Weed Science

www.cambridge.org/wsc

Are our weeds changing? A survey of stakeholders from the Australian grain production systems

Ali Ahsan Bajwa[1], Aakansha Chadha[2] and Bill Grant[3]

[1]Senior Lecturer, La Trobe Institute for Sustainable Agriculture and Food (LISAF), Department of Ecological, Plant and Animal Sciences, AgriBio, La Trobe University, Melbourne, VIC, Australia; [2]Research Fellow, Centre for eResearch and Digital Innovation, Federation University, Mount Helen, VIC, Australia and [3]Research Fellow, Future Regions Research Centre, Federation University, Mount Helen, VIC, Australia

Research Article

Cite this article: Bajwa AA, Chadha A, Grant B (2025). Are our weeds changing? A survey of stakeholders from the Australian grain production systems. Weed Sci. **73**(e40), 1–12. doi: 10.1017/wsc.2025.16

Received: 18 December 2024
Revised: 17 March 2025
Accepted: 18 March 2025

Associate Editor:
Lovreet Singh Shergill, Colorado State University

Keywords:
Agronomic crops; climate change; driver weeds; herbicide efficacy; weed ecology; weed management

Corresponding author:
Ali Ahsan Bajwa;
Email: A.Bajwa@latrobe.edu.au

Abstract

The changing climate, land use, and agronomic practices are driving shifts in weed biology and management across Australia's grain production systems. A stakeholder survey was conducted to identify key weed species, adaptations, and factors influencing future research priorities in three major cropping regions. The most problematic and adaptive species included rigid ryegrass (*Lolium rigidum* Gaudin), hairy fleabane [*Conyza bonariensis* (L.) Cronquist; syn.: *Erigeron bonariensis* L.], *Bromus* spp. (ripgut brome [*Bromus diandrus* Roth; syn.: *Bromus rigidus* Roth]), annual sowthistle (*Sonchus oleraceus* L.), wild radish (*Raphanus raphanistrum* L.), and feather fingergrass (*Chloris virgata* Sw.). These weeds also ranked high for future research focus. Observed adaptive traits included changes in dormancy and emergence patterns, shifts in phenology, and a shift toward year-round growth driven by warmer winters and increased summer rainfall. Regional responses varied slightly, with soil and crop management practices ranked as the primary driver of changing weed biology (88%), followed by climatic factors (56%), while soil factors (13%) were not considered to be significant. Participants in the Northern region highlighted climate change (67%) as a major driver, while those in the Western region emphasized management practices (95%) and soil-related factors (32%). Sixty percent of participants noted that climatic changes were introducing new weeds, and 69% believed that changing weed biology was reducing control efficacy. National research priorities included understanding weed emergence dynamics (73%), effects of climate on herbicide efficacy (71%), and better understanding of weed ecology (68%). These findings highlight the trends in weed evolution and need for future research on changing weed biology and adaptive management strategies. Surveys of agronomists, farm advisors, researchers, and farmers provide a cost-effective method to monitor new weed adaptations. Refining survey methodologies and enhancing field data collection could improve the ability to track and manage weed adaptations to shifts in climate and management practices.

Introduction

Weeds are a consistent constraint in crop production systems around the world. They cause significant economic losses (Oerke 2006), while their management is becoming difficult due to widespread evolution of herbicide resistance in many weed species (Peterson et al. 2018). On the other hand, climate change is exacerbating the task of weed management due to negative impacts on crop growth and development and potential advantages to weeds (Jabran et al. 2020; Ramesh et al. 2017). The current and expected changes in climate and land use are causing alterations in weed biology, distribution, and interference potential, as well as weed management (Chauhan 2020; Ishizuka et al. 2020; Varanasi et al. 2016; Ziska 2016). Major climate change elements suspected to be driving these changes include rising temperatures and heat waves, frequent droughts, changing rainfall patterns, and extreme weather events (Clements and Jones 2021a).

Drastic changes have been observed in weed dynamics and functional traits such as seed dormancy, germination and emergence patterns, phenology (especially the timing of flowering, seed set, and shattering), morphological features, plant architecture, and physiological functions (Anwar et al. 2021; Bajwa et al. 2021a; Clements and Jones 2021a; Kathiresan and Gualbert 2016; Maity et al. 2021; Ziska et al. 2019). In addition, range expansion, abnormal growing patterns, and overall shift in seasonality with a preference toward year-round emergence and growth have been observed for several major cropping weeds (Han et al. 2023; Matzrafi et al. 2021). Similarly, climate change scenarios, especially drought and high temperatures are also known to reduce the efficacy of some herbicides (Jabran and Doğan 2018; Peerzada et al. 2021a, 2021b; Ziska and McConnell 2015; Ziska et al. 2004), although detailed studies for most weeds are still limited.

Weeds that are most problematic and costly to manage are generally the species that survive and thrive in multiple environments and are known to exhibit varying behavioral responses according to growing conditions (O'Donnell and Adkins 2001; Preston 2019). Unfortunately, those species are also the ones that have evolved resistance to many herbicides (Broster et al. 2019, 2023a, 2023b). These so-called 'driver' or 'key' weed species have evolved to compete with crops in changing crop production regimes and are expected to continue adaptive evolution to favor their spread, competitive ability, and persistence in the wake of a changing climate. For example, in Australia, rigid ryegrass (*Lolium rigidum* Gaudin) is a perfect example of a weed prepared for every challenge, and it is also Australia's worst cropping weed in terms of its economic impact and difficulty in its management (Bajwa et al. 2021b). Historically, *L. rigidum* has been a typical winter annual species with preference for cooler climates for optimal growth (Bajwa et al. 2021b), but it has started to adapt to much warmer climatic conditions over the past few years (Thompson and Chauhan 2022). It has been suggested that *L. rigidum* populations growing in warmer or summer months could initially grow slowly but could probably survive the hot conditions and still complete their life cycles (Thompson and Chauhan 2022). This range expansion and shifts in seasonality and phenology of a major weed of grain production systems are quite concerning, and there are other weeds demonstrating similar trends.

Clearly, cropping weeds are quickly adapting to the changing climate and management practices through phenotypic plasticity and genetic evolution, which is well documented for several invasive plant species or so-called 'environmental weeds' (Bajwa et al. 2019a; Bryson and Carter 2004; Clements and Jones 2021a; Mao et al. 2021; Prentis et al. 2008). While this is a global phenomenon, such trends are more frequent and visible in predominantly rainfed grain production systems of Australia. Australia is extremely vulnerable to major climatic changes (Hayman et al. 2012; CSIRO 2024). For example, modeling has indicated that in Australia warming is likely to reach 0.7 to 1.4°C in 2020 to 2039 and 1.4 to 2.4°C under Coupled Model Intercomparison Project (CMIP)-5 or 1.6 to 2.8°C under CMIP-6 in 2040 to 2059 (Grose et al. 2020). Modeling indicates that rainfall will be reduced very little over summer (1% to 3%, December to May, over 2000 to 2050), but to a greater extent over winter (5% to 10%, June to November, over 2000 to 2050) (Grose et al. 2020). Australian weed scientists, growers, and farm consultants are increasingly reporting changes in several key weed species of economic significance that are driven primarily by changes in climate and soil factors (McCallum 2024). While biological understanding of such impacts is relatively clear, connection between these adaptive changes in weeds and on-farm weed management is lacking. Similarly, the extent of change in weed ecology and its impact on weed management decisions is unknown.

Understanding how weeds of grain production systems are changing their biology in response to shifts in climate and soil and crop management practices is crucial for effective weed management and sustainable crop production. By comprehending how these weeds are adapting and responding to changing environmental conditions, farmers can develop proactive strategies to mitigate the negative impacts of weeds on grain production. This knowledge is also crucial for prioritizing key weeds and weed control strategies in regions that are most vulnerable to climate change. Despite some field observations and general recognition of "changing weed biology", we have some outstanding questions, such as which species are changing the most, what aspects of their biology and ecology are changing, which major factors are driving those changes across different regions in Australia, and what these changes mean for weed management. To address these knowledge gaps, we conducted a social survey to gather views and perceptions of the Australian grain crop growers, weed researchers, and farm consultants/agronomists on the changing weed biology and ecology in recent times.

The main objectives of this study were to:

1. identify major weed species affecting grain production systems and the weeds that are presenting major changes in their biology and ecology;
2. identify key adaptive changes being observed in major weeds and relative contribution of different factors driving those changes;
3. understand how weed adaptations are affecting the ability of grain growers to manage those weeds; and
4. identify major aspects for future research and development (R&D) to address the potential negative impacts of changing weed biology.

The outcomes of this study provide applied insights into changing dynamics of weed management for main stakeholders, including researchers, Grains Research and Development Corporation (GRDC), and the Australian grain growers.

Materials and Methods

Study Design and Data Collection

In this social study, an online survey questionnaire was used to gather data on stakeholder perceptions about the challenges faced due to changes in biology and ecology of weed species in grain production systems across Australia. A structured questionnaire was developed based on prior informal consultations with different stakeholders, frequent field observations, and anecdotal evidence on the topic of "changing weed biology" to obtain quantitative and qualitative data. A copy of the questionnaire is provided in the Supplementary Material (Survey Questionnaire). In total, there were 18 questions in the survey with yes/no, multiple-choice, or short-answer options for responses. Overall, the questions sought feedback on the following main themes: (1) main weeds displaying rapid adaptations, (2) major shifts in weed biology and ecology, (3) any new weed infestations resulting from these changes, (4) impact on current management, and (5) key priorities for future R&D relevant to this topic.

An ethics approval to conduct this research was received from La Trobe University's Human Research Ethics Committee (project approval no. HEC24117) under the "negligible – low risk category," which adhered to the national guidelines regulated by the Australian Government (NHMRC 2007). The participants were provided with a summary, background, and objectives of the survey along with a detailed participant information statement in the online portal. They provided an informed consent by clicking an "I agree, start questionnaire" button before commencing the formal survey. The participant information statement outlined the risk assessment, data management and privacy policy, expected outcomes, and details of the feedback mechanism. No personal questions relating to name, gender, address, age, education level, or contact details were asked. The participants were given the option to provide their locations by naming a town/city or just a postal code.

The survey was deployed using the university-approved Qualtrics platform (Seattle, WA, USA). Participation in the survey was voluntary, and none of the questions were compulsory. It was an anonymous survey that took approximately 10 min to complete. Potential participants from the Australian grains industry, as identified by the research team, were emailed an invitation to complete the survey. In addition, the survey was also circulated via institutional social media channels (LinkedIn and X) to increase the reach. The initial goal of 60 participants was set in accordance with the industry engagement standards. The survey was conducted from April 8 to May 27, 2024.

Data Analysis

One hundred and thirty responses were received during the data collection period. Data were screened and 40 responses were excluded before further analysis, as they did not go beyond the first three questions and therefore did not qualify for a meaningful analysis to meet the study objectives. The remaining 90 complete responses were used for analysis and are included in the results reported.

Responses to the online surveys were exported from Qualtrics to Microsoft Excel (Redmond, WA, USA). The data were de-identified, aggregated, and cleaned to get consistency in names of weed species. For example, participants from different regions had used the common names "annual sowthistle" and "milk thistle" for *Sonchus oleraceus* L., and we combined them for simplification and accuracy.

Analysis of responses to quantitative questions (multiple choice, yes/no) were tabulated and graphed, and qualitative responses to the survey questions (written responses) were reviewed and subsequently categorized into broad themes. The survey responses were aggregated and presented for the three broad grain-growing regions of Australia (Southern, Northern, and Western) as defined by the GRDC (2024). These are well-defined regions that differ significantly in terms of their climatic conditions, farming systems, and crop production practices. Descriptive statistics were applied to all datasets to present responses to most questions in percentage along with number of participants or average values with standard error (SE) for relevant questions. The chi-square (χ^2) test was used to assess variability across the three grain production regions for multiple-choice questions, as both the variables, region and answer to the multiple choice (yes/no), were categorical variables (as described by Bajwa et al. 2019b). The statistical software SPSS (v. 29, IBM SPSS Statistics, NY, USA) was used for data analysis.

After the analyses, the results were grouped into and discussed within the following major themes:

- Demographics
- Major weed species affecting grain production systems
- Key adaptive changes observed in weed biology and ecology
- Weed species that are changing the most and the reasons associated with the changes
- New weeds infesting grain crops
- Priority weed species and topics for future R&D as related to this study

Results and Discussion

Demographics

Out of the 90 completed responses, 41% were from the Southern grain-growing region, 30% from the Western grain-growing region, and 29% from the Northern grain-growing region. Although the number of responses is not large, different regions and subregions of Australian grain-growing areas were well represented in the survey (Figure 1). Nationally, the largest proportion of the participants (61%) were farm advisors (also known as agronomists or consultants), followed by researchers (22%), growers (14%), and other participants including the R&D representatives of chemical companies and non-research government officials (3%) (Supplementary Data; Supplementary Table S1).

The high proportion of farm advisors or agronomists increases the reliability of the data, as most Australian advisors serve a large clientele over very large area. They are also well informed about current agronomic issues, including weed management, and therefore present a more realistic, on-the-ground situation. For example, many agronomists and consultants are part of the world-leading WeedSmart extension and education network, which specifically promotes innovative management of weeds in grain production systems across Australia (WeedSmart 2024). Weed management is considered a key driver of agronomic practices and decision making in Australian broadacre production systems (Llewellyn et al. 2015).

The average area of cropping land owned, managed, or advised by the participants nationally was 54,907 ha per participant, with the Western region having the largest average at 101,500 ha (Supplementary Data; Supplementary Table S2). The Northern and Southern regions had lower averages at 33,725 and 44,241 ha, respectively. This is a typical representation of the large sizes of grain production farms in Australia (Sheng and Chancellor 2019). Australia's average grain-producing farm is ~4,700 ha (Statista 2024). However, the much larger averages presented in our results are due to greater representation of farm advisors who typically would advise several farms. Similarly, much greater averages from the Western region are a true representation of large grain farms in the wheatbelt of Western Australia (DPIRD 2024). This means the information gathered in this survey is representative of the Australian grains industry.

In terms of the experience of participants in grains industry, the participants from the Northern region had the highest average experience (23.0 yr), closely followed by those who participated from the Western region (21.5 yr). The Southern region participants had lower average experience (17.3 yr), while the national average was 20.2 yr. This shows wealth of knowledge and experience contributed toward the current study, further validating the results.

Major Weed Species Affecting Grain Production Systems

Several species were listed by the participants when asked about the top five weeds affecting their farming enterprises or in their area (for advisors or researchers) (Table 1). Nationally, *L. rigidum* was ranked as the most problematic weed (by 91% of participants) in their grain production systems (Table 1), indicating its significant impact on crop production. Wild radish (*Raphanus raphanistrum* L.), hairy fleabane [*Conyza bonariensis* (L.) Cronquist; syn.: *Erigeron bonariensis* L.], and *S. oleraceus* also ranked among the top five troublesome weed species, identified by 60%, 54%, and 41% of the participants, respectively.

All these species are recognized as major or so-called 'big-ticket weeds' in grain production systems in Australia. These species are not only the most prevalent, but they have also evolved resistance to several herbicide modes of action, making them extremely

https://doi.org/10.1017/wsc.2025.16 Published online by Cambridge University Press

Figure 1. A map of all valid survey participants with the locations of individual participants represented with red dots.

difficult to manage (Asaduzzaman et al. 2022a; Broster et al. 2019, 2023a, 2023b; Busi et al. 2021; Walsh et al. 2004). In a national study, *L. rigidum*, *R. raphanistrum*, wild oat (*Avena fatua* L.), and *Bromus* spp. were ranked among the most damaging weeds in terms of their economic impact (Llewellyn et al. 2016). Estimated revenue losses (AUD) attributed to these species were substantial, with *L. rigidum* alone costing the Australian grains industry A $93.1 million yr^{-1} (Llewellyn et al. 2016). *Raphanus raphanistrum*, *A. fatua*, and *Bromus* spp. were estimated to cost A$53 million, A $28.1 million, and A$22.5 million, respectively, in lost production and control expenses.

All these major weed species were highlighted by participants from all three grain-growing regions, except for *S. oleraceus*, which was absent in the Western region (Table 1). *Bromus* spp. appeared to be a smaller issue in the Northern region, as they were raised among the top five problematic weeds by only 4% participants in that region. Capeweed [*Arctotheca calendula* (L.) Levyns] and feather fingergrass (*Chloris virgata* Sw.) were cited less frequently as problematic, with only 19% and 13% of participants including them in their top five lists, respectively (Table 1). This is probably because *A. calendula* is generally managed well in grain crops with few herbicide-resistance issues. On the other hand, *C. virgata* is a relatively new weed for cropping systems mainly in the Northern region (Asaduzzaman et al. 2022b), but it has been spreading to other regions in recent years (Hasanfard and Chauhan 2024). Nevertheless, *C. virgata* was already costing the Australian grains industry A$7.7 million yr^{-1}in 2016 (Llewellyn et al. 2016).

Some of the species listed as most problematic in this study appeared in previous field surveys conducted in New South Wales between 2013 and 2017 (Broster et al. 2022). In that study, *L. rigidum* (present in 69% of fields), *A. fatua* (60%), and *S. oleraceus* (34%) were reported as the most prevalent weed species in grain production systems (Broster et al. 2022).

Key Adaptive Changes Observed in Weed Biology and Ecology

Nationally, 79% of the participants agreed that the biology and ecology of major weeds on their farm/region are currently changing or have changed in last 3 to 4 yr, whereas only 8% of the participants did not agree (Table 2). The majority of the participants (87%) noted potential changes in the timing of weed emergence, while changes in seed production were observed by the fewest participants (21%). Although the percentage of responses differs between the Western region and other two regions, it is statistically not different due to the combination of sample sizes and the relative difference between the percentages of different groups. Extended growing periods were reported by 65% of participants, with a significantly high response rate on this aspect in the Northern and Southern regions ($P = 0.007$). Other changes, such as the emergence of multiple cohorts of weeds during the season and overall increased infestation, received varied responses, but did not show any significant statistical differences among regions (Table 2). Some participants mentioned additional changes they had observed, which included changes in dormancy and seed

https://doi.org/10.1017/wsc.2025.16 Published online by Cambridge University Press

Table 1. The species identified among the top five most problematic weeds in the three main grain-growing regions across Australia.[a]

Weed species	National ($n = 90$)	Northern ($n = 26$)	Southern ($n = 37$)	Western ($n = 27$)
	%			
Lolium rigidum	91	85	92	96
Raphanus raphanistrum	60	35	51	96
Conyza bonariensis	54	88	46	33
Sonchus oleraceus	41	65	54	NA
Bromus spp.	39	4	32	81
Avena fatua	31	50	27	19
Hordeum murinum L. ssp. *murinum* and *Hordeum murinum* L. ssp. *glaucum* (Steud.) Tzvelev (barley grass)	23	15	8	52
Arctotheca calendula	19	12	19	26
Chloris virgata	13	23	14	4

[a]The table includes weed species with more than 10% responses nationally. NA, not applicable.

germination requirements, some weeds growing all year round instead of being winter or summer annual species, and morphological changes in the plants.

Survey responses regarding the changes observed in biology and ecology of weeds highlight the emerging trends in weed adaptations in grain-cropping systems across Australia. These results also underline the regional differences in observed changes, reflecting the diverse challenges faced by the grains industry across Australia. These changes indicate an adaptive response to climatic variability or agronomic practices and suggest a potential for greater resilience and invasiveness in certain weed species. These adaptations are evolutionary in most cases to prepare weeds for harsh climates (Chauhan et al. 2017; Clements et al. 2004). It is well established that weeds have greater phenotypic plasticity, which allows them to adapt and flourish in a broad spectrum of environments and agro-ecosystems (Clements and Jones 2021b; Davidson et al. 2011). The adaptive mechanisms are triggered and facilitated by regular disturbance in broadacre production. The high plasticity exhibited by many weed species, especially in seed germination behavior, leads to the emergence of multiple cohorts throughout the growing season (Clements and DiTommaso 2011; Zhou et al. 2005). It also allows for various morphological and phenological changes throughout the weed life cycle.

As highlighted in these results, growth and reproductive patterns are also shifting in major weeds in response to various selection pressures, including combinations of climatic, soil, and management factors. This is consistent with the field observations of growers and agronomists regarding changes in growth habit/plant architecture, plant height, and the timing and duration of flowering, especially in monocots such as *L. rigidum* and *A. fatua*. *Avena fatua* has shown greater variation in terms of early seed shattering, and *L. rigidum* may also be adapting for short stature and early seed shattering (Bajwa et al. 2024).

All these adaptive changes in weed biology have a direct impact on weed–crop competition dynamics and weed control efficacy, one that is often negative for crop growth and productivity. For example, staggered emergence allows for herbicide application evasion, while extended growing periods are making weed control a year-round job and not just an in-crop, seasonal agronomic practice. This is further discussed in the following sections.

Weed Species That Are Changing the Most

When asked about the most adaptive weeds in context of changes noted earlier, several major species appeared frequently in the responses (Table 3). Table 3 lists major weed species that were believed to be presenting the most adaptive changes by more than 10% of participants nationally.

Lolium rigidum was the most-mentioned weed across all regions (84% nationally). High regional variations were observed for some weeds, such as *Bromus* spp. being more of a concern in the Western region and *S. oleraceus* in the Northern and Southern regions. The proportion of participants from the Western region reporting changes in the biology of *R. raphanistrum* was much higher (58%) than those in the Southern (14%) and Northern (10%) regions (Table 3). This is possibly because *R. raphanistrum* has been prevalent in the wheatbelt of Western Australia for a long time and has become a highly problematic weed. In fact, it was ranked the top-most problematic weed alongside *L. rigidum* by Western region participants (96%) (Table 1).

Additional species were also raised as weeds of concern in terms of their changing biology and ecology; however, those were specific to different regions. For example, only participants from the northern region reported changes in barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] behavior (15%), while *Gazania* spp. (11%) and little mallow (*Malva parviflora* L.) (11%) were noted exclusively by Southern region participants. Stinknet [*Oncosiphon piluliferum* (L. f.) Källersjö] (16%) and Afghan melon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] (11%) were only reported as changing by Western region participants.

The species that appeared on this list of weeds changing their biology are almost the same species that were listed as overall most problematic species. This means major weeds of Australian grain production systems have remained major weeds due to their adaptability to a range of climatic and management factors. For example, *L. rigidum* has always been the most troublesome and difficult to manage weed in grain systems, especially in the Western and Southern regions (Bajwa et al. 2021b). As is evident from the results of this survey, it is also the weed that is changing its biology the most. Typically, *L. rigidum* is a winter annual, but it has been reported to germinate, grow, and survive in summer months in southeastern Australia in recent years (Thompson and Chauhan 2022). This indicates an opportunistic life-cycle shift of some populations to capitalize on changing rainfall patterns bringing more rain into summer months that used to be very dry historically.

On the other hand, typically summer-growing weeds such as *S. oleraceus* and *C. bonariensis* have become extremely robust in terms of their population dynamics and can be seen growing vigorously pretty much year-round (Bajwa et al. 2024). Similarly significant shifts have been reported in timing of flowering and seed shattering in *R. raphanistrum*, where flowering occurred up to 12 d earlier to escape the innovative technique of capturing weeds seeds at crop harvest, commonly known as harvest weed seed control (HWSC) (Somerville and Ashworth 2024). Despite numerous field observations, we do not have sufficient research data on different adaptive traits for major weeds.

Factors Driving Adaptive Changes in Problematic Weeds

When asked about the factors responsible for driving biological and ecological changes in weeds, the views of participants differed (Table 4). Nationally, a majority of participants (88%) attributed the changes to shifts in land or crop management practices.

Table 2. The response (%) of survey participants on key changes observed in biology and ecology of weeds in the three main grain-growing regions across Australia.

	National ($n = 71$)	Northern ($n = 21$)	Southern ($n = 30$)	Western ($n = 20$)	Statistical test (χ^2) and P-values[a]
	%				
Potential changes in time of emergence	87	90	83	90	0.305; P = 0.859
Multiple cohorts during the season	75	90	70	65	3.518; P = 0.172
Extended growing periods	65	81	73	35	10.006; P = 0.007
Increased infestation	41	38	53	25	4.405; P = 0.111
More vigorous weeds/bigger plants	27	24	37	15	3.327; P = 0.190
Unusual timing of flowering	27	24	23	35	0.538; P = 0.764
Changes in seed production	21	10	17	40	5.039; P = 0.080

[a]Statistical test was applied to compare the three grain-growing regions at P < 0.05.

Table 3. Major weeds that are changing the most according to survey participants (% responses) in the three main grain-growing regions across Australia.[a]

Weed species	National ($n = 67$)	Northern ($n = 20$)	Southern ($n = 28$)	Western ($n = 19$)
	%			
Lolium rigidum	84	85	82	79
Conyza bonariensis	45	40	54	37
Sonchus oleraceus	37	60	46	NA
Bromus spp.	28	10	25	53
Raphanus raphanistrum	25	10	14	58
Hordeum spp.	16	15	14	21
Avena fatua	13	15	14	NA
Chloris virgata	12	25	11	NA

[a]The table includes weed species for which more than 10% of participants had noticed changes nationally. NA, not applicable.

Nationwide, 56% of participants believed that changing climate is driving changes in weed biology and ecology. Soil factors were not considered as a major driver of changes in weed biology, with only 13% of participants identifying them as influential nationally (Table 4). However, a significant difference was observed among regions, with more (32%) participants in the Western region acknowledging soil-related factors as an important selection pressure.

These results underline the predominant role of agricultural practices and climate change in weed dynamics, with notable regional variations in perceptions.

Changes in Crop Management Practices

Broadacre grain production has rapidly evolved over the last three decades in Australia. Changing soil and crop management practices have greatly influenced weed distribution, dynamics, and behavior. The impact of these management factors is more pronounced than the climatic or soil factors alone, largely due to the interactive effects of these practices on the microenvironment where weeds grow. Modern agronomic practices significantly modify this microenvironment, thereby exerting a stronger influence on weed dynamics (Andreasen et al. 1991; Mahgoub 2021; Pätzold et al. 2020; Veisi et al. 2016). For instance, tillage systems play a critical role in altering weed flora, emergence patterns, and competition dynamics (Bajwa 2014; Chauhan et al. 2006). Conservation tillage and no-tillage are widely adopted for grain production across Australia (Dang et al. 2015) and have favored the proliferation of surface-germinating weed species such as *S. oleraceus*, *C. bonariensis*, and *C. virgata* (Bajwa et al. 2017).

Crop residue and stubble management can also influence weed germination and emergence by altering soil moisture, temperature, and light conditions, with effects varying depending on the amount of residue present (Chauhan et al. 2012; Nikolić et al. 2021). Similarly, harvesting methods can influence residue management and weed distribution. For example, HWSC impacts stubble retention and distribution postharvest, depending on the specific HWSC technique used (Walsh et al. 2017, 2022). The increasing adoption of HWSC and stubble retention is expected to drive significant shifts in weed behavior, although research in this area remains limited. Preliminary evidence suggests that weeds such as *R. raphanistrum* may adapt to HWSC by altering their flowering timing and pod-shattering behavior to evade control measures (Ashworth et al. 2016). Overall, weeds exhibit dynamic responses to cropping practices, highlighting the critical role of cropping system design in shaping weed community composition and management (Buhler 2003).

Changing Climate

Climate change factors such as increased temperature and atmospheric CO_2 or altered moisture regimes have been noted to expedite adaptive evolution in cropping weeds (Clements and Jones 2021b). The most important weeds identified by this survey are extremely plastic in nature and are pioneer species.; They have many biological characteristics and life-history traits that can be selected with climate change (Baker 1974; Clements and DiTommaso 2011).

In this study, more than 50% of participants acknowledged the role of climate change in driving modifications in weed biology. Interestingly, Northern region participants were more accommodating of these factors (67%) than their Southern and Western counterparts. This is probably due to large climatic variability in the Northern region that is potentially driving major shifts in weed dynamics (e.g., movement of *L. rigidum* into northern New South Wales and southern Queensland) (Thompson and Chauhan 2022).

A growing number of studies have reported various biological changes in weeds in response to climatic changes. A few relevant examples of such adaptive changes in weeds due to climatic variability include:

1. Changes in *R. raphanistrum* seedbank dynamics and dormancy, with dry spring conditions accelerating dormancy release compared with wet springs (Eslami et al. 2010). As a result, seeds from wet springs are more likely to contribute to a persistent soil seedbank, while those from drier seasons are fewer and less enduring.

https://doi.org/10.1017/wsc.2025.16 Published online by Cambridge University Press

Table 4. The response (%) of survey participants on key factors responsible for driving changes in the three main grain-growing regions across Australia.

	National ($n = 68$)	Northern ($n = 21$)	Southern ($n = 28$)	Western ($n = 19$)	Statistical test (χ^2) and P-values[a]
	%				
Changes in land/crop management practices	88	81	89	95	0.033; P = 0.984
Changing climate	56	67	50	53	2.029; P = 0.363
Natural evolution	47	57	39	47	1.881; P = 0.390
Soil factors	13	5	7	32	6.443; P = 0.040

[a]Statistical test was applied to compare the three grain-growing regions at P < 0.05.

Table 5. The response (%) of survey participants on key aspects of decreased weed control efficacy due to changing weed biology and ecology in the three main grain-growing regions across Australia.

	National ($n = 46$)	Northern ($n = 14$)	Southern ($n = 20$)	Western ($n = 12$)	Statistical test (χ^2) and P-values[a]
	%				
Decreased herbicide efficacy	67	71	60	75	0.267; P = 0.875
More in-crop application escapes	72	86	70	58	2.371; P = 0.306
Early seed shedding	46	29	35	83	4.156; P = 0.125

[a]Statistical test was applied to compare the three grain-growing regions at P < 0.05.

2. Survival and life-cycle completion of *S. oleraceus* and *C. bonariensis* despite suppression of plant growth under water-stress conditions (Peerzada et al. 2021b).
3. Early flowering in *L. rigidum* populations in Western Australian regions during short growing seasons (Gill et al. 1996).
4. Non-lethal stress events such as short-term drought have been suggested to trigger physiological and epigenetic modifications in *Lolium* spp. enabling them to become more stress tolerant (Matzrafi et al. 2021).
5. Increased plant height and seed production of *S. oleraceus* under elevated CO_2 levels enhancing its reproductive output and wind-dispersal capacity through taller plants (Mobli et al. 2020).

Field-scale studies evaluating the impact of climate change on weed biology and evolutionary dynamics are critically lacking.

Changes in Soil Factors

Soil factors, including soil physicochemical properties, normally do not change much over time. While soil type and fixed soil properties, such as soil texture, can influence the composition of weed flora, they have a minimal impact on the fundamental biology and behavior of existing weed species. However, soil management practices involving major changes in the soil profile can cause shifts in weed distribution and short- to medium-term weed emergence dynamics. For instance, in Western Australia, soil inversion with moldboard plowing to a depth of 10 to 20 cm effectively buried up to 89% of *L. rigidum* and *Bromus* spp. seeds (Borger et al. 2024). Additionally, clay addition to water-repellent soils increased the establishment of grass weeds by 64% following the first significant rainfall compared with untreated soils (Blake and Peltzer 2002).

Weeds in no-till systems have adapted to germinate in response to light exposure, exposed soil-surface conditions, and variations in soil temperature, moisture, aeration, and nutrient availability, all of which differ from the requirements of weeds in tilled systems (Manalil et al. 2018; Thompson et al. 2021). Strategic tillage in conservation systems has been shown to significantly affect weed seed dispersal and subsequent emergence patterns and growth (Mia et al. 2023). It could also alter the phytotoxicity of residual herbicides (Edwards et al. 2023). However, the impact of occasional or strategic tillage on weed behavior in no-till systems is understudied.

What Changing Weed Biology Means for Weed Management

About 70% of participants agreed that changes in weed biology and ecology are leading to a reduction in weed control, while 21% did not agree with this, and 10% were unsure, with no significant differences observed in the responses from the three grain production regions.

The participants who agreed that these changes were causing a decline in weed control efficacy were then asked to provide views on the key aspects contributing to this decline. Nationally, 67% of participants reported decreased herbicide efficacy, with little regional variation. Early seed shattering was particularly concerning in the Western region (83%) (Table 5). This adaptation is probably an evolutionary response in major weeds, especially *R. raphanistrum* and *L. rigidum* to HWSC which has been widely adopted for longer in the Western regions compared with other regions.

Changes in climate and weed biology are significantly increasing the complexity of weed management in cropping systems, making it a constantly shifting challenge. The presence of multiple weed cohorts throughout the year complicates the timing of herbicide applications, while late-season conditions favorable to weed growth lead to more weed escapes that persist into the fallow phase. This has been noted for *C. bonariensis*, which often germinates late in spring in-crop in response to unseasonal rainfall (Bajwa et al. 2024). There are usually no chemical control options available for these late-emerging cohorts.

https://doi.org/10.1017/wsc.2025.16 Published online by Cambridge University Press

Table 6. List of new weeds infesting grain production systems in the three main grain-growing regions across Australia, based on the responses of survey participants.

Northern region ($n = 15$)		Southern region ($n = 23$)		Western region ($n = 12$)	
Weed species	Response	Weed species	Response	Weed species	Response
	%		%		%
Chloris virgata	80	*Chloris virgata*	65	*Conyza bonariensis*	42
Windmill grass (*Chloris truncata* R. Br.)	33	*Conyza bonariensis*	30	*Oncosiphon piluliferum*	25
Echinochloa crus-galli	7	*Gazania* spp.	13	*Bromus* spp.	17
Jungle rice [*Echinochloa colona* (L.) Link]	7	*Pseudognaphalium luteoalbum*	13	Crownbeard [*Verbesina encelioides* (Cav.) Benth. & Hook. f. ex A. Gray]	8
Amaranthus spp.	7	*Bromus* spp.	9	Prickly lettuce (*Lactuca serriola* L.)	8
Common lambsquarters (*Chenopodium album* L.)	7	Button grass [*Dactyloctenium radulans* (R. Br.) P. Beauv.]	9	*Dactyloctenium radulans*	8
Lolium rigidum	7	*Chloris truncata*	4	Witchgrass (*Panicum capillare* L.)	8
Conyza bonariensis	7	Three-corner jack (*Emex australis* Steinh.)	4	*Sonchus oleraceus*	8
Everlasting cudweed (*Pseudognaphalium luteoalbum* (L.) Hilliard & B. L. Burtt)	7	*Lolium rigidum*	4	Green mulla mulla [*Ptilotus macrocephalus* (R. Br.) Poir.]	8
		Khakiweed (*Alternanthera pungens* Kunth)	4	Puncturevine (*Tribulus terrestris* L.)	8
		Rush skeletonweed (*Chondrilla juncea* L.)	4	Roly Poly (*Salsola australis* R. Br.)	8
		Amaranthus spp.	4	Volunteer canola (*Brassica napus* L.)	8
		Wholeleaf rosinweed (*Silphium integrifolium* Michx.)	4		
		Amsinckia spp.	4		

The shift toward summer-dominant rainfall patterns further exacerbates the problem, resulting in increased weed pressure during the fallow phase, requiring multiple chemical control passes and leaving more escapes to invade the following cropping phase (Michael et al. 2010). Additionally, if summer weeds are not controlled early, water-stressed weeds become harder to control, often requiring higher herbicide rates or multiple applications, which eventually leads to evolution of herbicide resistance. Similarly, the variable growth habits and early seed shattering of some weeds in response to environmental conditions and HWSC can reduce the effectiveness of HWSC and end of season weed management (Sun et al. 2021). Problematic weeds like *L. rigidum* and *Bromus* spp., for instance, often adapt to drier, warmer conditions by shortening their life cycles, which poses significant challenges for post-emergence herbicide applications and weed control near crop maturity (Bajwa et al. 2024). Late-season breaks (rainfall required to sow crops in rainfed cropping systems) are becoming common, which push growers to dry sow with little moisture in the soil profile to activate the pre-emergence herbicides. These conditions often provide weeds with a head start and greater competitive advantage.

The implications of these shifts for weed emergence dynamics, phenology, in-crop competition, seedbank buildup, and weed control could be significant yet poorly understood.

New/Emerging Weed Species Due to Changing Climate and Land Use

Nationally, 60% of participants reported observing new weeds infesting grain crops on their farms or in their regions. The list of new or emerging weeds largely differed for each region, but some species appeared as concerning across different regions (Table 6). *Cloris virgata* was noted as a major emerging species in both the Northern and Southern regions, while *C. bonariensis* was nominated as a new weed by 30% to 42% of participants in the Southern and Western regions (Table 6). Although both these species are considered widely established, these responses show that these weeds are still spreading into new areas and becoming a significant problem.

The variety of species listed as new weeds in different regions represent the geographic variations and potentially variable sources/points of introduction from natural environments and/or roadside infestations. The Southern region has a longer list, potentially due to a higher number of responses ($n = 23$).

Table 7. Weeds identified by the participants for further R&D related to changing weed biology in the three main grain-growing regions across Australia.[a]

Weed species	National ($n = 77$)	Northern ($n = 22$)	Southern ($n = 33$)	Western ($n = 22$)
	%			
Lolium rigidum	70	73	61	82
Conyza bonariensis	56	68	58	41
Bromus spp.	35	9	33	64
Sonchus oleraceus	34	50	45	NA
Raphanus raphanistrum	32	5	24	73
Chloris virgata	25	45	27	NA
Avena fatua	19	27	21	9
Hordeum spp.	14	9	6	32
Chloris truncata	9	27	3	NA
Echinochloa crus-galli	8	23	NA	5
Gazania spp.	6	NA	15	NA
Oncosiphon piluliferum	5	NA	NA	18
Arctotheca calendula	9	5	9	14

[a]The table includes weed species for which more than 10% of participants had noticed changes nationally or in one of the regions. NA, not applicable.

Priority Weed Species and Topics for Future R&D as Related to This Study

Priority Weed Species

Participants were asked to list the top five weeds they would like to be researched from a "changing weed biology" perspective.

https://doi.org/10.1017/wsc.2025.16 Published online by Cambridge University Press

Table 8. The response (%) of survey participants on the key aspects recommended for R&D related to changing weed biology and ecology in the three main grain-growing regions across Australia.

	National ($n = 80$)	Northern ($n = 23$)	Southern ($n = 34$)	Western ($n = 23$)	Statistical test (χ^2) and P-values[a]
	%				
Germination/emergence timing	73	65	71	83	0.934; P = 0.627
Herbicide efficacy in response to climatic factors	71	83	76	52	5.978; P = 0.050
Better understanding of weed biology and ecology	68	65	68	70	0.136; P = 0.934
Changes in weed–crop competition dynamics	51	39	53	61	1.829; P = 0.401
Understanding weed diversity across Australian soils	28	17	21	48	5.649; P = 0.059
Enhanced seed dispersal	21	22	12	35	3.611; P = 0.164

[a]Statistical test was applied to compare the three grain-growing regions at $P < 0.05$.

Nationally, *L. rigidum* (70%) and *C. bonariensis* (56%) were nominated by most participants, and these species also ranked high in most regions (Table 7). However, the priority species varied across different regions. For example, *Bromus* spp. (64%) and *R. raphanistrum* (73%) were high priority in the Western region, while *S. oleraceus* (50%) and *C. virgata* (45%) were emphasized in the Northern region (Table 7). These regional differences highlight the varying levels of infestations for major weeds in different regions, which could be due to several factors, including geo-climatic conditions, farming systems, and anthropogenic activities responsible for the movement of weed species in different areas. These results indicate a strong demand for focused research on these prevalent weed species to improve management and control strategies.

Importantly, the weed species identified by the participants for further R&D overlapped with the most problematic and most adaptable weeds identified across Australia (Tables 1 and 3). This is only logical but highlights the knowledge gaps present in evolutionary and management research of these high-impact weeds. Results also highlight the need to prioritize research on weeds unique to different regions. For example, *Gazania* spp. were only raised as priority species in the Southern region, whereas *O. piluliferum* seemed to be a problem only in the Western region. It is noteworthy that these species were also listed as new or emerging weeds in those regions and therefore should be prioritized for research into their biology and management before they become widespread and bigger problems.

Priority R&D Aspects Relating to "Changing Weed Biology"

When participants were asked to prioritize topics or aspects of "changing weed biology" for future R&D, germination and emergence timing (73%) and herbicide efficacy in response to climatic factors (71%) were selected by most participants nationwide (Table 8). The participants from the Western region placed higher emphasis on studying weed seed-dispersal mechanisms (35%) and understanding weed diversity across different soil types (48%) compared with the other two regions. On the other hand, research into herbicide efficacy in response to climatic factors was a high priority according to the participants from the Northern (83%) and Southern (76%) regions compared with those from the Western region (52%).

These results highlight the high level of awareness of changing weed biology among Australian grain growers, advisors, and researchers. It also shows that current research on the effects of climatic and soil factors on weed evolution and adaptive responses remains limited. There is a lack of information regarding the interactive effects of climatic factors, such as temperature, CO_2, and moisture availability, in conjunction with soil conditions and agronomic practices (Anwar et al. 2021). While it is well documented that climate change significantly alters land and crop management practices, there is sparse understanding of its direct and indirect impacts on weed biology and competition (Ramesh et al. 2017; Vila et al. 2021). Furthermore, research has predominantly focused on the isolated effects of climatic variables such as elevated CO_2, leaving critical gaps in understanding how combinations of climatic factors influence weed–crop competition across diverse cropping systems (Chauhan 2020; Chauhan et al. 2017; Clements and Jones 2021a; Ramesh et al. 2017).

The desire for research into climate change by chemical control interaction highlights the importance of this aspect for modern-day weed management. The projected climatic changes pose challenges to herbicide efficacy. For example, it has been established that elevated CO_2 levels induce morphological and physiological changes in weed plants, negatively influencing herbicide uptake, translocation, and retention (Manea et al. 2011; Ziska and Teasdale 2000). Variations in temperature and moisture availability could also influence herbicide uptake and translocation as well as their persistence in the soil (Jeena 2021). Additionally, shifts in temperature and changes in the frequency and intensity of rainfall have been proposed to affect plant biological traits, including leaf shape, cuticle thickness, stomatal density and aperture, and leaf area, which in turn can indirectly alter herbicide efficacy and selectivity (Anwar et al. 2021; Waryszak et al. 2018; Ziska and Teasdale 2000; Ziska et al. 2004). Changes in climatic conditions, particularly temperature and rainfall patterns, can also have profound effects on the germination, emergence, and spatiotemporal dynamics of weed populations, necessitating a more comprehensive and integrated research approach (Anwar et al. 2021; Ishizuka et al. 2020; Kebaso et al. 2020; Ramesh et al. 2017). While some international studies have reported on these aspects, information on most important weeds of Australian grain production systems, as well as for cropping weeds in general, is lacking.

In conclusion, this study demonstrates that there is significant awareness among growers, farm consultants, and researchers that most problematic weeds are rapidly adapting to changing climate, land use, and management practices. Several prolific weeds in modern broadacre grain production systems are also the ones that are most adaptable. The changing biology and ecology of these weeds are impacting growers' ability to effectively manage them. In

https://doi.org/10.1017/wsc.2025.16 Published online by Cambridge University Press

addition, changing climatic conditions are also fueling the introduction of new weeds or expansion of existing weeds into new areas. The changes are being observed across Australia, with some differences across three major grain-growing regions.

Future studies should focus on evaluating the influence of evolving farming systems on weed biology, evolution, and management. Long-term trials should simultaneously investigate the combined impacts of farming systems, agronomic practices, and varying climatic scenarios on weed adaptive biology, weed–crop competition, herbicide efficacy, and weed seedbank dynamics. These efforts are essential for developing sustainable, climate-resilient weed management strategies. We believe the findings of this social study are applicable to prioritizing the research agenda on this topic not only in Australia but also in most rainfed grain-producing regions under conservation tillage systems around the world.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2025.16

Acknowledgments. The authors are grateful to the Australian Grains Research & Development Corporation (GRDC) for investing in this research and acknowledge the ongoing support from La Trobe University and Federation University. The constructive feedback from Dr. Catherine Borger (Department of Primary Industries and Regional Development, Western Australia) and Dr. Sonia Graham (University of Wollongong) and La Trobe University's Human Ethics Committee on various aspects of the survey development and data management is acknowledged. The authors greatly appreciate the invaluable contribution of all the Australian grain growers, agronomists/consultants, and researchers who participated in this study.

Funding statement. This research was funded by a GRDC investment (GRDC code: ULA2402-003CAX) with co-contributions from La Trobe University and Federation University.

Competing interests. The authors declare that they have no conflict of interest in relation to this study and publication. The GRDC invested in this research but has not been involved in or influenced any aspects of data collection, analysis, or interpretation. The article was written independently by the authors with appropriate permission from the funding body to publish these results for public good benefit.

References

Andreasen C, Streibig JC, Haas HJWR (1991) Soil properties affecting the distribution of 37 weed species in Danish fields. Weed Res 31:181–187

Anwar MP, Islam AM, Yeasmin S, Rashid MH, Juraimi AS, Ahmed S, Shrestha A (2021) Weeds and their responses to management efforts in a changing climate. Agronomy 11:1921

Asaduzzaman M, Koetz E, Wu H, Shephard A (2022a) Paraquat resistance and hormetic response observed in *Conyza sumatrensis* (Retz.) E. Walker (tall fleabane) in Australian cotton cropping systems. Phytoparasitica 50:269–279

Asaduzzaman M, Wu H, Koetz E, Hopwood M, Shepherd A (2022b) Phenology and population differentiation in reproductive plasticity in feathertop Rhodes grass (*Chloris virgata* Sw.). Agronomy 12:736

Ashworth MB, Walsh MJ, Flower KC, Vila-Aiub MM, Powles SB (2016) Directional selection for flowering time leads to adaptive evolution in *Raphanus raphanistrum* (wild radish). Evol Appl 9:619–629

Bajwa A, Matzrafi M, Jugulam M (2021a) Editorial: biology and management of weeds and invasive plant species under changing climatic and management regimes. Front Agron 3:728144

Bajwa AA (2014) Sustainable weed management in conservation agriculture. Crop Prot 65:105–113

Bajwa AA, Chadha A, Grant B (2024) Consultative Report on Changing Ecology and Biology of Key Weed Species Impacting Australian Grains Due to Climate and Soil Factors. Australia: La Trobe University, Federation University and the Grains Research & Development Corporation. 125 p

Bajwa AA, Farooq M, Nawaz A, Yadav L, Chauhan BS, Adkins S (2019b) Impact of invasive plant species on the livelihoods of farming households: evidence from *Parthenium hysterophorus* invasion in rural Punjab, Pakistan. Biol Invasions 21:3285–3304

Bajwa AA, Latif S, Borger C, Iqbal N, Asaduzzaman M, Wu H, Walsh M (2021b) The remarkable journey of a weed: biology and management of annual ryegrass (*Lolium rigidum*) in conservation cropping systems of Australia. Plants 10:1505

Bajwa AA, Walsh M, Chauhan BS (2017) Weed management using crop competition in Australia. Crop Prot 95:8–13

Bajwa AA, Wang H, Chauhan BS, Adkins S (2019a) Effect of elevated carbon dioxide concentration on growth, productivity and glyphosate response of parthenium weed (*Parthenium hysterophorus* L.). Pest Manag Sci 75:2934–2941

Baker HG (1974) The evolution of weeds. Annu Rev Ecol Syst 5:1–24

Blake J, Peltzer S (2002) Impact of claying on grass weed management and profitability. Pages 716–719 *in* Proceedings of the 13th Australian Weeds Conference, Weeds "Threats Now and Forever." Perth: Plant Protection Society of WA

Borger CP, Mwenda G, Collins SJ, Davies SL, Peerzada AM, Van Burgel A (2024) Burial and subsequent growth of rigid ryegrass (*Lolium rigidum*) and ripgut brome (*Bromus diandrus*) following strategic deep tillage. Weed Sci 72:257–266

Broster JC, Boutsalis P, Gill GS, Preston C (2023a) Frequency of herbicide resistance in wild oats (*Avena* spp.), brome grass (*Bromus* spp.) and barley grass (*Hordeum* spp.) as determined by random surveys across south-eastern Australia. Crop Pasture Sci 74:1193–1200

Broster JC, Chambers AJ, Weston LA, Walsh MJ (2022) Annual ryegrass (*Lolium rigidum*), wild oats (*Avena* spp.) and sowthistle (*Sonchus oleraceus*) are the most commonly occurring weeds in New South Wales cropping fields. Agronomy 12:2914

Broster JC, Jalaludin A, Widderick MJ, Chambers AJ, Walsh MJ (2023b) Herbicide resistance in summer annual weeds of Australia's northern grains region. Agronomy 13:1862

Broster JC, Pratley JE, Ip RHL, Ang L, Seng KP (2019) A quarter of a century of monitoring herbicide resistance in *Lolium rigidum* in Australia. Crop Pasture Sci 70:283–293

Bryson CT, Carter R (2004) Biology of pathways for invasive weeds. Weed Technol 18:1216–1220

Buhler DD (2003) Weed biology, cropping systems, and weed management. J Crop Prod 8:245–270

Busi R, Beckie HJ, Bates A, Boyes T, Davey C, Haskins B, Mock S, Newman Porri A, Onofri A (2021) Herbicide resistance across the Australian continent. Pest Manag Sci 77:5139–5148

Chauhan BS (2020) Grand challenges in weed management. Front Agron 1:3

Chauhan BS, Gill GS, Preston C (2006) Tillage system effects on weed ecology, herbicide activity and persistence: a review. Aust J Exp Agric 46:1557–1570

Chauhan BS, Matloob A, Mahajan G, Aslam F, Florentine SK, Jha P (2017) Emerging challenges and opportunities for education and research in weed science. Front Plant Sci 8:1537

Chauhan BS, Singh RG, Mahajan G (2012) Ecology and management of weeds under conservation agriculture: a review. Crop Prot 38:57–65

Clements DR, DiTommaso A (2011) Climate change and weed adaptation: can evolution of invasive plants lead to greater range expansion than forecasted? Weed Res 51:227–240

Clements DR, DiTommaso A, Jordan N, Booth BD, Cardina J, Doohan D, Mohler CL, Murphy SD, Swanton CJ (2004) Adaptability of plants invading North American cropland. Agric Ecosyst Environ 104:379–398

Clements DR, Jones VL (2021a) Rapid evolution of invasive weeds under climate change: present evidence and future research needs. Front Agron 3:664034

Clements DR, Jones VL (2021b) Ten ways that weed evolution defies human management efforts amidst a changing climate. Agronomy 11:284

[CSIRO] Commonwealth Scientific and Industrial Research Organisation (2024) Climate Change in Australia. http://www.climatechangeinaustralia.gov.au. Accessed: June 14, 2024

Dang YP, Seymour NP, Walker SR, Bell MJ, Freebairn DM (2015) Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: I. Drivers and implementation. Soil Tillage Res 152:104–114

Davidson AM, Jennions M, Nicotra AB (2011) Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis. Ecol Lett 14:419–431

[DPIRD] Department of Primary Industries and Regional Development, Western Australia (2024) Western Australian Grains Industry. https://www.agric.wa.gov.au/grains-research-development/western-australian-grains-industry. Accessed: November 29, 2024

Edwards TJ, Davies SL, Yates RJ, Rose M, Howieson J G, O'Hara G, Steel EJ, Hall DJ (2023) The phytotoxicity of soil-applied herbicides is enhanced in the first-year post strategic deep tillage. Soil Tillage Res 231:105734

Eslami SV, Gill GS, McDonald G (2010) Effect of water stress during seed development on morphometric characteristics and dormancy of wild radish (*Raphanus raphanistrum* L.) seeds. Int J Plant Prod 4:159–168

Gill GS, Cousens RD, Allan MR (1996) Germination, growth, and development of herbicide resistant and susceptible populations of rigid ryegrass (*Lolium rigidum*). Weed Sci 44:252–256

[GRDC] Grains Research and Development Corporation (2024) Growing Regions. https://grdc.com.au/about/our-industry/growing-regions. Accessed: November 29, 2024

Grose MR, Narsey S, Delage FP, Dowdy AJ, Bador M, Boschat G, Chung C, Kajtar JB, Rauniyar S, Freund MB, Lyu K, Rashid H, Zhang X, Wales S, Trenham C, *et al.* (2020) Insights from CMIP6 for Australia's future climate. Earth's Future 8:e2019EF001469

Han Q, Liu Y, Jiang H, Chen X, Feng H (2023) Evaluation of climate change impacts on the potential distribution of wild radish in East Asia. Plants 12:3187

Hasanfard A, Chauhan BS (2024) Leveraging wheat competition to manage seasonal expansion of feathertop Rhodes grass (*Chloris virgata*). Agronomy 14:1708

Hayman P, Rickards L, Eckard R, Lemerle D (2012) Climate change through the farming systems lens: challenges and opportunities for farming in Australia. Crop Pasture Sci 63:203–214

Ishizuka W, Hikosaka K, Ito M, Morinaga SI (2020) Temperature-related cline in the root mass fraction in East Asian wild radish along the Japanese archipelago. Breeding Sci 70:321–330

Jabran K, Doğan MN (2018) High carbon dioxide concentration and elevated temperature impact the growth of weeds but do not change the efficacy of glyphosate. Pest Manag Sci 74:766–771

Jabran K, Florentine S, Chauhan BS (2020) Impacts of climate change on weeds, insect pests, plant diseases and crop yields: synthesis. Pages 189–195 *in* Jabran K, Florentine S, Chauhan BS, eds. Crop Protection Under Changing Climate. Cham, Switzerland: Springer

Jeena M (2021) Weeds and their management under changing climate: a review. Agric Rev 42:322–328

Kathiresan R, Gualbert G (2016) Impact of climate change on the invasive traits of weeds. Weed Biol Manag 16:59–66

Kebaso L, Frimpong D, Iqbal N, Bajwa AA, Namubiru H, Ali HH, Ramiz Z, Hashim S, Manalil S, Chauhan BS (2020) Biology, ecology and management of *Raphanus raphanistrum* L.: a noxious agricultural and environmental weed. Environ Sci Pollut Res 27:17692–17705

Llewellyn R, Ouzman J, Mayfield A, Walker S, Ronning D, Clark M (2015) Weed management as a key driver of crop agronomy. Pages 797–800 *in* Proceedings of the 17th Australian Society of Agronomy Conference, 20–24 September 2015, Hobart, Australia

Llewellyn R, Ronning D, Clarke M, Mayfield A, Walker S, Ouzman J (2016) Impact of Weeds in Australian Grain Production. Canberra, Australia: Grains Research and Development Corporation. 112 p

Mahgoub AM (2021) Measuring the ecological preference for growth of 150 of the most influential weeds in weed community structure associated with agronomic and horticultural crops. Saudi J Biol Sci 28:5593–5608

Maity A, Lamichaney A, Joshi DC, Bajwa A, Subramanian N, Walsh M, Bagavathiannan M (2021) Seed shattering: a trait of evolutionary importance in plants. Front Plant Sci 12:657773

Manalil S, Ali HH, Chauhan BS (2018) Germination ecology of turnip weed (*Rapistrum rugosum* (L.) in the northern regions of Australia. PLoS ONE 13: e0201023

Manea A, Leishman MR, Downey PO (2011) Exotic C_4 grasses have increased tolerance to glyphosate under elevated carbon dioxide. Weed Sci 59:28–36

Mao R, Bajwa AA, Adkins S (2021) A superweed in the making: adaptations of *Parthenium hysterophorus* to a changing climate. A review. Agron Sustain Dev 41:1–18

Matzrafi M, Preston C, Brunharo CA (2021) Evolutionary drivers of agricultural adaptation in *Lolium* spp. Pest Manag Sci 77:2209–2218

McCallum Q (2024) Weeding Out Problem Plants—Research Underway into Six of the Worst. https://www.stockjournal.com.au/story/8678188/changing-behaviour-of-broadacre-weeds-investigated. Accessed: November 29, 2024

Mia MS, Azam G, Nouraei S, Borger C (2023) Strategic tillage in Australian conservation agricultural systems to address soil constraints: how does it impact weed management? Weed Res 63:12–26

Michael PJ, Borger CP, MacLeod WJ, Payne PL (2010) Occurrence of summer fallow weeds within the grain belt region of southwestern Australia. Weed Technol 24:562–568

Mobli A, Florentine SK, Jha P, Chauhan BS (2020) Response of glyphosate-resistant and glyphosate-susceptible biotypes of annual sowthistle (*Sonchus oleraceus*) to increased carbon dioxide and variable soil moisture. Weed Sci 68:575–581

[NHMRC] National Health and Medical Research Council (2007) National Statement on Ethical Conduct in Human Research, Australian Government. https://www.nhmrc.gov.au/about-us/publications/national-statement-ethical-conduct-human-research-2007-updated-2018. Accessed: November 29, 2024

Nikolić N, Loddo D, Masin R (2021) Effect of crop residues on weed emergence. Agronomy 11:163

O'Donnell CC, Adkins SW (2001) Wild oat and climate change: the effect of CO_2 concentration, temperature, and water deficit on the growth and development of wild oat in monoculture. Weed Sci 49:694–702

Oerke EC (2006) Crop losses to pests. J Agric Sci 144:31–43

Pätzold S, Hbirkou C, Dicke D, Gerhards R, Welp G (2020) Linking weed patterns with soil properties: a long-term case study. Precis Agric 21:569–588

Peerzada AM, Williams A, O'Donnell C, Adkins S (2021a) Effect of elevated temperature on growth and glyphosate susceptibility of *Chloris truncata* R. Br., *Sonchus oleraceus* L., and *Conyza bonariensis* (L.) Cronq. Arch Agron Soil Sci 69:358–373

Peerzada AM, Williams A, O'Donnell C, Adkins S (2021b) Effect of soil moisture regimes on the glyphosate sensitivity and morpho-physiological traits of windmill grass (*Chloris truncata* R. Br.), common sowthistle (*Sonchus oleraceus* L.), and flaxleaf fleabane [*Conyza bonariensis* (L.) Cronq.]. Plants 10:2345

Peterson MA, Collavo A, Ovejero R, Shivrain V, Walsh MJ (2018) The challenge of herbicide resistance around the world: a current summary. Pest Manag Sci 74:2246–2259

Prentis PJ, Wilson JRU, Dormontt EE, Richardson DM, Lowe AJ (2008) Adaptive evolution in invasive species. Trends Plant Sci 13:288–294

Preston A (2019) Profiles of common weeds of cropping. Section 6 *in* Integrated Weed Management in Australian Cropping Systems. Grains Research and Development. https://grdc.com.au/__data/assets/pdf_file/0029/47873/Integrated-weed-management-manual-section-6-profiles-of-common-weeds-of-cropping.pdf. Accessed: July 10, 2024

Ramesh K, Matloob A, Aslam F, Florentine SK, Chauhan BS (2017) Weeds in a changing climate: vulnerabilities, consequences, and implications for future weed management. Front Plant Sci 8:95

Sheng Y, Chancellor W (2019) Exploring the relationship between farm size and productivity: evidence from the Australian grains industry. Food Policy 84:196–204

Somerville GJ, Ashworth MB (2024) Adaptations in wild radish (*Raphanus raphanistrum*) flowering time, Part 2: harvest weed seed control shortens flowering by twelve days. Weed Sci 72:143–150

Statista (2024) Average Area Operated of Cropping Farms in Australia from 2010 to 2022. https://www.statista.com. Accessed: November 29, 2024

Sun C, Ashworth MB, Flower K, Vila-Aiub MM, Rocha RL, Beckie HJ (2021) The adaptive value of flowering time in wild radish (*Raphanus raphanistrum*). Weed Sci 69:203–209

Thompson M, Chauhan BS (2022) Changing seasonality of *Lolium rigidum* (annual ryegrass) in southeastern Australia. Front Agron 4:897361

Thompson M, Mahajan G, Chauhan BS (2021) Seed germination ecology of southeastern Australian rigid ryegrass (*Lolium rigidum*) populations. Weed Sci 69:454–460

Varanasi A, Prasad PV, Jugulam M (2016) Impact of climate change factors on weeds and herbicide efficacy. Adv Agron 135:107–146

Veisi M, Rahimian H, Alizade H, Minbashi M, Oveisi M (2016) Survey of associations among soil properties and climatic factors on weed distribution in wheat (*Triticum aestivum* L.) in Kermanshah Province. J Agroecology 8:197–211

Vila M, Beaury EM, Blumenthal DM, Bradley BA, Early R, Laginhas BB, Trillo A, Dukes JS, Sorte CJB, Ibáñez I (2021) Understanding the combined impacts of weeds and climate change on crops. Environ Res Lett 16:034043

Walsh MJ, Aves C, Powles SB (2017) Harvest weed seed control systems are similarly effective on rigid ryegrass. Weed Technol 31:178–183

Walsh MJ, Powles SB, Beard BR, Parkin BT, Porter SA (2004) Multiple-herbicide resistance across four modes of action in wild radish (*Raphanus raphanistrum*). Weed Sci 52:8–13

Walsh MJ, Powles SB, Rengel Z (2022) Harvest weed seed control: impact on weed management in Australian grain production systems and potential role in global cropping systems. Crop Pasture Sci 73:313–324

Waryszak P, Lenz TI, Leishman MR, Downey PO (2018) Herbicide effectiveness in controlling invasive plants under elevated CO2: sufficient evidence to rethink weeds management. J Environ Manag 226:400–407

WeedSmart (2024) WeedSmart's Innovative Industry Partnership at Work. https://www.weedsmart.org.au/content/weedsmarts-innovative-industry-partnership-at-work. Accessed: November 29, 2024

Zhou D, Wang T, Valentine I (2005) Phenotypic plasticity of life-history characters in response to different germination timing in two annual weeds. Can J Bot 83:28–36

Ziska LH (2016) The role of climate change and increasing atmospheric carbon dioxide on weed management: herbicide efficacy. Agric Ecosyst Environ 231:304–309

Ziska LH, Blumenthal DM, Franks SJ (2019) Understanding the nexus of rising CO2, climate change, and evolution in weed biology. Invasive Plant Sci Manag 12:79–88

Ziska LH, Faulkner SS, Lydon J (2004) Changes in biomass and root: shoot ratio of field-grown Canada thistle (*Cirsium arvense*), a noxious, invasive weed, with elevated CO_2: implications for control with glyphosate. Weed Sci 52:584–588

Ziska LH, McConnell LL (2015) Climate change, carbon dioxide, and pest biology: monitor, mitigate, manage. J Agric Food Chem 64:6–12

Ziska LH, Teasdale JR (2000) Sustained growth and increased tolerance to glyphosate observed in a C3 perennial weed, quackgrass (*Elytrigia repens*), grown at elevated carbon dioxide. Funct Plant Biol 27:159–166