the quality assessment of narrative review articles. *Research Integrity and Peer Review*, *4*(1), Article 5. https://doi.org/10.1186/s41073-019-0064-8

Bajwa, A. A., Jabran, K., Shahid, M., Ali, H. H., Chauhan, B. S., & Ehsanullah. (2015). Eco-biology and management of *Echinochloa crus-galli*. *Crop Protection*, *75*, 151–162. https://doi.org/10.1016/j.cropro.2015.06.001

Baraibar, B., Hunter, M. C., Schipanski, M. E., Hamilton, A., & Mortensen, D. A. (2018). Weed suppression in cover crop monocultures and mixtures. *Weed Science*, *66*(1), 121–133. https://doi.org/10.1017/wsc.2017.59

Bàrberi, P., & Lo Cascio, B. (2001). Long-term tillage and crop rotation effects on weed seedbank size and composition. *Weed Research*, *41*(4), 325–340. https://doi.org/10.1046/j.1365-3180.2001.00241.x

Bastiaans, L., Paolini, R., & Baumann, D. T. (2008). Focus on ecological weed management: What is hindering adoption? *Weed Research*, *48*(6), 481–491. https://doi.org/10.1111/j.1365-3180.2008.00662.x

Beckie, H. J., & Harker, K. N. (2017). Our top 10 herbicide-resistant weed management practices. *Pest Management Science*, *73*(6), 1045–1052. https://doi.org/10.1002/ps.4543

Beckie, H. J., & Reboud, X. (2009). Selecting for weed resistance: Herbicide rotation and mixture. *Weed Technology*, *23*(3), 363–370. https://doi.org/10.1614/wt-09-008.1

Beckie, H. J., Francis, A., & Hall, L. M. (2012). The biology of Canadian weeds. 27. *Avena fatua* L. (updated). *Canadian Journal of Plant Science*, *92*(7), 1329–1357. https://doi.org/10.4141/cjps2012-005

Belz, R. G. (2007). Allelopathy in crop/weed interactions: An update. *Pest Management Science*, *63*(4), 308–326. https://doi.org/10.1002/ps.1320

Bitarafan, Z., & Andreasen, C. (2020). Seed retention of ten common weed species at oat harvest reveals the potential for harvest weed seed control. *Weed Research*, *60*(5), 343–352. https://doi.org/10.1111/wre.12438

Blackshaw, R. E., Brandt, R. N., Janzen, H. H., Entz, T., Grant, C. A., & Derksen, D. A. (2003). Differential response of weed species to added nitrogen. *Weed Science*, *51*(4), 532–539. [https://doi.org/10.1614/0043-1745(2003)051\[0532:drowst\]2.0.co;2](https://doi.org/10.1614/0043-1745%282003%29051%5B0532:drowst%5D2.0.co;2)

Brouder, S. M., & Gomez-Macpherson, H. (2014). The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence. *Agriculture, Ecosystems & Environment*, *187*, 11–32. https://doi.org/10.1016/j.agee.2013.08.010

Busi, R., Neve, P., & Powles, S. (2013). Evolved polygenic herbicide resistance in *Lolium rigidum* by low-dose herbicide selection within standing genetic variation. *Evolutionary Applications*, *6*(2), 231–242. https://doi.org/10.1111/j.1752-4571.2012.00282.x

Busi, R., Vila-Aiub, M. M., Beckie, H. J., Gaines, T. A., Goggin, D. E., Kaundun, S. S., Lacoste, M., Neve, P., Nissen, S. J., Norsworthy, J. K., Renton, M., Shaner, D. L., Tranel, P. J., Wright, T., Yu, Q., & Powles, S. B. (2013). Herbicide-resistant weeds: From research and knowledge to future needs. *Evolutionary Applications*, *6*(8), 1218–1221. https://doi.org/10.1111/eva.12098

Chauhan, B. S. (2012). Weed ecology and weed management strategies for dry-seeded rice in Asia. *Weed Technology*, *26*(1), 1–13. https://doi.org/10.1614/wt-d-11-00105.1

Chauhan, B. S. (2013). Strategies to manage weedy rice in Asia. *Crop Protection*, *48*, 51–56. https://doi.org/10.1016/j.cropro.2013.02.015

Chauhan, B. S., & Johnson, D. E. (2011). Row spacing and weed control timing affect yield of aerobic rice. *Field Crops Research*, *121*(2), 226–231. https://doi.org/10.1016/j.fcr.2010.12.008

Chauhan, B. S., & Opeña, J. (2012). Effect of tillage systems and herbicides on weed emergence, weed growth, and grain yield in dry-seeded rice systems. *Field Crops Research*, *137*, 56–69. https://doi.org/10.1016/j.fcr.2012.08.016

Chauhan, B. S., Singh, R. G., & Mahajan, G. (2012). Ecology and management of weeds under conservation agriculture: A review. *Crop Protection*, *38*, 57–65. https://doi.org/10.1016/j.cropro.2012.03.010

Chen, L. J., Lee, D. S., Song, Z. P., Suh, H. S., & Lu, B.-R. (2004). Gene flow from cultivated rice (*Oryza sativa*) to its weedy and wild relatives. *Annals of Botany*, *93*(1), 67–73. https://doi.org/10.1093/aob/mch006

Chhokar, P. K., Chaudhary, A., Prajapat, K., & Chhokar, R. S. (2025). Management practices to control multiple herbicide resistant *Phalaris minor* in wheat. *Weed Biology and Management*, *25*(3), Article e70006. https://doi.org/10.1111/wbm.70006

Chhokar, R. S., & Malik, R. K. (2002). Isoproturon-resistant littleseed canarygrass (*Phalaris minor*) and its response to alternate herbicides. *Weed Technology*, *16*(1), 116–123. [https://doi.org/10.1614/0890-037x(2002)016\[0116:irlcpm\]2.0.co;2](https://doi.org/10.1614/0890-037x%282002%29016%5B0116:irlcpm%5D2.0.co;2)

Chhokar, R. S., & Sharma, R. K. (2008). Multiple herbicide resistance in littleseed canarygrass (*Phalaris minor*): A threat to wheat production in India. *Weed Biology and Management*, *8*(2), 112–123. https://doi.org/10.1111/j.1445-6664.2008.00283.x

Chhokar, R. S., Sharma, R. K., Jat, G. R., Pundir, A. K., & Gathala, M. K. (2007). Effect of tillage and herbicides on weeds and productivity of wheat under rice–wheat growing system. *Crop Protection*, *26*(11), 1689–1696. https://doi.org/10.1016/j.cropro.2007.01.010

Chikoye, D., Schulz, S., & Ekeleme, F. (2004). Evaluation of integrated weed management practices for maize in the northern Guinea savanna of Nigeria. *Crop Protection*, *23*(10), 895–900. https://doi.org/10.1016/j.cropro.2004.01.013

Colbach, N., Adeux, G., Cordeau, S., & Moreau, D. (2023). Weed-induced yield loss through resource competition cannot be sidelined. *Trends in Plant Science*, *28*(12), 1329–1330. https://doi.org/10.1016/j.tplants.2023.08.004

Comont, D., Lowe, C., Hull, R., Crook, L., Hicks, H. L., Onkokesung, N., Beffa, R., Childs, D. Z., Edwards, R., Freckleton, R. P., & Neve, P. (2020). Evolution of generalist resistance to herbicide mixtures reveals a trade-off in resistance management. *Nature Communications*, *11*(1), Article 3086. https://doi.org/10.1038/s41467-020-16896-0

Cordeau, S., Triolet, M., Wayman, S., Steinberg, C., & Guillemin, J.-P. (2016). Bioherbicides: Dead in the water? A review of the existing products for integrated weed management. *Crop Protection*, *87*, 44–49. https://doi.org/10.1016/j.cropro.2016.04.016

Cousens, R. (1985). A simple model relating yield loss to weed density. *Annals of Applied Biology*, *107*(2), 239–252. https://doi.org/10.1111/j.1744-7348.1985.tb01567.x

Cummins, I., Wortley, D. J., Sabbadin, F., He, Z., Coxon, C. R., Straker, H. E., Sellars, J. D., Knight, K., Edwards, L., Hughes, D., Kaundun, S. S., Hutchings, S.-J., Steel, P. G., & Edwards, R. (2013). Key role for a glutathione transferase in multiple-herbicide resistance in grass weeds. *Proceedings of the National Academy of Sciences*, *110*(15), 5812–5817. https://doi.org/10.1073/pnas.1221179110

Darbyshire, M., Coutts, S., Bosilj, P., Sklar, E., & Parsons, S. (2024). Review of weed recognition: A global agriculture perspective. *Computers and Electronics in Agriculture*, *227*, Article 109499. https://doi.org/10.1016/j.compag.2024.109499

Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M., & Liebman, M. (2012). Increasing cropping system diversity balances productivity, profitability and environmental health. *PLoS ONE*, *7*(10), Article e47149. https://doi.org/10.1371/journal.pone.0047149

Davis, A. S., Renner, K. A., & Gross, K. L. (2005). Weed seedbank and community shifts in a long-term cropping systems experiment. *Weed Science*, *53*(3), 296–306. https://doi.org/10.1614/ws-04-182

Dayan, F. E. (2019). Current status and future prospects in herbicide discovery. *Plants*, *8*(9), Article 341. https://doi.org/10.3390/plants8090341

de Mol, F., von Redwitz, C., & Gerowitt, B. (2015). Weed species composition of maize fields in Germany is influenced by site and crop sequence. *Weed Research*, *55*(6), 574–585. https://doi.org/10.1111/wre.12169

Délye, C., Jasieniuk, M., & Le Corre, V. (2013). Deciphering the evolution of herbicide resistance in weeds. *Trends in Genetics*, *29*(11), 649–658. https://doi.org/10.1016/j.tig.2013.06.001

Duke, S. O. (2012). Why have no new herbicide modes of action appeared in recent years? *Pest Management Science*, *68*(4), 505–512. https://doi.org/10.1002/ps.2333

Evans, J. A., Tranel, P. J., Hager, A. G., Schutte, B., Wu, C., Chatham, L. A., & Davis, A. S. (2016). Managing the evolution of herbicide resistance. *Pest Management Science*, *72*(1), 74–80. https://doi.org/10.1002/ps.4009

Evans, S. P., Knezevic, S. Z., Lindquist, J. L., Shapiro, C. A., & Blankenship, E. E. (2003). Nitrogen application influences the critical period for weed control in corn. *Weed Science*, *51*(3), 408–417. [https://doi.org/10.1614/0043-1745(2003)051\[0408:naitcp\]2.0.co;2](https://doi.org/10.1614/0043-1745%282003%29051%5B0408:naitcp%5D2.0.co;2)

Flessner, M. L., Burke, I. C., Dille, J. A., Everman, W. J., VanGessel, M. J., Tidemann, B., Manuchehri, M. R., Soltani, N., & Sikkema, P. H. (2021). Potential wheat yield loss due to weeds in the United States and Canada. *Weed Technology*, *35*(6), 916–923. https://doi.org/10.1017/wet.2021.78

Frei, B., Guenay, Y., Bohan, D. A., Traugott, M., & Wallinger, C. (2019). Molecular analysis indicates high levels of carabid weed seed consumption in cereal fields across Central Europe. *Journal of Pest Science*, *92*(3), 935–942. https://doi.org/10.1007/s10340-019-01109-5

Fried, G., Kazakou, E., & Gaba, S. (2012). Trajectories of weed communities explained by traits associated with species' response to management practices. *Agriculture, Ecosystems & Environment*, *158*, 147–155. https://doi.org/10.1016/j.agee.2012.06.005

Fried, G., Norton, L. R., & Reboud, X. (2008). Environmental and management factors determining weed species composition and diversity in France. *Agriculture, Ecosystems & Environment*, *128*(1–2), 68–76. https://doi.org/10.1016/j.agee.2008.05.003

Gaba, S., Chauvel, B., Dessaint, F., Bretagnolle, V., & Petit, S. (2010). Weed species richness in winter wheat increases with landscape heterogeneity. *Agriculture, Ecosystems & Environment*, *138*(3–4), 318–323. https://doi.org/10.1016/j.agee.2010.06.005

Gaines, T. A., Duke, S. O., Morran, S., Rigon, C. A. G., Tranel, P. J., Küpper, A., & Dayan, F. E. (2020). Mechanisms of evolved herbicide resistance. *Journal of Biological Chemistry*, *295*(30), 10307–10330. https://doi.org/10.1074/jbc.rev120.013572

Gerhards, R., & Christensen, S. (2003). Real-time weed detection, decision making and patch spraying in maize, sugarbeet, winter wheat and winter barley. *Weed Research*, *43*(6), 385–392. https://doi.org/10.1046/j.1365-3180.2003.00349.x

Gerhards, R., Andújar Sanchez, D., Hamouz, P., Peteinatos, G. G., Christensen, S., & Fernandez-Quintanilla, C. (2022). Advances in site-specific weed management in agriculture: A review. *Weed Research*, *62*(2), 123–133. https://doi.org/10.1111/wre.12526

Gharde, Y., Singh, P. K., Dubey, R. P., & Gupta, P. K. (2018). Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection*, *107*, 12–18. https://doi.org/10.1016/j.cropro.2018.01.007

Gianessi, L. P. (2013). The increasing importance of herbicides in worldwide crop production. *Pest Management Science*, *69*(10), 1099–1105. https://doi.org/10.1002/ps.3598

Gobena, D., Shimels, M., Rich, P. J., Ruyter-Spira, C., Bouwmeester, H., Kanuganti, S., Mengiste, T., & Ejeta, G. (2017). Mutation in sorghum *LOW GERMINATION STIMULANT 1* alters strigolactones and causes *Striga* resistance. *Proceedings of the National Academy of Sciences*, *114*(17), 4471–4476. https://doi.org/10.1073/pnas.1618965114

Greenhalgh, T., Thorne, S., & Malterud, K. (2018). Time to challenge the spurious hierarchy of systematic over narrative reviews? *European Journal of Clinical Investigation*, *48*(6), Article e12931. https://doi.org/10.1111/eci.12931

Gunton, R. M., Petit, S., & Gaba, S. (2011). Functional traits relating arable weed communities to crop characteristics. *Journal of Vegetation Science*, *22*(3), 541–550. https://doi.org/10.1111/j.1654-1103.2011.01273.x

Haggblade, S., Minten, B., Pray, C., Reardon, T., & Zilberman, D. (2017). The herbicide revolution in developing countries: Patterns, causes, and implications. *The European Journal of Development Research*, *29*(3), 533–559. https://doi.org/10.1057/s41287-017-0090-7

Han, H., Yu, Q., Beffa, R., González, S., Maiwald, F., Wang, J., & Powles, S. B. (2021). Cytochrome P450 CYP81A10v7 in *Lolium rigidum* confers metabolic resistance to herbicides across at least five modes of action. *The Plant Journal*, *105*(1), 79–92. https://doi.org/10.1111/tpj.15040

Harker, K. N., & O'Donovan, J. T. (2013). Recent weed control, weed management, and integrated weed management. *Weed Technology*, *27*(1), 1–11. https://doi.org/10.1614/wt-d-12-00109.1

Hasan, A. S. M. M., Sohel, F., Diepeveen, D., Laga, H., & Jones, M. G. K. (2021). A survey of deep learning techniques for weed detection from images. *Computers and Electronics in Agriculture*, *184*, Article 106067. https://doi.org/10.1016/j.compag.2021.106067

Heap, I. (2014). Global perspective of herbicide-resistant weeds. *Pest Management Science*, *70*(9), 1306–1315. https://doi.org/10.1002/ps.3696

Heap, I., & Duke, S. O. (2018). Overview of glyphosate-resistant weeds worldwide. *Pest Management Science*, *74*(5), 1040–1049. https://doi.org/10.1002/ps.4760

Hicks, H. L., Comont, D., Coutts, S. R., Crook, L., Hull, R., Norris, K., Neve, P., Childs, D. Z., & Freckleton, R. P. (2018). The factors driving evolved herbicide resistance at a national scale. *Nature Ecology & Evolution*, *2*(3), 529–536. https://doi.org/10.1038/s41559-018-0470-1

Horvath, D. P., Clay, S. A., Swanton, C. J., Anderson, J. V., & Chao, W. S. (2023). Weed-induced crop yield loss: A new paradigm and new challenges. *Trends in Plant Science*, *28*(5), 567–582. https://doi.org/10.1016/j.tplants.2022.12.014

Hurley, T. M., & Frisvold, G. (2016). Economic barriers to herbicide-resistance management. *Weed Science*, *64*(SP1), 585–594. https://doi.org/10.1614/ws-d-15-00046.1

Hyvönen, T., Ketoja, E., Salonen, J., Jalli, H., & Tiainen, J. (2003). Weed species diversity and community composition in organic and conventional cropping of spring cereals. *Agriculture, Ecosystems & Environment*, *97*(1–3), 131–149. https://doi.org/10.1016/s0167-8809(03)00117-8

Ismail, A. M., Johnson, D. E., Ella, E. S., Vergara, G. V., & Baltazar, A. M. (2012). Adaptation to flooding during emergence and seedling growth in rice and weeds, and implications for crop establishment. *AoB Plants*, *2012*, Article pls019. https://doi.org/10.1093/aobpla/pls019

Iwakami, S., Endo, M., Saika, H., Okuno, J., Nakamura, N., Yokoyama, M., Watanabe, H., Toki, S., Uchino, A., & Inamura, T. (2014). Cytochrome P450 CYP81A12 and CYP81A21 are associated with resistance to two acetolactate synthase inhibitors in *Echinochloa phyllopogon*. *Plant Physiology*, *165*(2), 618–629. https://doi.org/10.1104/pp.113.232843

Iwakami, S., Hashimoto, M., Matsushima, K.-I., Watanabe, H., Hamamura, K., & Uchino, A. (2015). Multiple-herbicide resistance in *Echinochloa crus-galli* var. *formosensis*, an allohexaploid weed species, in dry-seeded rice. *Pesticide Biochemistry and Physiology*, *119*, 1–8. https://doi.org/10.1016/j.pestbp.2015.02.007

Iwakami, S., Kamidate, Y., Yamaguchi, T., Ishizaka, M., Endo, M., Suda, H., Nagai, K., Sunohara, Y., Toki, S., Uchino, A., Tominaga, T., & Matsumoto, H. (2019). CYP81A P450s are involved in concomitant cross-resistance to acetolactate synthase and acetyl-CoA carboxylase herbicides in *Echinochloa phyllopogon*. *New Phytologist*, *221*(4), 2112–2122. https://doi.org/10.1111/nph.15552

Jabran, K., & Chauhan, B. S. (2015). Weed management in aerobic rice systems. *Crop Protection*, *78*, 151–163. https://doi.org/10.1016/j.cropro.2015.09.005

Jabran, K., Mahajan, G., Sardana, V., & Chauhan, B. S. (2015). Allelopathy for weed control in agricultural systems. *Crop Protection*, *72*, 57–65. https://doi.org/10.1016/j.cropro.2015.03.004

Jabran, K., Mahmood, K., Melander, B., Bajwa, A. A., & Kudsk, P. (2017). Weed dynamics and management in wheat. *Advances in Agronomy*, *145*, 97–166. https://doi.org/10.1016/bs.agron.2017.05.002

Johnson, D. E., & Kent, R. J. (2002). The impact of cropping on weed species composition in rice after fallow across a hydrological gradient in West Africa. *Weed Research*, *42*(2), 89–99. https://doi.org/10.1046/j.1365-3180.2002.00265.x

Jussaume, R. A., & Ervin, D. (2016). Understanding weed resistance as a wicked problem to improve weed management decisions. *Weed Science*, *64*(SP1), 559–569. https://doi.org/10.1614/ws-d-15-00131.1

Kanampiu, F. K., Kabambe, V., Massawe, C., Jasi, L., Friesen, D., Ransom, J. K., & Gressel, J. (2003). Multi-site, multi-season field tests demonstrate that herbicide seed-coating herbicide-resistance maize controls *Striga* spp. and increases yields in several African countries. *Crop Protection*, *22*(5), 697–706. https://doi.org/10.1016/s0261-2194(03)00007-3

Kaundun, S. S. (2010). An aspartate to glycine change in the carboxyl transferase domain of acetyl CoA carboxylase and non-target-site mechanism(s) confer resistance to ACCase inhibitor herbicides in a *Lolium multiflorum* population. *Pest Management Science*, *66*(11), 1249–1256. https://doi.org/10.1002/ps.2003

Kaur, S., Kaur, R., & Chauhan, B. S. (2018). Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. *Crop Protection*, *103*, 65–72. https://doi.org/10.1016/j.cropro.2017.09.011

Khan, Z. R., Hassanali, A., Overholt, W., Khamis, T. M., Hooper, A. M., Pickett, J. A., Wadhams, L. J., & Woodcock, C. M. (2002). Control of witchweed *Striga hermonthica* by intercropping with *Desmodium* spp., and the mechanism defined as allelopathic. *Journal of Chemical Ecology*, *28*(9), 1871–1885. https://doi.org/10.1023/a:1020525521180

Khan, Z. R., Midega, C. A. O., Amudavi, D. M., Hassanali, A., & Pickett, J. A. (2008). On-farm evaluation of the 'push–pull' technology for the control of stemborers and *Striga* weed on maize in western Kenya. *Field Crops Research*, *106*(3), 224–233. https://doi.org/10.1016/j.fcr.2007.12.002

Knezevic, S. Z., Evans, S. P., Blankenship, E. E., Van Acker, R. C., & Lindquist, J. L. (2002). Critical period for weed control: The concept and data analysis. *Weed Science*, *50*(6), 773–786. [https://doi.org/10.1614/0043-1745(2002)050\[0773:cpfwct\]2.0.co;2](https://doi.org/10.1614/0043-1745%282002%29050%5B0773:cpfwct%5D2.0.co;2)

Kniss, A. R. (2017). Long-term trends in the intensity and relative toxicity of herbicide use. *Nature Communications*, *8*(1), Article 14865. https://doi.org/10.1038/ncomms14865

Kong, C.-H., Hu, F., Wang, P., & Wu, J.-L. (2008). Effect of allelopathic rice varieties combined with cultural management options on paddy field weeds. *Pest Management Science*, *64*(3), 276–282. https://doi.org/10.1002/ps.1521

Korres, N. E., Norsworthy, J. K., Tehranchian, P., Gitsopoulos, T. K., Loka, D. A., Oosterhuis, D. M., Gealy, D. R., Moss, S. R., Burgos, N. R., Miller, M. R., & Palhano, M. (2016). Cultivars to face climate change effects on crops and weeds: A review. *Agronomy for Sustainable Development*, *36*(1), Article 12. https://doi.org/10.1007/s13593-016-0350-5

Kudsk, P., & Mathiassen, S. K. (2020). Pesticide regulation in the European Union and the glyphosate controversy. *Weed Science*, *68*(3), 214–222. https://doi.org/10.1017/wsc.2019.59

Kumar, V., & Ladha, J. K. (2011). Direct seeding of rice. *Advances in Agronomy*, *111*, 297–413. https://doi.org/10.1016/b978-0-12-387689-8.00001-1

Kumar, V., Singh, S., Chhokar, R. S., Malik, R. K., Brainard, D. C., & Ladha, J. K. (2013). Weed management strategies to reduce herbicide use in zero-till rice–wheat cropping systems of the Indo-Gangetic Plains. *Weed Technology*, *27*(1), 241–254. https://doi.org/10.1614/wt-d-12-00069.1

Lacroix, C., Vandenberghe, C., Monty, A., & Dumont, B. (2024). Effect of long-term tillage and residue managements on weed flora and its impact on winter wheat development. *Agriculture, Ecosystems & Environment, 366*, Article 108937. https://doi.org/10.1016/j.agee.2024.108937

Lechenet, M., Dessaint, F., Py, G., Makowski, D., & Munier-Jolain, N. (2017). Reducing pesticide use while preserving crop productivity and profitability on arable farms. *Nature Plants*, *3*(3), Article 17008. https://doi.org/10.1038/nplants.2017.8

Légère, A., Stevenson, F. C., & Benoit, D. L. (2011). The selective memory of weed seedbanks after 18 years of conservation tillage. *Weed Science*, *59*(1), 98–106. https://doi.org/10.1614/ws-d-10-00092.1

Lemerle, D., Cousens, R. D., Gill, G. S., Peltzer, S. J., Moerkerk, M., Murphy, C. E., Collins, D., & Cullis, B. R. (2004). Reliability of higher seeding rates of wheat for increased competitiveness with weeds in low rainfall environments. *The Journal of Agricultural Science*, *142*(4), 395–409. https://doi.org/10.1017/s002185960400454x

Lemerle, D., Gill, G. S., Murphy, C. E., Walker, S. R., Cousens, R. D., Mokhtari, S., Peltzer, S. J., Coleman, R., & Luckett, D. J. (2001). Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. *Australian Journal of Agricultural Research*, *52*(5), 527–548. https://doi.org/10.1071/ar00056

Liebman, M., & Davis, A. S. (2000). Integration of soil, crop and weed management in low-external-input farming systems. *Weed Research*, *40*(1), 27–47. https://doi.org/10.1046/j.1365-3180.2000.00164.x

Liebman, M., & Dyck, E. (1993). Crop rotation and intercropping strategies for weed management. *Ecological Applications*, *3*(1), 92–122. https://doi.org/10.2307/1941795

Llewellyn, R. S., Lindner, R. K., Pannell, D. J., & Powles, S. B. (2004). Grain grower perceptions and use of integrated weed management. *Australian Journal of Experimental Agriculture*, *44*(10), 993–1001. https://doi.org/10.1071/ea03115

Lowry, C. J., Brainard, D. C., Kumar, V., Smith, R. G., Singh, M., Kumar, P., Kumar, A., Kumar, V., Joon, R. K., Jat, R. K., Poonia, S., Malik, R. K., & McDonald, A. (2021). Weed germinable seedbanks of rice–wheat systems in the Eastern Indo-Gangetic Plains: Do tillage and edaphic factors explain community variation? *Weed Research*, *61*(6), 475–485. https://doi.org/10.1111/wre.12505

Ludwig, T. D., Borgato, E. A., de Avila, L. A., Roncaglia, L. M., & Zucchi, M. I. (2026). Climate change-driven expansion of goosegrass highlights risks to global food production. *Pest Management Science*, *82*(7), 6494–6508. https://doi.org/10.1002/ps.70731

Luo, Q., & Liu, Y.-G. (2025). Breeding herbicide-resistant rice using CRISPR-Cas gene editing and other technologies. *Plant Communications*, *6*(2), Article 101172. https://doi.org/10.1016/j.xplc.2024.101172

Lutman, P. J. W., Moss, S. R., Cook, S., & Welham, S. J. (2013). A review of the effects of crop agronomy on the management of *Alopecurus myosuroides*. *Weed Research*, *53*(5), 299–313. https://doi.org/10.1111/wre.12024

Machleb, J., Peteinatos, G. G., Kollenda, B. L., Andújar, D., & Gerhards, R. (2020). Sensor-based mechanical weed control: Present state and prospects. *Computers and Electronics in Agriculture*, *176*, Article 105638. https://doi.org/10.1016/j.compag.2020.105638

MacLaren, C., Storkey, J., Menegat, A., Metcalfe, H., & Dehnen-Schmutz, K. (2020). An ecological future for weed science to sustain crop production and the environment: A review. *Agronomy for Sustainable Development*, *40*(4), Article 24. https://doi.org/10.1007/s13593-020-00631-6

MacLaren, C., Storkey, J., Strauss, J., Swanepoel, P., & Dehnen-Schmutz, K. (2019). Livestock in diverse cropping systems improve weed management and sustain yields whilst reducing inputs. *Journal of Applied Ecology*, *56*(1), 144–156. https://doi.org/10.1111/1365-2664.13239

Mahajan, G., & Chauhan, B. S. (2013a). Herbicide options for weed control in dry-seeded aromatic rice in India. *Weed Technology*, *27*(4), 682–689. https://doi.org/10.1614/wt-d-13-00016.1

Mahajan, G., & Chauhan, B. S. (2013b). The role of cultivars in managing weeds in dry-seeded rice production systems. *Crop Protection*, *49*, 52–57. https://doi.org/10.1016/j.cropro.2013.03.008

Mahajan, G., & Chauhan, B. S. (2021). Interference of wild oat (*Avena fatua*) and sterile oat (*Avena sterilis* ssp. *ludoviciana*) in wheat. *Weed Science*, *69*(4), 485–491. https://doi.org/10.1017/wsc.2021.25

Mahajan, G., Chauhan, B. S., & Gill, M. S. (2013). Dry-seeded rice culture in Punjab State of India: Lessons learned from farmers. *Field Crops Research*, *144*, 89–99. https://doi.org/10.1016/j.fcr.2013.01.008

Malik, R. K., & Singh, S. (1995). Littleseed canarygrass (*Phalaris minor*) resistance to isoproturon in India. *Weed Technology*, *9*(3), 419–425. https://doi.org/10.1017/s0890037x00023629

Marshall, E. J. P., Brown, V. K., Boatman, N. D., Lutman, P. J. W., Squire, G. R., & Ward, L. K. (2003). The role of weeds in supporting biological diversity within crop fields. *Weed Research*, *43*(2), 77–89. https://doi.org/10.1046/j.1365-3180.2003.00326.x

Masamba, B. R., MacLaren, C., Mabasa, S., Chikowo, R., & Thierfelder, C. (2026). Strip crops and intercrops outperform crop rotations for weed management under conservation agriculture in Zimbabwe. *Weed Research*, *66*(1), Article e70061. https://doi.org/10.1111/wre.70061

Mashingaidze, A. B., Van Der Werf, W., Lotz, L. A. P., Chipomho, J., & Kropff, M. J. (2009). Narrow rows reduce biomass and seed production of weeds and increase maize yield. *Annals of Applied Biology*, *155*(2), 207–218. https://doi.org/10.1111/j.1744-7348.2009.00331.x

Massinga, R. A., Currie, R. S., Horak, M. J., & Boyer, J. (2001). Interference of Palmer amaranth in corn. *Weed Science*, *49*(2), 202–208. [https://doi.org/10.1614/0043-1745(2001)049\[0202:iopaic\]2.0.co;2](https://doi.org/10.1614/0043-1745%282001%29049%5B0202:iopaic%5D2.0.co;2)

Matloob, A., Khaliq, A., & Chauhan, B. S. (2015). Weeds of direct-seeded rice in Asia: Problems and opportunities. *Advances in Agronomy*, *130*, 291–336. https://doi.org/10.1016/bs.agron.2014.10.003

Matzrafi, M., Scarabel, L., Milani, A., Iamonico, D., Torra, J., Recasens, J., Montull, J. M., Llenes, J. M., Gazoulis, I., Tataridas, A., Rubin, B., Pardo, G., Cirujeda, A., Marí, A. I., Mennan, H., Kanatas, P., Dogan, M. N., Beffa, R., & Travlos, I. (2025). *Amaranthus palmeri* S. Watson: A new threat to agriculture in Europe and the Mediterranean region. *Weed Research*, *65*(1), Article e12596. https://doi.org/10.1111/wre.12596

Melander, B., Jabran, K., De Notaris, C., Znova, L., Green, O., & Olesen, J. E. (2018). Inter-row hoeing for weed control in organic spring cereals: Influence of inter-row spacing and nitrogen rate. *European Journal of Agronomy*, *101*, 49–56. https://doi.org/10.1016/j.eja.2018.08.005

Melander, B., Rasmussen, I. A., & Bàrberi, P. (2005). Integrating physical and cultural methods of weed control: Examples from European research. *Weed Science*, *53*(3), 369–381. https://doi.org/10.1614/ws-04-136r

Mhlanga, B., Ercoli, L., Thierfelder, C., & Pellegrino, E. (2022). Conservation agriculture practices lead to diverse weed communities and higher maize grain yield in Southern Africa. *Field Crops Research*, *289*, Article 108724. https://doi.org/10.1016/j.fcr.2022.108724

Midega, C. A. O., Bruce, T. J. A., Pickett, J. A., Pittchar, J. O., Murage, A., & Khan, Z. R. (2015). Climate-adapted companion cropping increases agricultural productivity in East Africa. *Field Crops Research*, *180*, 118–125. https://doi.org/10.1016/j.fcr.2015.05.022

Milberg, P., & Hallgren, E. (2004). Yield loss due to weeds in cereals and its large-scale variability in Sweden. *Field Crops Research*, *86*(2–3), 199–209. https://doi.org/10.1016/j.fcr.2003.08.006

Mishra, J. S., Kumar, R., Mondal, S., Poonia, S. P., Rao, K. K., Dubey, R., Raman, R. K., Dwivedi, S. K., Kumar, R., Saurabh, K., Monobrullah, M., Kumar, S., Bhatt, B. P., Malik, R. K., Kumar, V., McDonald, A., & Bhaskar, S. (2022). Tillage and crop establishment effects on weeds and productivity of a rice–wheat–mungbean rotation. *Field Crops Research*, *284*, Article 108577. https://doi.org/10.1016/j.fcr.2022.108577

Mobli, A., & Chauhan, B. S. (2020). Crop residue retention suppresses seedling emergence and biomass of winter and summer Australian weed species. *Weed Biology and Management*, *20*(3), 118–128. https://doi.org/10.1111/wbm.12208

Moss, S. R. (2019). Integrated weed management (IWM): Why are farmers reluctant to adopt non-chemical alternatives to herbicides? *Pest Management Science*, *75*(5), 1205–1211. https://doi.org/10.1002/ps.5267

Moss, S. R., Perryman, S. A. M., & Tatnell, L. V. (2007). Managing herbicide-resistant blackgrass (*Alopecurus myosuroides*): Theory and practice. *Weed Technology*, *21*(2), 300–309. https://doi.org/10.1614/wt-06-087.1

Moss, S. R., Storkey, J., Cussans, J. W., Perryman, S. A. M., & Hewitt, M. V. (2004). The Broadbalk long-term experiment at Rothamsted: What has it told us about weeds? *Weed Science*, *52*(5), 864–873. https://doi.org/10.1614/ws-04-012r1

Murphy, K. M., Dawson, J. C., & Jones, S. S. (2008). Relationship among phenotypic growth traits, yield and weed suppression in spring wheat landraces and modern cultivars. *Field Crops Research*, *105*(1–2), 107–115. https://doi.org/10.1016/j.fcr.2007.08.004

Mwangi, O., Mucheru-Muna, M., Kinyua, M., Bolo, P., & Kihara, J. (2024). Organic farming practices increase weed density and diversity over conventional practices: A meta-analysis. *Heliyon*, *10*(12), Article e32761. https://doi.org/10.1016/j.heliyon.2024.e32761

Mwendwa, J. M., Brown, W. B., Weidenhamer, J. D., Weston, P. A., Quinn, J. C., Wu, H., & Weston, L. A. (2020). Evaluation of commercial wheat cultivars for canopy architecture, early vigour, weed suppression, and yield. *Agronomy*, *10*(7), Article 983. https://doi.org/10.3390/agronomy10070983

Neve, P., & Powles, S. (2005). Recurrent selection with reduced herbicide rates results in the rapid evolution of herbicide resistance in *Lolium rigidum*. *Theoretical and Applied Genetics*, *110*(6), 1154–1166. https://doi.org/10.1007/s00122-005-1947-2

Nichols, V., Verhulst, N., Cox, R., & Govaerts, B. (2015). Weed dynamics and conservation agriculture principles: A review. *Field Crops Research*, *183*, 56–68. https://doi.org/10.1016/j.fcr.2015.07.012

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., & Barrett, M. (2012). Reducing the risks of herbicide resistance: Best management practices and recommendations. *Weed Science*, *60*(SP1), 31–62. https://doi.org/10.1614/ws-d-11-00155.1

Nzioki, H. S., Oyosi, F., Morris, C. E., Kaya, E., Pilgeram, A. L., Baker, C. S., & Sands, D. C. (2016). *Striga* biocontrol on a toothpick: A readily deployable and inexpensive method for smallholder farmers. *Frontiers in Plant Science*, *7*, Article 1121. https://doi.org/10.3389/fpls.2016.01121

O'Donovan, J. T., Blackshaw, R. E., Harker, K. N., Clayton, G. W., Moyer, J. R., Dosdall, L. M., Maurice, D. C., & Turkington, T. K. (2007). Integrated approaches to managing weeds in spring-sown crops in western Canada. *Crop Protection*, *26*(3), 390–398. https://doi.org/10.1016/j.cropro.2005.09.018

Oerke, E. C. (2006). Crop losses to pests. *The Journal of Agricultural Science*, *144*(1), 31–43. https://doi.org/10.1017/s0021859605005708

Olsen, J., Kristensen, L., Weiner, J., & Griepentrog, H. W. (2005). Increased density and spatial uniformity increase weed suppression by spring wheat. *Weed Research*, *45*(4), 316–321. https://doi.org/10.1111/j.1365-3180.2005.00456.x

Osipitan, O. A., Dille, J. A., Assefa, Y., & Knezevic, S. Z. (2018). Cover crop for early season weed suppression in crops: Systematic review and meta-analysis. *Agronomy Journal*, *110*(6), 2211–2221. https://doi.org/10.2134/agronj2017.12.0752

Osipitan, O. A., Dille, J. A., Assefa, Y., Radicetti, E., Ayeni, A., & Knezevic, S. Z. (2019). Impact of cover crop management on level of weed suppression: A meta-analysis. *Crop Science*, *59*(3), 833–842. https://doi.org/10.2135/cropsci2018.09.0589

Owen, M. D. K., Beckie, H. J., Leeson, J. Y., Norsworthy, J. K., & Steckel, L. E. (2015). Integrated pest management and weed management in the United States and Canada. *Pest Management Science*, *71*(3), 357–376. https://doi.org/10.1002/ps.3928

Owen, M. J., Martinez, N. J., & Powles, S. B. (2014). Multiple herbicide-resistant *Lolium rigidum* (annual ryegrass) now dominates across the Western Australian grain belt. *Weed Research*, *54*(3), 314–324. https://doi.org/10.1111/wre.12068

Page, E. R., Cerrudo, D., Westra, P., Loux, M., Smith, K., Foresman, C., Wright, H., & Swanton, C. J. (2012). Why early season weed control is important in maize. *Weed Science*, *60*(3), 423–430. https://doi.org/10.1614/ws-d-11-00183.1

Paril, J. F., Zhang, T. L., Camm, B. J., Barnett, E., Migneault, A., & Fournier-Level, A. (2025). Pattern of herbicide multi-resistance in annual ryegrass (*Lolium rigidum* Gaud.) weedy populations across Southeast Australia. *Weed Research, 65*(2), Article e70014. https://doi.org/10.1111/wre.70014

Peña, J. M., Torres-Sánchez, J., de Castro, A. I., Kelly, M., & López-Granados, F. (2013). Weed mapping in early-season maize fields using object-based analysis of unmanned aerial vehicle (UAV) images. *PLoS ONE*, *8*(10), Article e77151. https://doi.org/10.1371/journal.pone.0077151

Peters, K., Breitsameter, L., & Gerowitt, B. (2014). Impact of climate change on weeds in agriculture: A review. *Agronomy for Sustainable Development*, *34*(4), 707–721. https://doi.org/10.1007/s13593-014-0245-2

Peterson, M. A., Collavo, A., Ovejero, R., Shivrain, V., & Walsh, M. J. (2018). The challenge of herbicide resistance around the world: A current summary. *Pest Management Science*, *74*(10), 2246–2259. https://doi.org/10.1002/ps.4821

Pittelkow, C. M., Liang, X., Linquist, B. A., van Groenigen, K. J., Lee, J., Lundy, M. E., van Gestel, N., Six, J., Venterea, R. T., & van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature*, *517*(7534), 365–368. https://doi.org/10.1038/nature13809

Plaza, E. H., Kozak, M., Navarrete, L., & Gonzalez-Andujar, J. L. (2011). Tillage system did not affect weed diversity in a 23-year experiment in Mediterranean dryland. *Agriculture, Ecosystems & Environment*, *140*(1–2), 102–105. https://doi.org/10.1016/j.agee.2010.11.016

Powles, S. B., & Yu, Q. (2010). Evolution in action: Plants resistant to herbicides. *Annual Review of Plant Biology*, *61*(1), 317–347. https://doi.org/10.1146/annurev-arplant-042809-112119

Ramesh, K., Matloob, A., Aslam, F., Florentine, S. K., & Chauhan, B. S. (2017). Weeds in a changing climate: Vulnerabilities, consequences, and implications for future weed management. *Frontiers in Plant Science*, *8*, Article 95. https://doi.org/10.3389/fpls.2017.00095

Ramesh, K., Rao, A. N., & Chauhan, B. S. (2017). Role of crop competition in managing weeds in rice, wheat, and maize in India: A review. *Crop Protection*, *95*, 14–21. https://doi.org/10.1016/j.cropro.2016.07.008

Rao, A. N., Johnson, D. E., Sivaprasad, B., Ladha, J. K., & Mortimer, A. M. (2007). Weed management in direct-seeded rice. *Advances in Agronomy*, *93*, 153–255. https://doi.org/10.1016/s0065-2113(06)93004-1

Rao, A. N., Wani, S. P., Ramesha, M., & Ladha, J. K. (2015). Weeds and weed management of rice in Karnataka State, India. *Weed Technology*, *29*(1), 1–17. https://doi.org/10.1614/wt-d-14-00057.1

Rasmussen, I. A. (2004). The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. *Weed Research*, *44*(1), 12–20. https://doi.org/10.1046/j.1365-3180.2003.00367.x

Riechers, D. E., Soltani, N., Chauhan, B. S., Concepcion, J. C. T., Geddes, C. M., Jugulam, M., Kaundun, S. S., Preston, C., Wuerffel, R. J., & Sikkema, P. H. (2024). Herbicide resistance is complex: A global review of cross-resistance in weeds within herbicide groups. *Weed Science*, *72*(5), 465–486. https://doi.org/10.1017/wsc.2024.33

Riemens, M., Sønderskov, M., Moonen, A.-C., Storkey, J., & Kudsk, P. (2022). An integrated weed management framework: A pan-European perspective. *European Journal of Agronomy*, *133*, Article 126443. https://doi.org/10.1016/j.eja.2021.126443

Rodenburg, J., & Johnson, D. E. (2009). Weed management in rice-based cropping systems in Africa. *Advances in Agronomy*, *103*, 149–218. https://doi.org/10.1016/s0065-2113(09)03004-1

Rodenburg, J., Demont, M., Zwart, S. J., & Bastiaans, L. (2016). Parasitic weed incidence and related economic losses in rice in Africa. *Agriculture, Ecosystems & Environment*, *235*, 306–317. https://doi.org/10.1016/j.agee.2016.10.020

Saharawat, Y. S., Singh, B., Malik, R. K., Ladha, J. K., Gathala, M., Jat, M. L., & Kumar, V. (2010). Evaluation of alternative tillage and crop establishment methods in a rice–wheat rotation in North Western IGP. *Field Crops Research*, *116*(3), 260–267. https://doi.org/10.1016/j.fcr.2010.01.003

Salonen, J., Hyvönen, T., & Jalli, H. (2011). Composition of weed flora in spring cereals in Finland – a fourth survey. *Agricultural and Food Science*, *20*(3), 245–261. https://doi.org/10.2137/145960611797471534

Salonen, J., Jalli, H., Muotila, A., Niemi, M., Ojanen, H., Ruuttunen, P., & Hyvönen, T. (2023). Fifth survey on weed flora in spring cereals in Finland. *Agricultural and Food Science*, *32*(2), 51–68. https://doi.org/10.23986/afsci.130009

Savary, S., Willocquet, L., Elazegui, F. A., Castilla, N. P., & Teng, P. S. (2000). Rice pest constraints in tropical Asia: Quantification of yield losses due to rice pests in a range of production situations. *Plant Disease*, *84*(3), 357–369. https://doi.org/10.1094/pdis.2000.84.3.357

Schulz, M., Marocco, A., Tabaglio, V., Macias, F. A., & Molinillo, J. M. G. (2013). Benzoxazinoids in rye allelopathy: From discovery to application in sustainable weed control and organic farming. *Journal of Chemical Ecology*, *39*(2), 154–174. https://doi.org/10.1007/s10886-013-0235-x

Selby, T. P., Satterfield, A. D., Puri, A., Stevenson, T. M., Travis, D. A., Campbell, M. J., Taggi, A. E., Hughes, K. A., & Bereznak, J. (2023). Bioisosteric tactics in the discovery of tetflupyrolimet: A new mode-of-action herbicide. *Journal of Agricultural and Food Chemistry*, *71*(47), 18197–18204. https://doi.org/10.1021/acs.jafc.3c01634

Shekhawat, K., Rathore, S. S., & Chauhan, B. S. (2020). Weed management in dry direct-seeded rice: A review on challenges and opportunities for sustainable rice production. *Agronomy*, *10*(9), Article 1264. https://doi.org/10.3390/agronomy10091264

Shergill, L. S., Schwartz-Lazaro, L. M., Leon, R., Ackroyd, V. J., Flessner, M. L., Bagavathiannan, M., Everman, W., Norsworthy, J. K., VanGessel, M. J., & Mirsky, S. B. (2020). Current outlook and future research needs for harvest weed seed control in North American cropping systems. *Pest Management Science*, *76*(12), 3887–3895. https://doi.org/10.1002/ps.5986

Simić, M., Dragićević, V., Tataridas, A., Krachunova, T., Srdić, J., Gazoulis, I., & Brankov, M. (2025). Integrated effects of crop rotation and different herbicide rates in maize (*Zea mays* L.) production in central Serbia. *Crop Protection, 187*, Article 106913. https://doi.org/10.1016/j.cropro.2024.106913

Sindhu, V. K., Chaudhary, A., Singh, S., Punia, S. S., & Singh, S. (2026). Strategic integration of rice residue mulch, high seeding rates and pre-emergence herbicide mixtures for weed management in zero-till wheat. *Weed Research, 66*(2), Article e70073. https://doi.org/10.1111/wre.70073

Singh, R., Yadav, D. B., Yadav, A., & Punia, S. S. (2021). Characterization of herbicide use and factors responsible for herbicide resistance in *Phalaris minor* in wheat in Haryana, India. *Crop Protection*, *144*, Article 105581. https://doi.org/10.1016/j.cropro.2021.105581

Singh, S., Ladha, J. K., Gupta, R. K., Bhushan, L., & Rao, A. N. (2008). Weed management in aerobic rice systems under varying establishment methods. *Crop Protection*, *27*(3–5), 660–671. https://doi.org/10.1016/j.cropro.2007.09.012

Singh, S., Ladha, J. K., Gupta, R. K., Bhushan, L., Rao, A. N., Sivaprasad, B., & Singh, P. P. (2007). Evaluation of mulching, intercropping with *Sesbania* and herbicide use for weed management in dry-seeded rice (*Oryza sativa* L.). *Crop Protection*, *26*(4), 518–524. https://doi.org/10.1016/j.cropro.2006.04.024

Soltani, N., Dille, J. A., Burke, I. C., Everman, W. J., VanGessel, M. J., Davis, V. M., & Sikkema, P. H. (2016). Potential corn yield losses from weeds in North America. *Weed Technology*, *30*(4), 979–984. https://doi.org/10.1614/wt-d-16-00046.1

Somerville, G. J., Powles, S. B., Walsh, M. J., & Renton, M. (2018). Modeling the impact of harvest weed seed control on herbicide-resistance evolution. *Weed Science*, *66*(3), 395–403. https://doi.org/10.1017/wsc.2018.9

Spallek, T., Mutuku, M., & Shirasu, K. (2013). The genus *Striga*: A witch profile. *Molecular Plant Pathology*, *14*(9), 861–869. https://doi.org/10.1111/mpp.12058

Sparks, T. C., Lorsbach, B. A., Sparks, J. M., & Duke, S. O. (2025). Origins of new modes of action for fungicides, herbicides and insecticides: A review and analysis. *Pest Management Science*, *81*(10), 6019–6028. https://doi.org/10.1002/ps.8962

Storkey, J., & Neve, P. (2018). What good is weed diversity? *Weed Research*, *58*(4), 239–243. https://doi.org/10.1111/wre.12310

Storkey, J., Meyer, S., Still, K. S., & Leuschner, C. (2012). The impact of agricultural intensification and land-use change on the European arable flora. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1732), 1421–1429. https://doi.org/10.1098/rspb.2011.1686

Storkey, J., Moss, S. R., & Cussans, J. W. (2010). Using assembly theory to explain changes in a weed flora in response to agricultural intensification. *Weed Science*, *58*(1), 39–46. https://doi.org/10.1614/ws-09-096.1

Sudianto, E., Beng-Kah, S., Ting-Xiang, N., Saldain, N. E., Scott, R. C., & Burgos, N. R. (2013). Clearfield® rice: Its development, success, and key challenges on a global perspective. *Crop Protection*, *49*, 40–51. https://doi.org/10.1016/j.cropro.2013.02.013

Tidemann, B. D., Geddes, C. M., & Sharpe, S. M. (2024). Early adopter insights on physical impact mill technology for harvest weed seed control in Canada. *Canadian Journal of Plant Science*, *104*(5), 485–494. https://doi.org/10.1139/cjps-2024-0015

Timmermann, C., Gerhards, R., & Kühbauch, W. (2003). The economic impact of site-specific weed control. *Precision Agriculture*, *4*(3), 249–260. https://doi.org/10.1023/a:1024988022674

Tørresen, K. S., Skuterud, R., Tandsæther, H. J., & Hagemo, M. B. (2003). Long-term experiments with reduced tillage in spring cereals. I. Effects on weed flora, weed seedbank and grain yield. *Crop Protection*, *22*(1), 185–200. https://doi.org/10.1016/s0261-2194(02)00145-x

Turra, G. M., Angonese, P. S., Rudell, E. C., Tasca, V. F., Markus, C., & Merotto Junior, A. (2026). Legacy of recurrent gene flow and evidence of independent evolution of ALS resistance mutations in weedy rice. *Evolutionary Applications*, *19*(11), Article e70342. https://doi.org/10.1111/eva.70342

Varah, A., Ahodo, K., Coutts, S. R., Hicks, H. L., Comont, D., Crook, L., Hull, R., Neve, P., Childs, D. Z., Freckleton, R. P., & Norris, K. (2020). The costs of human-induced evolution in an agricultural system. *Nature Sustainability*, *3*(1), 63–71. https://doi.org/10.1038/s41893-019-0450-8

Verret, V., Gardarin, A., Pelzer, E., Médiène, S., Makowski, D., & Valantin-Morison, M. (2017). Can legume companion plants control weeds without decreasing crop yield? A meta-analysis. *Field Crops Research*, *204*, 158–168. https://doi.org/10.1016/j.fcr.2017.01.010

Walsh, M. J., & Powles, S. B. (2014). High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. *Weed Technology*, *28*(3), 486–493. https://doi.org/10.1614/wt-d-13-00183.1

Walsh, M. J., Broster, J. C., Schwartz-Lazaro, L. M., Norsworthy, J. K., Davis, A. S., Tidemann, B. D., Beckie, H. J., Lyon, D. J., Soni, N., Neve, P., & Bagavathiannan, M. V. (2018). Opportunities and challenges for harvest weed seed control in global cropping systems. *Pest Management Science*, *74*(10), 2235–2245. https://doi.org/10.1002/ps.4802

Walsh, M. J., Newman, P., & Powles, S. B. (2013). Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. *Weed Technology*, *27*(3), 431–436. https://doi.org/10.1614/wt-d-12-00181.1

Walsh, M. J., Ouzman, J., Newman, P., Powles, S., & Llewellyn, R. (2017). High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. *Weed Technology*, *31*(3), 341–347. https://doi.org/10.1017/wet.2017.9

Webster, T. M., & Nichols, R. L. (2012). Changes in the prevalence of weed species in the major agronomic crops of the southern United States: 1994/1995 to 2008/2009. *Weed Science*, *60*(2), 145–157. https://doi.org/10.1614/ws-d-11-00092.1

Weiner, J. (2023). Weed suppression by cereals: Beyond 'competitive ability'. *Weed Research*, *63*(3), 133–138. https://doi.org/10.1111/wre.12572

Weiner, J., Griepentrog, H.-W., & Kristensen, L. (2001). Suppression of weeds by spring wheat *Triticum aestivum* increases with crop density and spatial uniformity. *Journal of Applied Ecology*, *38*(4), 784–790. https://doi.org/10.1046/j.1365-2664.2001.00634.x

Weisberger, D., Nichols, V., & Liebman, M. (2019). Does diversifying crop rotations suppress weeds? A meta-analysis. *PLOS ONE*, *14*(7), Article e0219847. https://doi.org/10.1371/journal.pone.0219847

Westerman, P. R., Wes, J. S., Kropff, M. J., & Van Der Werf, W. (2003). Annual losses of weed seeds due to predation in organic cereal fields. *Journal of Applied Ecology*, *40*(5), 824–836. https://doi.org/10.1046/j.1365-2664.2003.00850.x

Westwood, J. H., Charudattan, R., Duke, S. O., Fennimore, S. A., Marrone, P., Slaughter, D. C., Swanton, C., & Zollinger, R. (2018). Weed management in 2050: Perspectives on the future of weed science. *Weed Science*, *66*(3), 275–285. https://doi.org/10.1017/wsc.2017.78

Wilson, R. S., Hooker, N., Tucker, M., LeJeune, J., & Doohan, D. (2009). Targeting the farmer decision making process: A pathway to increased adoption of integrated weed management. *Crop Protection*, *28*(9), 756–764. https://doi.org/10.1016/j.cropro.2009.05.013

Worthington, M., & Reberg-Horton, C. (2013). Breeding cereal crops for enhanced weed suppression: Optimizing allelopathy and competitive ability. *Journal of Chemical Ecology*, *39*(2), 213–231. https://doi.org/10.1007/s10886-013-0247-6

Xu, M., Galhano, R., Wiemann, P., Bueno, E., Tiernan, M., Wu, W., Chung, I.-M., Gershenzon, J., Tudzynski, B., Sesma, A., & Peters, R. J. (2012). Genetic evidence for natural product-mediated plant–plant allelopathy in rice (*Oryza sativa*). *New Phytologist*, *193*(3), 570–575. https://doi.org/10.1111/j.1469-8137.2011.04005.x

Yu, Q., & Powles, S. (2014). Metabolism-based herbicide resistance and cross-resistance in crop weeds: A threat to herbicide sustainability and global crop production. *Plant Physiology*, *166*(3), 1106–1118. https://doi.org/10.1104/pp.114.242750

Zhao, D. L., Atlin, G. N., Bastiaans, L., & Spiertz, J. H. J. (2006). Cultivar weed-competitiveness in aerobic rice: Heritability, correlated traits, and the potential for indirect selection in weed-free environments. *Crop Science*, *46*(1), 372–380. https://doi.org/10.2135/cropsci2005.0192

Ziska, L. H. (2016). The role of climate change and increasing atmospheric carbon dioxide on weed management: Herbicide efficacy. *Agriculture, Ecosystems & Environment*, *231*, 304–309. https://doi.org/10.1016/j.agee.2016.07.014

Ziska, L. H., Gealy, D. R., Burgos, N., Caicedo, A. L., Gressel, J., Lawton-Rauh, A. L., Avila, L. A., Theisen, G., Norsworthy, J., Ferrero, A., Vidotto, F., Johnson, D. E., Ferreira, F. G., Marchesan, E., Menezes, V., Cohn, M. A., Linscombe, S., Carmona, L., Tang, R., & Merotto, A. (2015). Weedy (red) rice: An emerging constraint to global rice production. *Advances in Agronomy*, *129*, 181–228. https://doi.org/10.1016/bs.agron.2014.09.003

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2026): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here: https://pr.sdiarticle5.com/review-history/170346