Rural R&D for Profit Program

Area Wide Management for cropping systems weeds: investigating the weed management, social and economic opportunity

Final Report

January 2020 – May 2023

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Plain English summary

The *Area Wide Management for cropping systems weeds: investigating the weed management, social and economic opportunity* was project led by CSIRO in partnership with the Grains Research and Development Corporation and the Cotton Research and Development Corporation. Research and industry partners in the project included University of Adelaide, University of Queensland, University of Wollongong, Irrigation and Extension Committee, Mallee Sustainable Farming, Millmerran Landcare, and Toowoomba Regional Council.

Objectives

The objectives of this project were to identify the benefits, key principles and practices which are required for successful area-wide management (AWM) approaches for weeds in cropping regions. By focusing on key weed mobile weed species in agricultural communities with multiple cropping land uses, the project has been able to generate new understanding of the social, bio-physical, geographic, and economic drivers that will contribute to area-wide weed management success. The project has integrated multi-disciplinary research results with the on-ground testing and experiences from cross-sector regional community partnerships. Approaches to implementing area-wide weed management best able to reduce the negative impact of highly mobile weeds in cropping regions of Australia have been identified through this process.

What we did and found

The project established regional partnerships with influential farmer-based agricultural organisations in three cropping regions involving dryland, irrigated, grains, cotton, horticulture, and viticulture. The regions and local community networks in Riverina (Irrigation Research and Extension Committee, IREC, New South Wales), Sunraysia (Mallee Sustainable Farming, Victoria) and Darling Downs (Millmerran Landcare, Queensland) were the primary focus of trials and research involving social science (led by University of Wollongong); herbicide resistance analysis (led by University of Adelaide); genetic mobility analysis (led by University of Queensland) and spatial analysis and economics (with CSIRO). A multi-disciplinary approach was brought together to conduct a co-ordinated series of research with engagement activities to address the weed management, social and economic opportunity:

- To identify weed issues of most concern, current levels of participation in relevant weed management activities, and attitudes towards area-wide weed management-related and related practices, 84 in-depth interviews were conducted with agronomists, consultants, contractors, extension officers, biosecurity officers and public land managers from each region. The findings were used to inform the projects direction for impact.

  Spread of herbicide resistant weeds was identified as the most common major concern, with fleabane, ryegrass and feathertop Rhodes the most cited mobile weeds of concern.

- To determine the extent and spatial patterns of herbicide resistance in mobile weeds that had been identified as a priority within the focus regions, the project engaged the regional partners to collect over 400 geo-referenced weed samples from crop and non-crop land such as roadsides. These were tested for resistance to key herbicides such as glyphosate and the results mapped and spatially analysed for identification of local clustering and association with land use (e.g. crop land vs roadside).

Reducing the spread of major weeds found to have high levels of resistance into crop land was identified as the most likely benefit of an AWM approach.

- To identify the spatial extent of weed gene mobility in the regions, 1920 individual weed samples (fleabane, feathertop Rhodes and annual ryegrass) were collected from 60 sites over 2 years and DNA analysis conducted. The genetic structure of the populations was mapped for spatial analysis to identify mobility at the regional and cross-regional level.

  High potential for spread of commonly glyphosate-resistant ryegrass (a winter weed) and major summer weeds (e.g. feathertop Rhodes) into crop land was found, with fleabane demonstrating more genetic differences (less mobility) across the regions than expected.

  Spatial analysis of resistance patterns across land uses showed no major sub-regional areas with or without resistance, and similarly high (but not fully extensive) proportions of resistance 'scattered' across public land, non-crop land and crop land.

- To better understand the likely cost of gaining these types of resistant weeds at the paddock-level, bio-economic models (Resistance Integrated Management (RIM) and $ummer) were applied to evaluate the economic benefit and practice change implications of avoiding an incursion.

  Integrated weed management strategies aimed at reducing seed banks which are already becoming widely adopted by broadacre growers were found to reduce the economic impact of gaining glyphosate resistant ryegrass. Economic analysis showed that early control of summer fallow weeds was typically optimal at very low densities, so additional densities from mobile seeds did not affect the optimal strategy.

- Regional partners in collaboration with researchers and industry expanded the scope of local trialling and associated extension to all major land types ('public', non-crop, dryland farm, irrigated farm, and horticulture) to identify cost-effective methods to reduce risk of weed spread from crop land, horticulture, and non-crop areas, including:

  1) the testing of improved summer weed herbicide options better suited to control and timely seed set reduction of potentially resistant mobile summer weeds on neighbouring horticultural and crop land.

  2) testing and on-farm demonstration of novel non-herbicide technology designed to control herbicide resistant summer weeds prior to seed set in fallow (weed sensing mechanical precision chipper).

  3) collaborating with local government to conduct roadside weed management trials to identify benefits of targeted practices and timings to reduce the potential for roadsides (and channel areas and road-edge crops) to be weed sources for crop land.

  4) partnered with Wine Australia and local weed experts to conduct trials of improved weed management options within vines aimed at control of mobile weeds with high risk of spread.

5) partnered with Murrumbidgee Irrigation to implement trials of channel bank weed suppression options to reduce risk of channel bank weeds as a source of spread.

6) partnered with the RRD4P project to facilitate monitoring and area-wide release of the fungus biocontrol for the priority mobile weed fleabane.

7) expanded regional herbicide resistance sampling and testing to two new spreading weeds identified by regional growers as having potential high future cost (silverleaf nightshade and sowthistle).

Trials identified effective methods to reduce seed set of key weeds including cross-sector extension opportunities. Regional stakeholder engagement experience from the local activity experience supported interview findings that indicated that costs of participation (particularly time) was a major reason for the relatively low prior involvement in collaborative or co-ordinated area-wide resistant weed management programs by the farming businesses in these regions.

A series of project extension outputs are accessible at https://research.csiro.au/weed-awm/

- To gain further understanding of attitudes and potential motivations for greater engagement in area-wide weed management approaches among the wider farmer population, 604 phone interviews were conducted with cropping land managers across the Darling Downs, Riverina and Sunraysia region.

  There is almost universal acknowledgement that individual growers had an area-wide responsibility to control weeds on their property but only 24% currently worked with other land managers on weed management. It was those who were more concerned about the spread of weeds from their properties to others that were more likely to cooperate in area-wide related weed management activities.

- In addition to the monthly on-line meetings of the project team that were held throughout the project, face to face workshops of the full team were held as soon as possible post-covid.

  Based on the combined learnings from the bio-physical, social, economic, and regional experiences, the team articulated the promising path to impact of 'neighbourly' / 'better neighbour' approaches to promoting area-wide weed management approaches in cropping regions.

- To identify the potential for area-wide weed management approaches nationally, an extensive survey of growers also including SA and WA was conducted including evaluation of economic willingness to invest in AWM activity relative to reduce weed spread.

  Consistent with previous findings across the focus regions, there were not substantial differences between cropping regions (or states) in prior or expected engagement in AWM approaches, or likely drivers. Willingness to invest in additional weed management to prevent spread of a new glyphosate resistant summer weed was only likely if it could reduce the risk of spread by at least 50%. Growers were most concerned about the risk of weeds spreading from public land (e.g. roadsides) to their land.

- To further pursue opportunities and best practice for more effective collaboration and weed management on public lands (e.g. roadsides), a review of weed management programs for 22 local governments with major cropping land use was conducted.

  Local government focus was found to be primarily on 'declared' weeds which does not necessarily correlate with major concerns to the cropping land users. There was evidence of some previous 'area-wide' collaborative efforts, but few seem enduring.

Outcomes, Conclusions & Recommendations

Further to the conclusions included above, the project has learnt from the diversity of stakeholders and new multi-disciplinary research to identify the needs and path for successful deployment of multi-stakeholder weed management approaches with area-wide management benefit in Australian cropping regions. The large potential for greater cross-sector area-wide collaboration and delivery has been identified and welcomed by growers. The demonstrated opportunity for greater attention to management of source weeds on public roadsides is an important result in a cropping environment where near-zero in-field weed tolerance by growers is increasingly the norm. Weed science, social science, economic, spatial, and local grass-roots experience from trialling implementation in pilot regions have all pointed to major opportunities for localised near-neighbour approaches to weed management of mobile weeds. In the context of the historical time and administration-heavy approaches to regional area-wide schemes, this is an important step towards improved management of mobile weeds in the low-labour, large-scale commercial cropping environments of Australia.

Benefits of the project to industry/primary producers

At the local weed management level, the project has generated findings and on-going demonstration of successful weed management practices that offer area-wide benefit (e.g. double-knock application in horticulture; channel bank and roadside weed suppression). Herbicide resistance risk has been shown to be a key concern and driver and this project has provided the most intensive status and spatial information for growers planning resistance management strategies. By including resistance status information outside of crop areas (e.g. roadsides) it has the potential to shift land manager attitudes. The project has also catalysed new cross-sector extension and delivery partnerships. This has already led to new and ongoing information sharing opportunities that did not exist prior to the project e.g. WeedSmart extension into horticulture. It has provided a legacy of research and local experience-based direction to regions and industry wanting to improve management of mobile weeds.

Project rationale and objectives

The potential for weeds, seeds, and herbicide resistance genes to move across farm boundaries and between different land uses is widely recognised. In cases where the management of a pest or weed involves risks and impacts that extend beyond the scale of management at the individual property level there is potential for benefit from 'area-wide' collective action. While there are several examples of successful area-wide management action for highly mobile insect pests and some environmental weed incursions, it has received little attention for weeds of cropping. This is despite increasing spread and importance of weeds with highly mobile seeds and herbicide resistance risk in major cropping regions of Australia.

Further, the Australian cropping belt has expansive areas where irrigated agriculture, horticulture and viticulture are neighbours to dryland cropping, in these interface zones weed problems and weed management can become a cross-industry issue. All these factors point to an increasing need for greater coordination of weed management activities beyond an individual farm boundary and across a broader local area.

The project aimed to identify the benefits, key principles, and practices of successful weed Area Wide Management (AWM). AWM is typically seen to involve multiple stakeholders in a coordinated effort to reduce the impact of mobile weeds and the objective of this project was to test this approach in key regions. Through doing this in partnership with a multi-disciplinary research team, the objective was to develop an improved understanding of the bio-physical, geographic, economic, and social drivers of AWM success by tackling key weed management issues across diverse landscapes.

This project involved forming a network of AWM groups, comprising of representatives from key growers and industries, in three case study regions: Darling Downs, Sunraysia and Riverina. By conducting activities in these regions including applied field trials and demonstrations the objective was to identify appropriate and effective weed control strategies that reduce weed dispersal as well as test the potential for engagement in AWM effort. The final objective is to achieve greater understanding of the key principles and deliver recommendations for area-wide weed management approaches that can be deployed in other Australian cropping regions to reduce the cost of mobile weeds.

Method and project locations

The project took a multi-disciplinary approach involving 11 Australian research and industry organisations and additional regional industry and research partnerships. Influential farmer-based agricultural organisations were engaged as core project partners in three cropping regions involving dryland, irrigated, grains, cotton, horticulture, and viticulture. The regions and local community networks in Riverina (IREC, New South Wales), Sunraysia (Mallee Sustainable Farming, Victoria) and Darling Downs (Millmerran Landcare, Queensland) were the primary focus of trials and research involving social science (led by University of Wollongong); herbicide resistance analysis (led by University of Adelaide); genetic mobility analysis (led by University of Queensland) and spatial analysis and economics (with CSIRO).

Changes to methods over life of the project

The project had to be very adaptive to respond to several major events throughout the life of the project. CSIRO was contracted as project lead January 28, 2020, and the core regional partners were then able to be sub-contracted by CSIRO by March 2020. Following staff changes at the University of Newcastle who were originally proposed to be partners for social science, CSIRO identified Dr. Sonia Graham as a social scientist with strong expertise in collective weed management approaches and her and her team at the University of Wollongong were able to be sub-contracted by CSIRO in June 2020.

In the same month that all contracting was completed in 2020, the covid pandemic led to border restrictions and subsequent lockdowns. With project participants across 5 states and territories and key regional partners being based across state borders, including Victoria, this led to a major revision of project activity plans and prevented face to face engagement of not only regional growers and stakeholders, but the project team. The project team developed online plans for engagement and shifted to producing key electronic materials to introduce the project and concept (see AWM concept video and other materials accessible here https://research.csiro.au/weed-awm/). Most face-to-face engagement activities and collaborative trials/field days etc had to be postponed to when restrictions could be lifted, facilitated by the DAWE project extension. At the local regional level extra effort was made to present trial results in an engaging online format in the absence of many of the regular extension for a (e.g. https://immersiveag.com.au/area-wide-weed-management/). Social research employed greater use of phone interviews than planned face to face focus groups due to covid restrictions.

In June 2022, travel restrictions had eased sufficiently to allow the first face-face meeting of the AWM project team (Mildura). The second face to face meeting during the project occurred three months after the project was initially scheduled to end.

The major flooding across the Murray Darling Basin, including on the Darling Downs where trial sites were inundated, then affected access to many sites. Additional capacity was introduced to accelerate trialling and delivery across 2022. This included shifting resources from CSIRO to the regions to support additional trial and regional engagement activity in 2022-23, and additional resources to pursue areas recognised as priorities (e.g. roadside and local government weed management). The production of high-quality additional legacy communication materials was also increased as a priority. Overall, these major events that occurred over what was almost the entirety of the originally planned project length has led substantial adaptation of the planned methods and the sequence of research findings becoming available. Methods of engagement had to be adapted as full weed status (resistance and genetics) were not available as early as planned due to these delays. The shift to production of high-quality electronic communication materials (e.g. the major videos) reflects the change of method. It also has resulted in a body of materials with greater scope for national reach than the more intensive and regular face-face delivery methods initially proposed. The final results of the project highlight the potential for national-scale impact through broader communications, so the impact on methodological approach caused by covid and other events have not all been negative.

Locations

The regional boundaries are shown in the figure below, with the areas of focus for weed analysis in the following figures, followed by the list of trial and analysis localities. Additional localities of activities are included in the extension/communications listings. The final survey exploring willingness to engage in area-wide activities covered all grain and cotton growing regions of Australia.

Following the first possible face-face meeting of the project team in Mildura June 2022, a final project workshop with the project team was held in Sydney May 2023 to consolidate findings and recommendations from across the project and regions. Research recommendations from the project are relevant for all cropping regions of Australia.

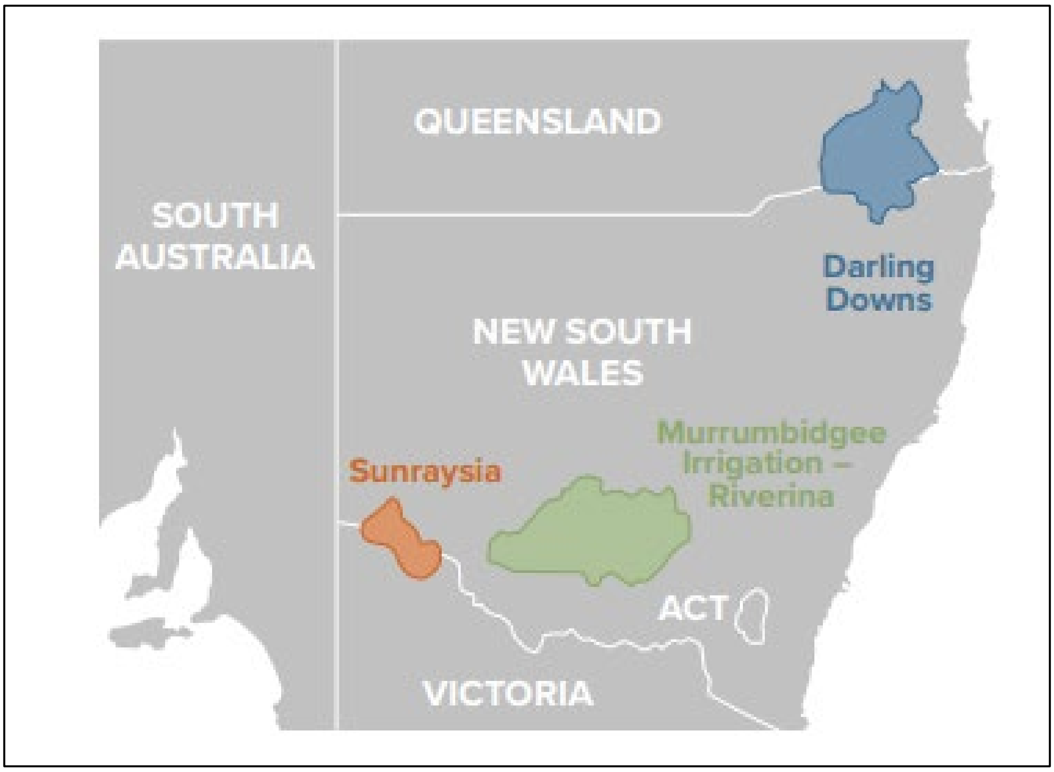


Figure 1. The three regional focus areas for the project.

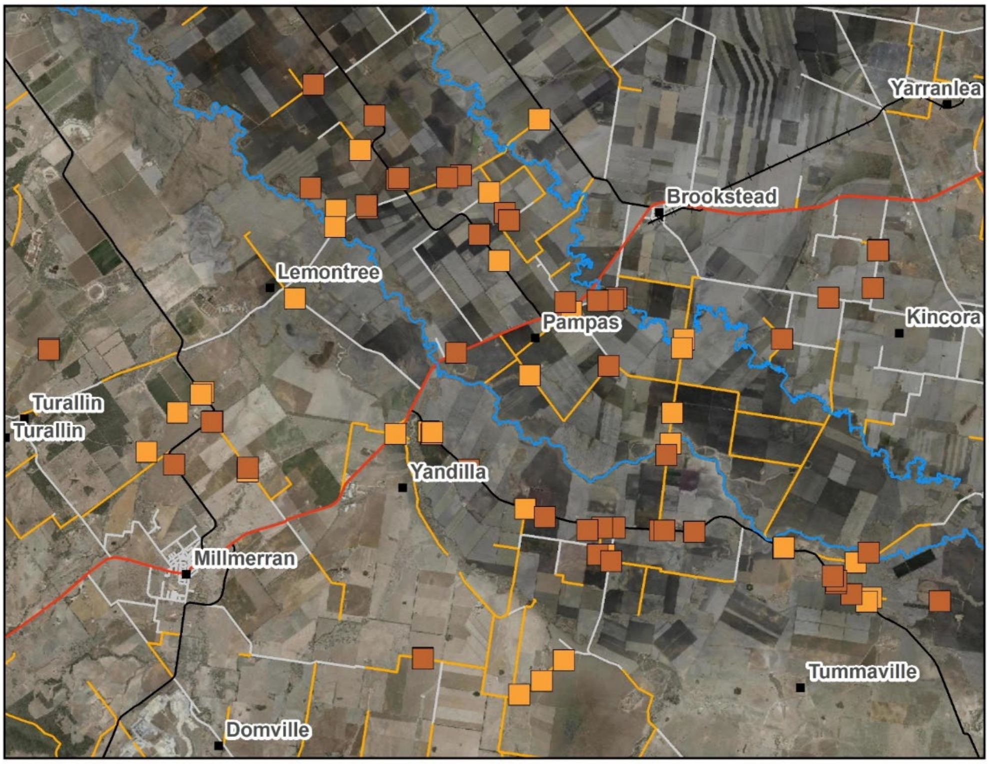


Figure 2. Darling Downs focus region for activities including sampling sites.

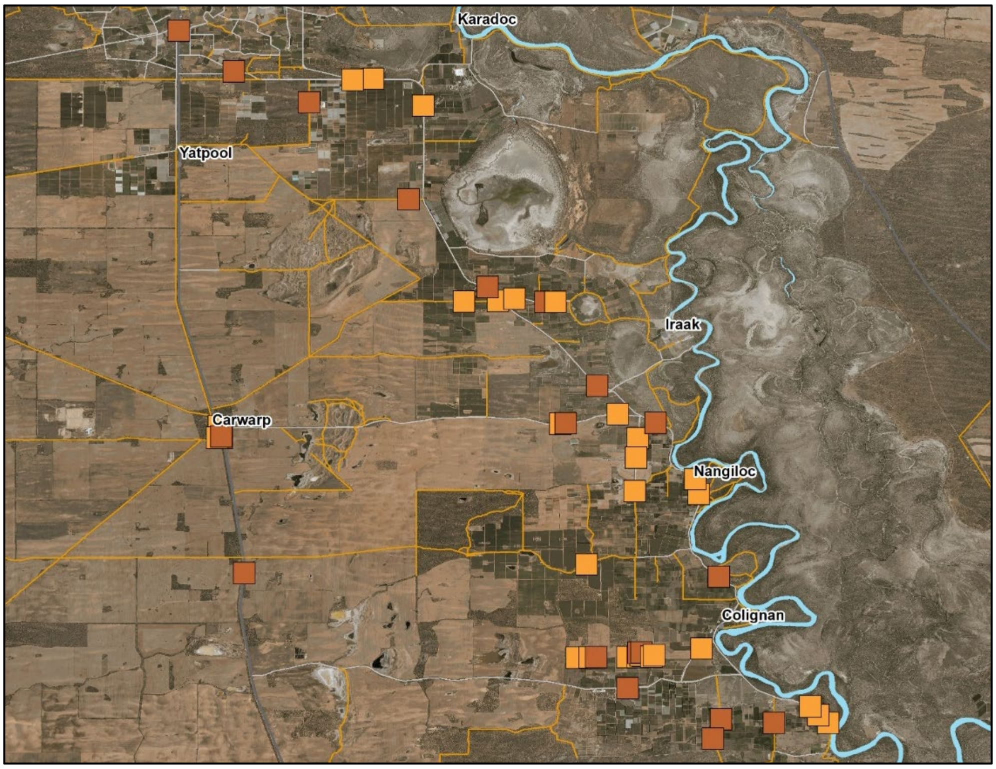


Figure 3. Sunraysia focus region for activities including sampling sites.

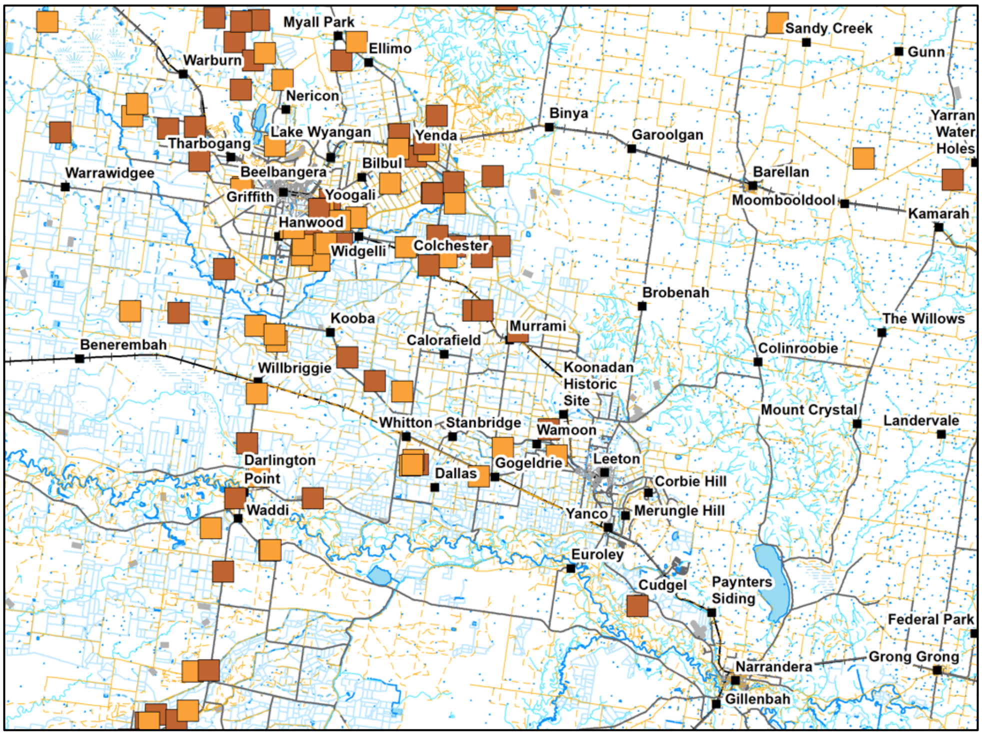


Figure 4. Riverina (Murrumbidgee Irrigation Area) focus region for activities including sampling sites.

Table 1. On-farm trials and related activities were conducted at a range of localities across NSW, Vic, Qld and SA

Type of activity	**Location**	**Lead partner**
Low drift risk summer weed control options trial	Yatpool, Victoria	Mallee Sustainable Farming
Fleabane control in dried fruit vines trial	Irymple, Victoria	Mallee Sustainable Farming, Dried Fruit Association.
Alternative options for optical summer weed control application trial	Yatpool, Victoria	Mallee Sustainable Farming
Ryegrass control in viticulture trial	Irymple, Victoria	Mallee Sustainable Farming
Doubleknock application for fleabane in citrus	Irymple, Victoria	Mallee Sustainable Farming
Timing of spray application for summer weeds to reduce seed set	Yatpool, Victoria	Mallee Sustainable Farming

Type of activity	Location	Lead partner
On-farm application of weed chipper technology for fallow weeds	Pampas, Qld	Millmerran Landcare Group, University of Sydney
Management strategies for roadside weeds trial	Pampas, Qld	Millmerran Landcare Group, CSIRO
Increasing weed suppression by reducing row spacing near roadsides trial	Brookstead, Qld	Millmerran Landcare Group, CSIRO
Crop weed suppression options for shallow irrigation channels trial	Brookstead, Qld	Millmerran Landcare Group, CSIRO
Better mobile weed control in citrus orchards trial	Cudgel NSW	Irrigation Research & Extension Committee, Summit Ag
Better mobile weed control in vineyards trials	Yenda; Hanwood; Willbriggiie; Warburn, NSW	Irrigation Research & Extension Committee, Wine Australia, Nutrien, Ag n Vet Services, Yenda Producers Co-operative, NSW DPI
Weed suppression treatments on irrigation channel banks trial	Griffith, NSW	Irrigation Research & Extension Committee, Summit Ag, Murrumbidgee Irrigation
Kikuyu establishment for weed suppression on channel banks demonstration	Bilbul, NSW	Irrigation Research & Extension Committee, Summit Ag, Murrumbidgee Irrigation
Weed control options around irrigation infrastructure demonstration	Griffith, NSW	Irrigation Research & Extension Committee, Summit Ag, Murrumbidgee Irrigation
Fleabane rust fungus biocontrol release monitoring and release site	Griffith, NSW	Irrigation Research & Extension Committee, CSIRO
Social research with regional stakeholders and growers	Wollongong and each region	University of Wollongong
Resistance bioassays	Adelaide, Waite Campus	University of Adelaide
Economic analysis of willingness for AWM (national survey)	Canberra, Black Mountain; Waite	CSIRO Environment, Agriculture and Food

Type of activity	Location	Lead partner
	Campus	
Spatial analysis / GIS	Adelaide, Waite Campus	CSIRO Agriculture & Food
Economic analysis of crop weeds	Adelaide, Waite Campus	CSIRO, Agriculture & Food
Population genetics analysis	Brisbane, St Lucia	University of Queensland
Study of potential best practice in local government roadside weed management	Wollongong (national study)	University of Wollongong

Core Team Members:

CSIRO (Rick Llewellyn, Christina Ratcliff, Tim Capon, Marta Monjardino)

University of Wollongong (Sonia Graham, Gina Hawkes)

University of Adelaide (Chris Preston)

University of Queensland (James Hereward)

Irrigation Research and Extension Committee (Iva Quarisa)

Mallee Sustainable Farming (Tanja Morgan, Michael Moodie, Jay Cummins)

Millmerran Landcare (Bec Kirby)

Grains Research and Development Corporation

Cotton Research and Development Corporation

Project Outcomes

3.1 Project level achievements

Activity 2 – Project planning and management

KPI 1 Provide a summary of project planning and management activities.

The project was led by CSIRO and informed by an advisory committee comprising weed management and relevant program delivery experts established and managed by GRDC. As detailed in the previous section the project was required to adopt a highly flexible and adaptive approach to management as covid gathering and travel restrictions impacted almost the entire originally planned duration of the project.

A central data repository and share site was managed by CSIRO.

Monthly videoconferences were conducted throughout the project to ensure agile responses to rapidly changing restrictions across the 5 states/ territories in which the project operated.

In June 2022, it became possible to stage the first face-to-face workshop and a professional facilitator was engaged to maximise value from this workshop. A final workshop was also held near the end of the project to consolidate the most recent results and recommendations and plan for finalisation of legacy outputs and ongoing developments. This extended to further cross-discipline working groups producing further integrated and legacy outputs.

At the regional level, local project planning workshops were able to be initiated in all regions with key local stakeholders and local project team members prior to the project partners being contracted and covid restrictions. These workshops were held at Pampas Hall (Darling Downs) November 2019; Mildura (November & December 2019) and Griffith (December 2019). Thirty-five participants were engaged in the initial pre-project planning workshops.

After the beginning of covid, partners were still able to find windows to hold multiple stakeholder and grower meetings across the project life. For example, in Sunraysia these meetings involved bringing together the Almond industry; Dried Fruits Industry, grain grower groups, Citrus industry representatives and agronomy groups and multiple stakeholder meetings across grains and horticulture to plan a major cross-sector delivery in conjunction with WeedSmart. The extension and communications listing includes details of other regional fora used for planning project activities at the regional level.

Photo: Project planning meeting in Darling Downs at Pampas Hall with local cotton and grain growers, Millmerran Landcare Group, Toowoomba Regional Council, GRDC and CSIRO.

Activity 3 – Communication and extension

KPI 2 Provide a summary of communication and extension activities.

Appendix 7.1 includes details of over 100 communication and extension activities ranging from local field activities to digital extension through video production and podcasts to international research papers and national presentations.

Activity 5 – Research activities

Activity 5.1 Mobilise local networks to address landscape-scale cropping system weed management.
KPI 3 Conduct one annual AWM group meeting; KPI 4 Conduct one research trial field walk in each region

The project established extensive local networks through the regional partnerships with influential farmer-based agricultural organisations in three cropping regions involving dryland, irrigated, grains, cotton, horticulture, and viticulture.

The regions and local community networks in Riverina (IREC, New South Wales), Sunraysia (Mallee Sustainable Farming, Victoria) and Darling Downs (Millmerran Landcare, Queensland) were the primary focus of trials and research activity.

Table 1 demonstrates the extent of network activity and Appendix 7.1 includes the details of extension activities including over 30 field-oriented group activities. The multiple AWM stakeholder meetings held in each region have been included in Appendix 7.1 and in the project management section above.

Photo: Trial inspection of optical sensing weed chipper technology, Pampas Qld

KPI 5 Report against communication outputs outlined in regional communication plan

Communication and Extension Plans were generated for each of the regional groups. The communications and extension activity list (Appendix 7.1) has been set up with the key categories of target activities from those plans.

Total outputs have exceeded the plan across the regions. Additional information about events is available from the very large activity data base on request (extracts from the database are included in Appendix 7.1).

The key messages to be targeted in the C&E Plans have also been addressed through the range of materials co-developed for delivery through regional groups by the project leads (see videos and short materials at https://research.csiro.au/weed-awm/).

Photo: IREC Research Update featuring 5 sessions from AWM project speakers, July 2022, Griffith (https://irec.org.au/event/irec-irrigation-research-update-2/)

Activity 5.2 Evaluate suitable weed management tactics to mitigate highly mobile cropping system weeds. KPI 6 Report on progress from all AWM relevant research trials in each region

Research trials in each region took a variety of forms, as summarized in the previous activity location table. Trial and demonstration activity was driven by local priority issues and opportunities, in consultation with the research team.

In *Sunraysia* the trials have spanned dryland irrigated horticulture/viticulture sectors.

The completed trials results have been presented at a range of fora as well as presented in an interactive visual format accessible to all through MSF's immersive ag format:

https://immersiveag.com.au/area-wide-management-for-fleabane/

https://immersiveag.com.au/area-wide-management-for-ryegrass/

https://immersiveag.com.au/area-wide-weed-spraying/

https://immersiveag.com.au/area-wide-weed-management-summer-weeds/

Photo: In crop trial of double knock applications for fleabane control in Sunraysia.

On the *Darling Downs*, in addition to early trials of prospective weed management options at the grower paddock scale, research then focused on 3 replicated trials addressing the local priority issue of roadside and near-roadside weed management.

The report of results from these three trials is attached, with local stakeholders expected to continue to monitor the successful sites for seed set control in the summer.

Key findings were that targeted and timely low-cost slashing can greatly reduce feathertop Rhodes grass populations (blue line compared to red line which is the control, Figure 5).

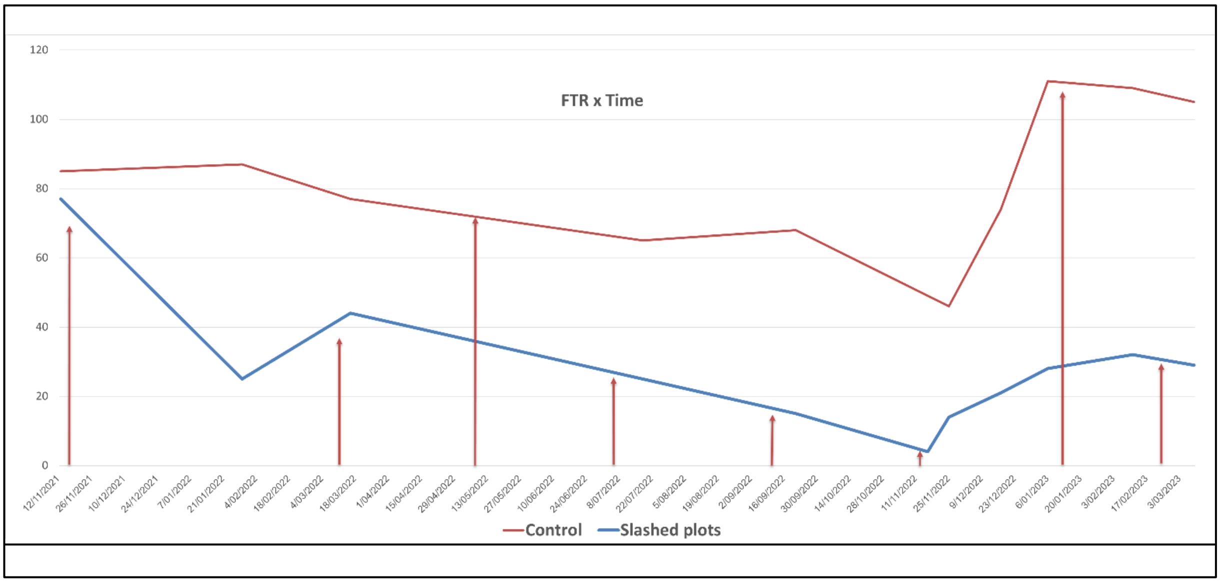


Figure 5. Feathertop Rhodes grass density x Time (vertical arrows show slashing of treatments)

Reducing row spacing of sorghum planted on roadside and irrigation ditch areas demonstrated how 0.25m crop row spacing can lead to negligible weed incidence offering major opportutnity for non-herbicide feathertop Rhodes control in strategically targeted areas of potential weed source (see Figure 6). Similar results were found on a roadside (non-irrigation ditch trials site).

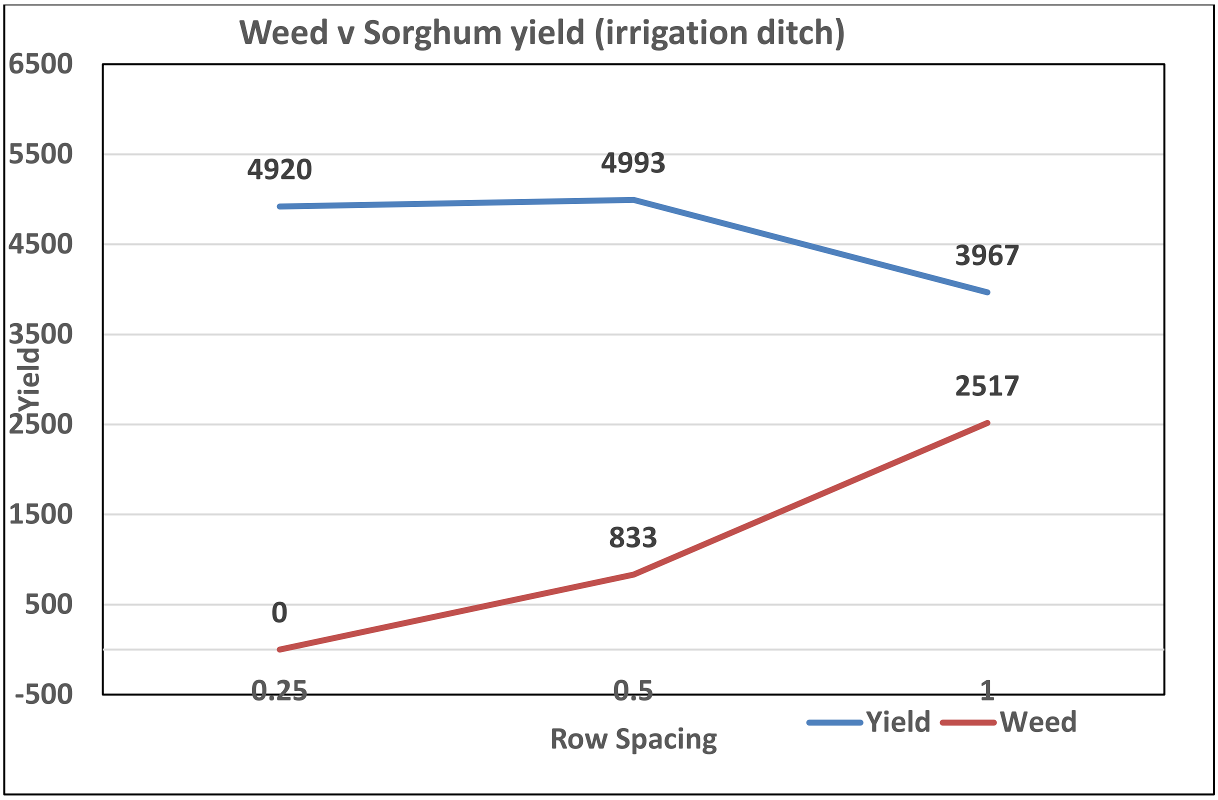


Figure 6. Relationship between sorgum yield and weed pressure on roadside irrigation ditch showing how 0.25m crop row spacing can lead to negligible weed incidence.

In the *Riverina* (Murrumbidgeee Irrigation Area), trial results spanned irrigation bank management through to in-crop trials. The first of these was the Weeds in Vineyards project conducted after the AWM project attracted a new partnership with Wine Australia. This enabled IREC to facilitate collaboration and involvement of local viticulture agronomists from four of the commercial advisor companies (Yenda Producers Cooperative, Elders, Nutrien Ag and AGnVet) and deliver an extensive range of research trials.

Results are captured in the IRAC AWM site here (https://irec.org.au/research/).

Findings included, evidence that turf along channel banks has the potential to suppress and reduce the movement of weeds, with the capability of surviving extreme weather conditions to continue spreading along banks, obtaining water from the channel for self-management (see photo below). Residual herbicides were also shown to have major potential in reducing the risk of channel banks becoming major weed and resistance sources.

Photo: Channel bank weed suppression trial treatment, Murrumbidgee Irrigation Area.

KPI 7 Complete and report on genetic analysis of post-trial weed samples

The genetic analysis of key weed populations has been completed and reports are attached. We found high levels of movement for ryegrass across the Riverina region, and for feathertop Rhodes grass in the Darling Downs region, and both species also showed high levels of outcrossing in the genetic data. Populations from farms and roadsides were genetically the same. This means that for these two species, herbicide resistance can spread by the movement of pollen as well as seeds. High levels of outcrossing also enable a weed species to 'stack' different herbicide resistance mechanisms and more rapidly acquire resistance to multiple herbicide modes of action.

In contrast with ryegrass (see Figures 7 and 8 for comparison), fleabane populations showed significant structure across the Riverina region and the patterns of genetic structure were the same across the two seasons sampled, indicating that local scale movement is a more important driver of local population structure in this species. The genetic data indicated high levels of inbreeding in fleabane – consistent with its reputation for self-pollination, however, the genotypic diversity of fleabane populations does indicate that outcrossing does occur in this species although likely at very low rates.

Comparison of fleabane between regions shows evidence of some long-distance dispersal of Fleabane between regions (see Figure 9).

All three species are highly mobile but feathertop Rhodes and ryegrass more so. The high mobility of the species within regions will lead to the rapid spread of herbicide resistance genes across the landscape, highlighting the importance of early detection and elimination of herbicide resistant populations.

Photo: Weed sampling on the Darling Downs for DNA analysis

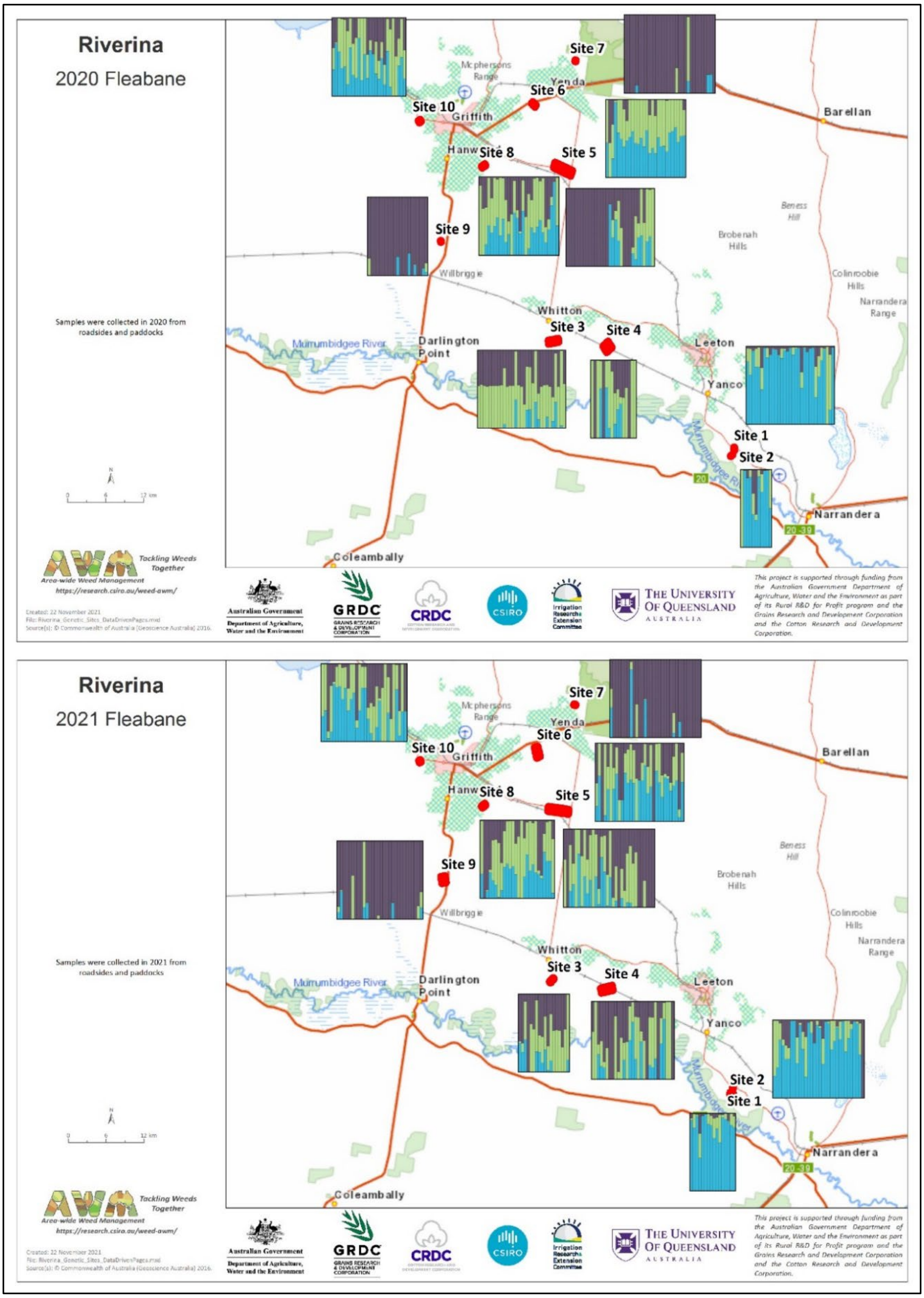


Figure 7. Maps of the results of the STRUCTURE analysis for all fleabane samples from the Riverina in the 2020 season (top) and 2021 season (below), each bar represents one individual weed, the colours within each bar represent the posterior probability of assignment of that individual to each of three different clusters.

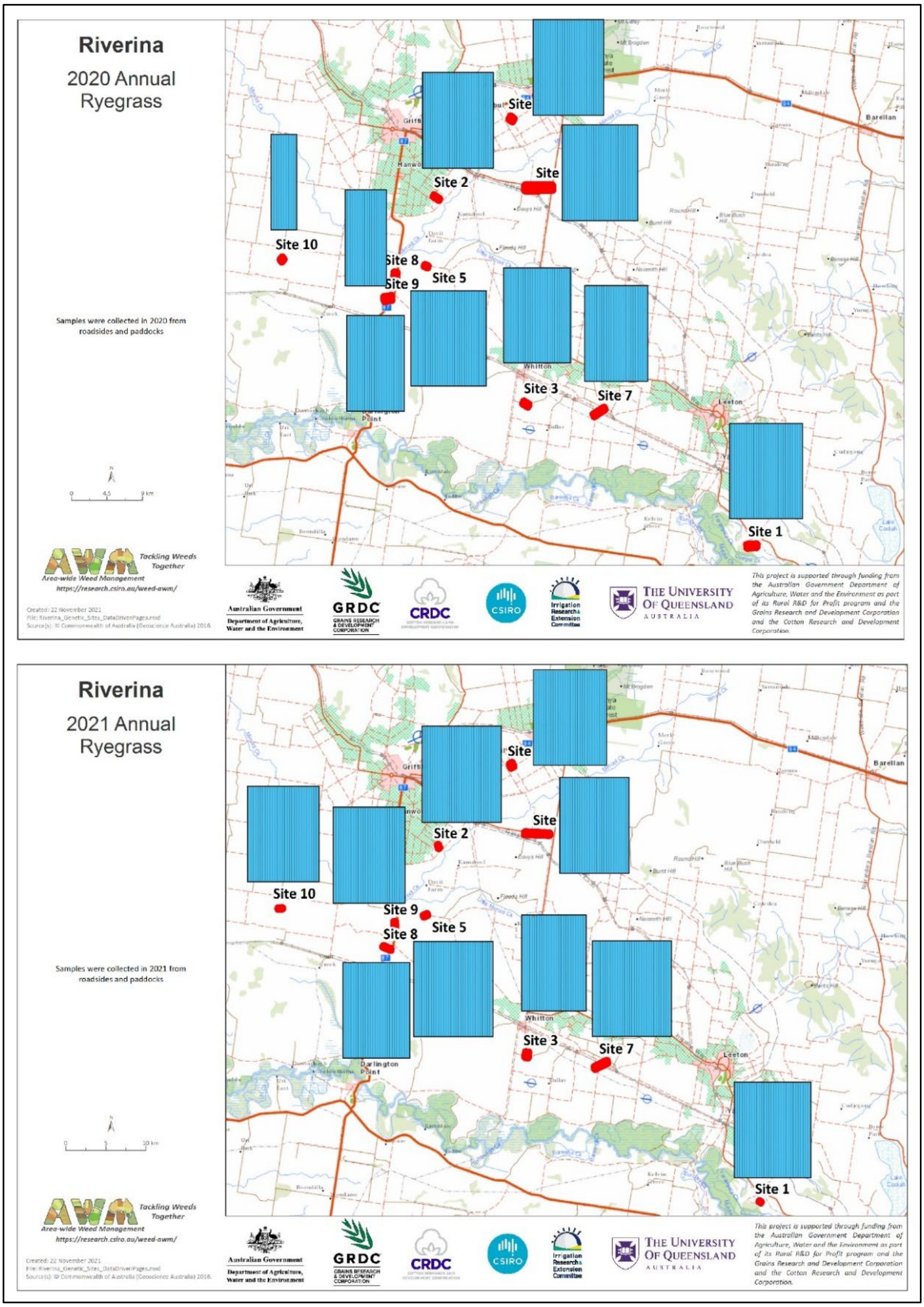


Figure 8. Maps of the results of the STRUCTURE analysis for all ryegrass samples from the Riverina in the 2020 season (top) and 2021 season (below), each bar represents one individual weed, the colours within each bar represent the posterior probability of assignment of that individual to each of three different clusters.

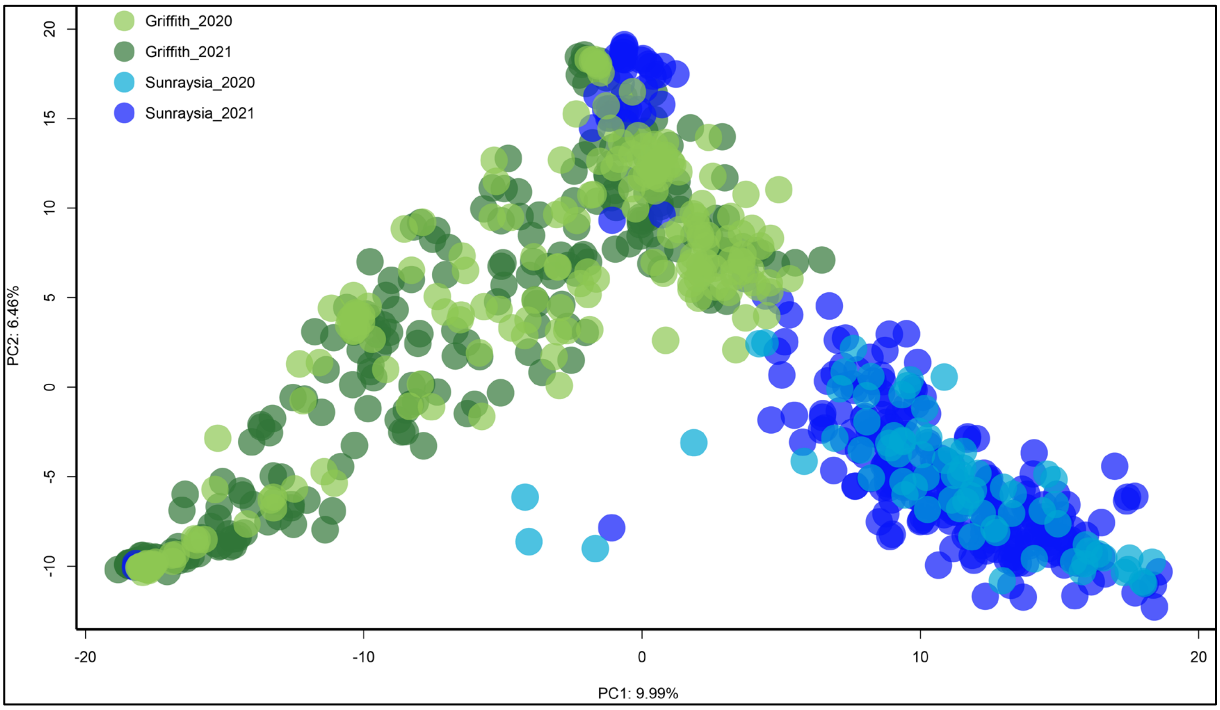


Figure 9. Genetic clustering (principal component analysis (PCA) axes one and two) for all fleabane samples collected in 2020 and 2021 (Griffith and Sunraysia). Samples from the two regions largely form two distinct genetic clusters, although some samples collected from Sunraysia Vic in 2021 were placed in the same cluster as the samples from Griffith NSW indicating movement between these regions.

KPI 8 Communicate findings and progress from AWM relevant research trials to each regional AWM group and the wider research community

The communications and extension activity list (Appendix 7.1) demonstrates the extent of delivery of results to regional groups.

More recent products (e.g. found at https://research.csiro.au/weed-awm/) will also be gaining new audiences over 2023. Further delivery is planned as the 2023 summer approaches and follow-on extension events utilising project results are delivered.

Activity 5.3 Characterise the economic costs of weeds across landscapes and for AWM opportunities

KPI 9 Validate the economic costs and benefits of weed management for traditional and AWM focal economic study scenarios with regional case study coordinators and stakeholders.

KPI 10 Progress toward identifying the economic aspects of the conditions and AWM approach and related practices require and how these relate to landscape and weed characteristics

Paddock-level economic analyses

The social research found that cost (including time) of engaging in collective AWM activity was most commonly stated as the major barrier to participation. This means that consideration of relative benefit is also needed. We did this for both winter and summer weed scenarios at the paddock scale on grain growing farms using scenarios relevant to Sunraysia and Riverina. The economic and weed population costs of gaining glyphosate resistant ryegrass at the paddock-level was evaluated with the bio-economic models Resistance Integrated Management (RIM).

Results showed that the cost of gaining glyphosate resistant ryegrass can be significant and risk of weed population blow-outs increases when no IWM practices in place (see Figure 10). However, when IWM practices offering weed seed kill are already in place, or introduced, the cost can be kept low. For many grain growers such practices are already common. The results highlight the potential for IWM for AWM – with weed seed set control being a major feature of IWM strategies and thereby also reducing risk of spread. The results also highlight the potential for IWM seed control to be promoted to increase cropping system resilience to new weed incursions with the additional benefit of reducing risk of spread to neighbouring land.

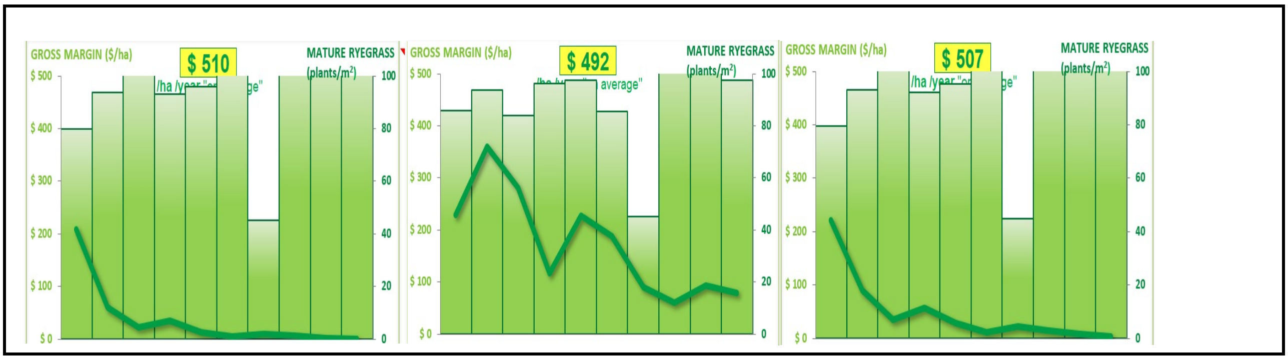


Figure 10. Ryegrass RIM simulation results for a representative 10 year crop sequence in Northern Vic/SW NSW L-R 1) with glyphosate effective at 95% efficacy and no weed seed control; 2) With glyphosate efficacy reduce by resistance incursion to 40% with no weed seed control 3) with glyphosate efficacy reduced by resistance incursion to 40% with weed seed control IWM practices causing 80% seed kill.

Analysis of summer weed control timing was evaluated using a newly developed tool called $ummer, developed in partnership with this project and utilising a large data base of crop-soil-water-nitrogen based modelling for over 60 season types (see paper in Appendix 7.1). Results show the impact of delayed control of a weed such as feathertop Rhodes and allow testing of additional densities (e.g. if additional fallow weeds are gained through seed mobility). For the Mallee agro-ecological zone which includes Sunraysia, the results highlight the benefit of early weed control, even at very low densities of deep-rooted summer weeds. This highlights that even when existing densities are relatively low e.g. 1/m2 that it is economically optimal to implement early control so optimal action in early control regardless of weed density gain through mobile seed. However, in the rare cases where existing densities due to seedbank emergence are extremely low or zero, the results show how gaining only a low density will most likely lead to crop yield and soil nitrogen loss if not controlled.

Regional scale study of perceived weed costs

To explore the socio-economic costs of weeds at the regional landscape scale and the potential for AWM approaches to reduce those costs a study involving 604 grower interviews was conducted (Riverina (n=218), Sunraysia (n=200), and Darling Downs (n=186).

Almost all (95%) growers agreed or strongly agreed that each land manager has a responsibility to the whole region to control weeds and 84% agreed or strongly agreed that effective control of weeds requires land managers to work together. Yet only 24% of growers currently worked with others on weed management. This misalignment between stated expectations of benefit of AWM and relatively low level of AWM action (largely attributable to cost factors including time) was common across all regions.

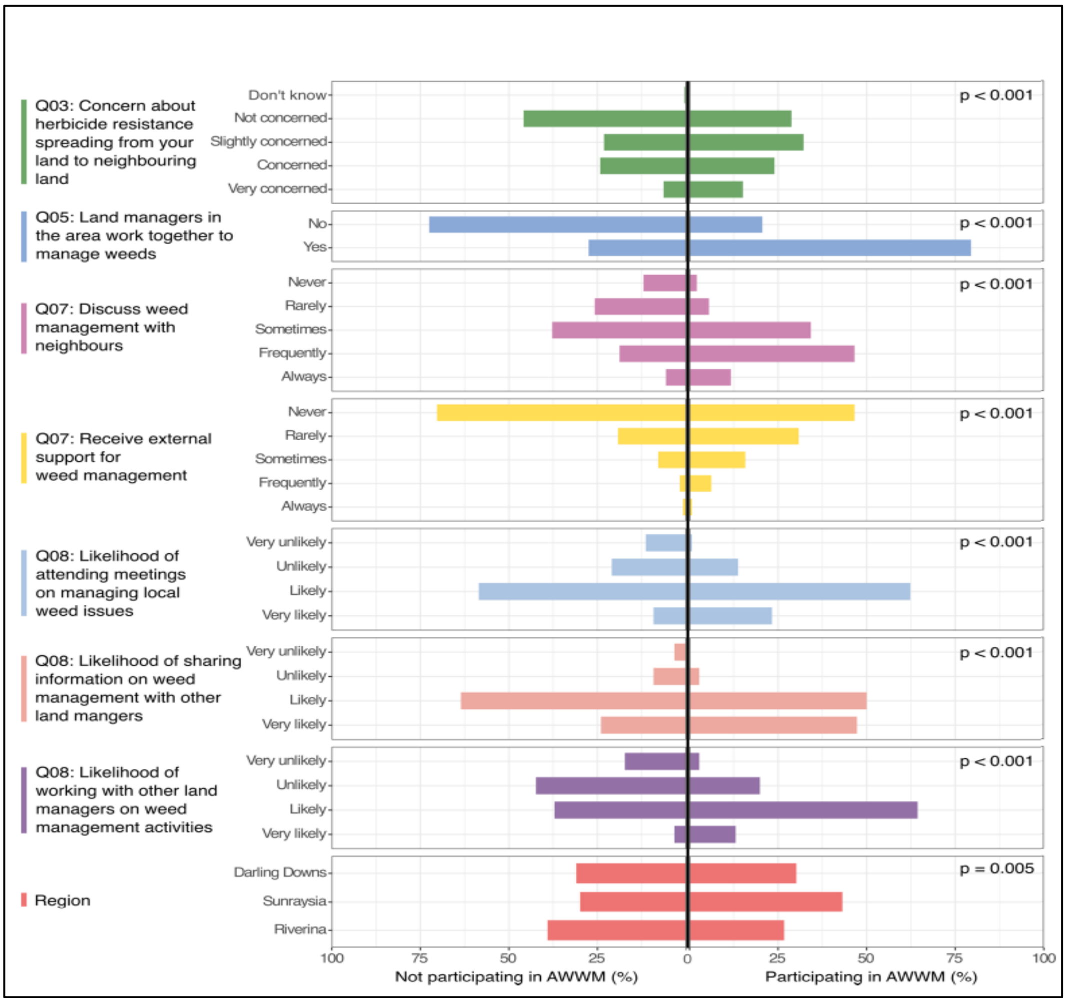


Figure 11. Distribution of answers to selected features of participants and non-participants of

Area wide weed management across the three regions, including relative importance of concern about spreading weeds to neighbours (n=604)

In the later stages of the project a further national extensive survey was conducted, eliciting economic perceptions relating to cost-benefit trade-offs (n=155). Results showed that there was no detectable difference between regions (or states) in economic willingness to invest extra in reducing weed spread.

Results from the national survey of 155 respondents came mostly from family-managed and run farms, with an average area under production of around 1,900ha, an average annual farm operating income of around $1.5M and an average annual weed expenditure of around $230,000.

The Willingness to Pay (WTP) study showed that to avoid a 90% chance of a new herbicide-resistant summer weed spreading to neighbouring farmland, WTP for additional weed management almost 85% of farmers were willing to invest in extra weed management activity. The WTP to reduce weed spread risk from a 75% chance down to 10% ranged from $1,500 to $15,000. However, if the risk of spread was only reduced to 50% there was no willingness to pay for any category of farmers.

As a baseline for reference, farmers were asked about their current expectations about the risk of a new summer growing weed that is resistant to glyphosate spreading from their land to their neighbours' land at some point over the next 3 years. On average this was perceived to be a 37% chance of occurring, with around half of growers considering there to be less than a 25% chance of this occurring.

Overall, the results supported the finding of earlier studies in the project about there being a willingness towards AWM by a majority of growers but AWM participation costs having to be low (including financial and time). The lack of notable differences between different regions and States also supported earlier observations that agro-ecology or landscape factors do not seem to be primary drivers of perceived cost: benefit of AWM investment. However, it needs to be kept in mind that most respondents of the national survey were broadacre dryland farmers. Earlier social science interviews with diverse stakeholders had suggested that a key barrier to AWM participation was perceived to be the diverse agricultural industries in some regions.

Activity 5.4 Understand social attitudes related to the success of weed AWM

KPI 12 Report on findings from extensive survey;

KPI 13 Progress toward identifying the social costs and benefits of AWM and related practices, and how these relate to economic, landscape and weed characteristics

In addition to the economic willingness to pay results reported, the national survey found that concerns about weeds spreading was varied greatly for different sources and destinations. Results provided evidence of earlier suggestions about the high level of concern relating to roadsides as a source (see below).

Level of concern (out of 5) for weeds spreading:

… from public land (e.g., roadside) to your land	3.8
… from neighbouring farmland to your land	3.5
… from your land to neighbouring farmland	3.1
… from your land to public land (e.g., roadside)	2.6

5.4 Understand social attitudes related to the success of weed AWM

Understanding the social barriers to the adoption of weed management and participation in AWM is a fundamental component in determining its ultimate success. This activity will identify the human drivers and barriers to AWM through exploring attitudes of various land managers and other stakeholders applicable to an AWM approach to weed management.

(a) Synthesise existing international social science research on AWM in cropping systems.

(b) Investigate farmers, agronomists, public land managers, industry representatives and government staff attitudes to AWM across the case study regions.

(c) Identify the drivers and barriers that explain participation in individual and area-wide weed management.

(d) Identify the social costs and benefits of AWM and related practices, and how these relate to economic, landscape and weed characteristics (in collaboration with 5.3).

A synthesis of international research was conducted and from an original list of 327 articles found using Scopus, 14 articles were identified for review. The selected articles provided social science results, or in-depth descriptive case studies, of how growers and others work together to manage a joint problem in cropping systems. Only three of these studies examined the challenge of weed management.

Across the studies, most attention was paid to individual-level drivers and barriers to collaborative management in cropping systems. Individual-level key enablers included:

- growers' concerns about pests and the environment.
- beliefs about the benefits and effectiveness of collective pest control measures.
- a preference for working in and belonging to groups; and
- the nature of their relationships with other growers and extension personnel.

The most reported individual-level barrier involved an individualistic or anti-cooperative attitude. A small number of community, institutional and system-level drivers were also identified as limiting the development or uptake of collaborative weed management programs.

Investigating diverse stakeholders' attitudes to AWM

Through the 84 semi-structured phone interviews were undertaken with growers, agronomists, contractors, extension officers, biosecurity officers and public land managers fleabane and feathertop Rhodes grass were consistently identified as the weeds of most concern among interviewees, being mentioned by 36 and 32 interviewees, respectively.

Herbicide resistance was the most frequently identified issue of concern; more than half (43/84) of the interviewees expressed concern about this issue.
The eight key ideas that emerged during the interviews as to what AWM of weeds involves, are:

- Greater shared awareness and understanding (education) of how practices affect one another
- Developing relationships and understanding the system holistically
- Best (integrated weed) management practice
- Integrated biosecurity approaches across properties
- Eradication of individual/multiple weeds
- Minimising seed set from non-cropping areas
- A coordinated program with clear weed targets, and a plan for working together
- Pooling funds across farms to purchase machinery and chemicals for weed management

Identifying drivers and barriers to growers' participation

From the 604 structured phone-surveys were undertaken with growers, only 24% of growers surveyed work with other land managers to control weeds. Statistical analyses revealed that the following eight factors were key in determining whether growers work together with others on weeds:

- Concern about herbicide resistance spreading from ones' land to neighbouring land
- Land managers in the area work together on weeds
- Frequency with which grower discusses weed management with neighbours
- Frequency with which grower receives external support for weed management
- Likelihood of grower working with other land managers on weed management activities

- Likelihood of grower attending meetings about managing weeds in the area
- Likelihood of grower sharing information about weed management with other land managers
- Region – 31.5% of growers from Sunraysia worked together with others on weeds, compared to 24% and 17.9% of growers from the Darling Downs and Riverina, respectively

Identifying social benefits and costs of AWM

Synthesis of the interviews and survey reveals that stakeholders perceive there to be diverse benefits associated with more collaborative management of weeds in cropping regions.

In the interviews with diverse stakeholders, the two most identified benefits were financial benefits and knowledge benefits. Financial benefits included easier and more effective weed control, a better return on weed control investments, and less disagreement between stakeholders. Knowledge benefits included a greater awareness of weed issues and improvements in best practice. Knowledge of which weeds are in an area, especially herbicide resistant weeds, was the most identified benefit in the survey.

A small number of costs, mostly associated with time, money and equipment, were identified in the interviews. In the survey, too much time spent in meetings was the most common barrier to AWM. Results of extensive grower interviews across the focus regions indicated that greater uptake of AWM of weeds in the future will be highly influenced by the existence and awareness of herbicide resistance spread risks, building of new networks among growers and other key stakeholders, and recognition of weed management actions that align with the importance of time and cost constraints.

Together, these findings suggest that organisations seeking to development and implement areawide management of weeds need to:

- Clearly define what the project is seeking to do and over what area
- Provide evidence on how weed mobility affects neighbouring properties
- Address growers concern about the costs associated with participating, such as by minimising the amount of time spent in meetings or by providing evidence of the financial benefits of participating
- Promote the program widely

Activity 5.5 Data integration and spatial analysis to outscale findings of trials and mobility components to demonstrate the value of AWM at regional and/or national scale.

KPI 14 Report on integrating research trial data to produce maps and summaries

KPI 15 Report on indicative maps demonstrating the potential of AWM across similar agricultural regions.

Collate the trial results, georeferenced genetic data, economic data and other available data to provide summaries and maps of the potential benefit to be derived from application of AWM within the broader study region, and within agriculturally similar regions nationally.

(a) Mapping using relevant available spatial data to characterise each of the three defined regions region (Sunraysia, Riverina, Darling Downs):

(b) Map the distribution of herbicide resistant weeds in each region where trials are conducted.

(c) Integrate the research trial data to summarise and visualise results and findings.

(d) Combine results and findings into indicative maps that relates the potential for of AWM across similar agricultural regions.

As described above, there were no clear agro-ecological or regional differences in existing or intended AWM activity to suggest that there are particular cropping-based regions, region types or cropping landscapes to be targeted. The national survey described above did not identify opportunities for mapping regions with higher or lower levels of potential AWM adoption. This finding supports the potential for communications based on understanding of common principles likely to influence adoption to be effectively delivered widely.

However, given the importance of the cost: benefit relationship in driving intentions towards collaborative weed management action it is likely that a district or region facing a recognised high cost weed incursion and spread risk (e.g. a new mobile weed that may threaten markets or be uncontrollable with existing control methods) is likely to see greater action towards the more resource-intensive co-ordinated approaches to area-wide weed management.

What is clear is that herbicide resistance and its spread is a notable motivating factor towards an area wide weed management approach. When available new GRDC research and databasing from random paddock surveys is potentially capable of mapping early stage of spread of resistance types that could motivate greater AWM opportunity.

Resistance distribution and spatial analysis

In this project, major effort was made to map and spatially analyse resistance to the priority weeds. Over 400 geo-referenced weed samples fleabane, feathertop Rhodes grass, annual ryegrass, common sowthistle and silverleaf nightshade were tested for resistance to glyphosate. Fleabane was also tested for resistance to paraquat + diquat and common sowthistle to 2,4-D.

Resistance to glyphosate was identified in fleabane samples from Sunraysia and Riverina. The frequency of resistance varied with year. In both regions, glyphosate-resistant samples were distributed across the sampled region. None of the fleabane samples tested was resistant to paraquat + diquat. Resistance to glyphosate was found in most of the annual ryegrass samples from Riverina in both years. Glyphosate-resistant annual ryegrass was distributed across the sampled region. Glyphosate resistance was identified in feathertop Rhodes grass samples collected from the Darling Downs in both years. Glyphosate-resistant samples of feathertop Rhodes grass were also distributed across the sampled region. One sample of silverleaf nightshade from Riverina survived glyphosate on testing. A dose response experiment showed this sample had increased tolerance to glyphosate compared to a sample of silverleaf nightshade that was controlled by glyphosate. No resistance to glyphosate or 2,4-D was identified in common sowthistle.

Sunraysia

There were 50 samples of fleabane from Sunraysia tested in 2020 and 55 samples tested in 2021. In 2020, 21 fleabane samples were resistant to glyphosate (see Table 2). In 2021, only 3 samples were resistant to glyphosate. None of the samples in either year survived paraquat + diquat. There was much lower resistance in fleabane in Sunraysia in 2021 (5% of samples) compared to 2020 when 42% of the samples tested were resistant to glyphosate. This may be because 2019 was a drought year and fleabane seed was mostly collected from roadsides and the banks of irrigation channels. In 2020, fleabane was more widespread across the region. This highlights that fleabane populations can be ephemeral and high levels of resistance across a region in one year do not mean high levels of resistance will be always found. No resistance to either glyphosate or 2,4-D was identified in samples collected in 2023.

Table 2. Results of resistance testing for fleabane from the Sunraysia to glyphosate and paraquat + diquat in 2020 and 2021 and for common sowthistle to glyphosate and 2,4-D in 2023.

Weed species	Year	Samples tested	Resistant to glyphosate	Resistant to paraquat + diquat	Resistant to 2,4-D
Fleabane	2020	50	21	0	-
	2021	55	3	0	-
Common sowthistle	2023	25	0	-	0

- not tested.

In 2020, the distribution of resistant and susceptible fleabane is shown in Figure 12. Resistance was scattered across the region surveyed with susceptible samples interspersed with resistant samples.

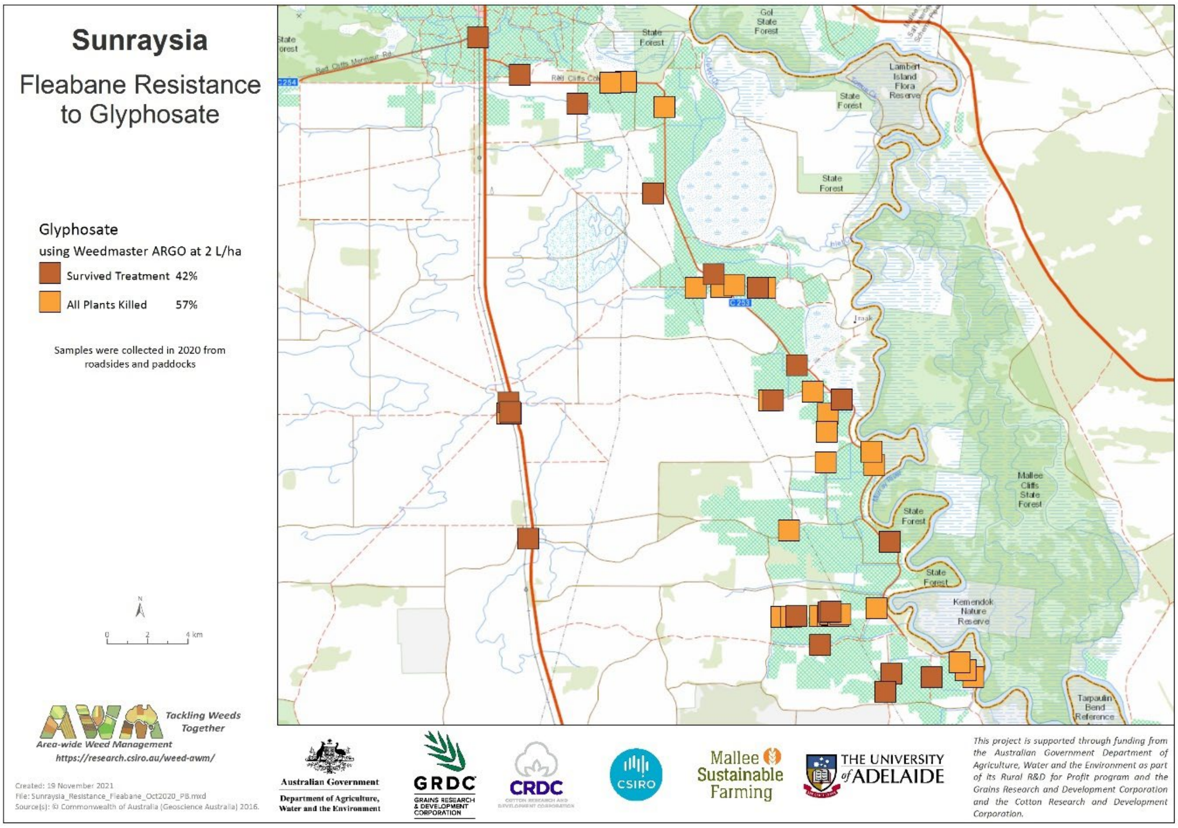


Figure 12. Distribution of glyphosate-resistant (dark symbols) and glyphosate-susceptible (light symbols) fleabane in Sunraysia in 2020.

Riverina

Three weed species (fleabane, annual ryegrass and silverleaf nightshade) were collected in the Riverina and tested for resistance to glyphosate (Table 3).

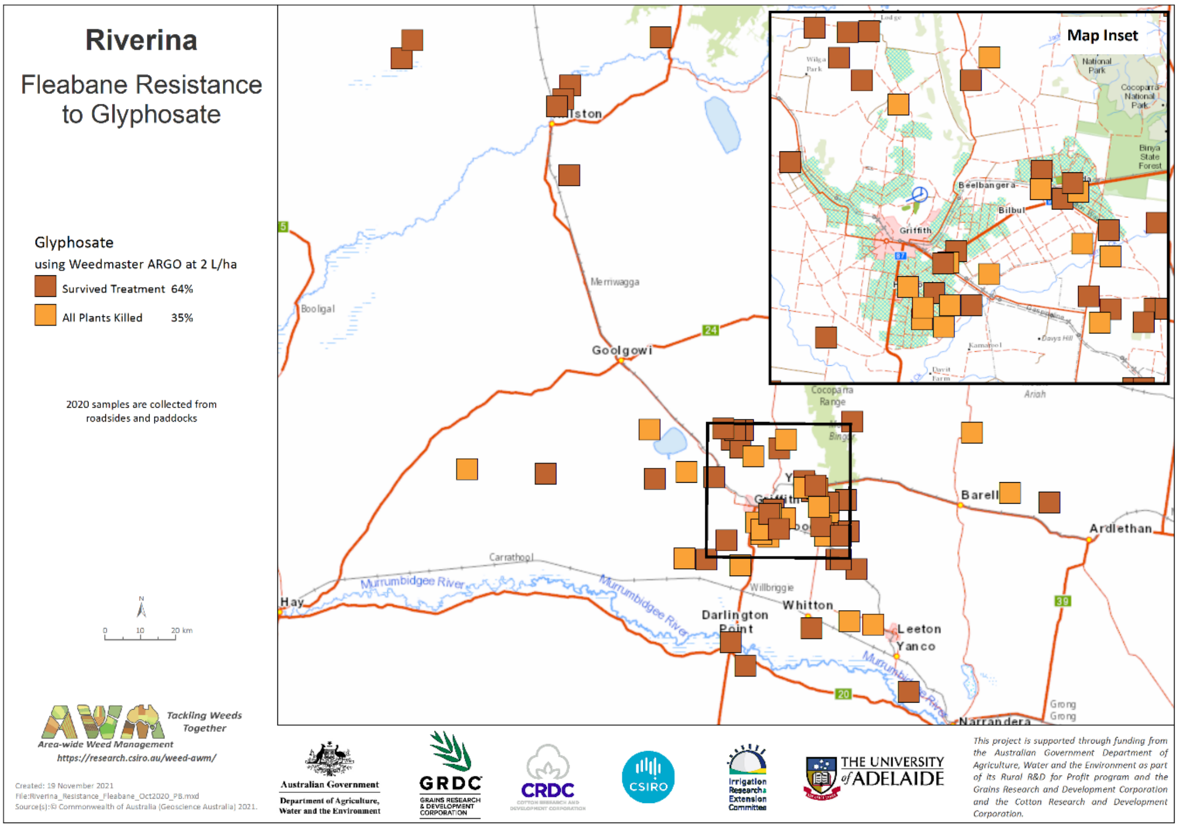
In 2020, 64 samples of fleabane were tested with a further 57 samples tested in 2021. In 2020, 64% of the tested samples were resistant to glyphosate and in 2021 37% of the samples tested were resistant. There was no resistance identified in either year to paraquat + diquat. The amount of resistance to glyphosate detected in 2021 was lower than 2020.

Silverleaf nightshade was identified by regional stakeholders as being potentially high cost to manage, therefore was added to the study. A total of 11 samples of silverleaf nightshade were also tested in 2021. A single sample had survivors to glyphosate (Table 3). It was tested a second time and also had survivors. There is no label rate for glyphosate for controlling silverleaf nightshade, so a dose response experiment was conducted to confirm resistance in 2022. This demonstrated that the sample that survived in 2021 had greater tolerance to glyphosate compared to a sample that was killed in 2021. Silverleaf nightshade is a deep-rooted perennial weed that is poorly controlled by glyphosate due to its ability to re-shoot from its extensive root system. Increased tolerance to glyphosate in silverleaf nightshade would be a major challenge to grape growers in the region, as they have no other effective tactics to control this weed species.

Table 3. Results of resistance testing for fleabane, annual ryegrass and silverleaf nightshade from the Riverina to glyphosate and fleabane to paraquat + diquat in 2020 and 2021.

Weed species	Year	Samples tested	Resistant to glyphosate	Resistant to paraquat + diquat
Fleabane	2020	64	41	0
	2021	57	21	0
Annual ryegrass	2020	20	13	-
	2021	16	13	-
Vineyard samples				
Fleabane	2021	22	9	0
Silverleaf nightshade	2021	11	1	-

- not tested.



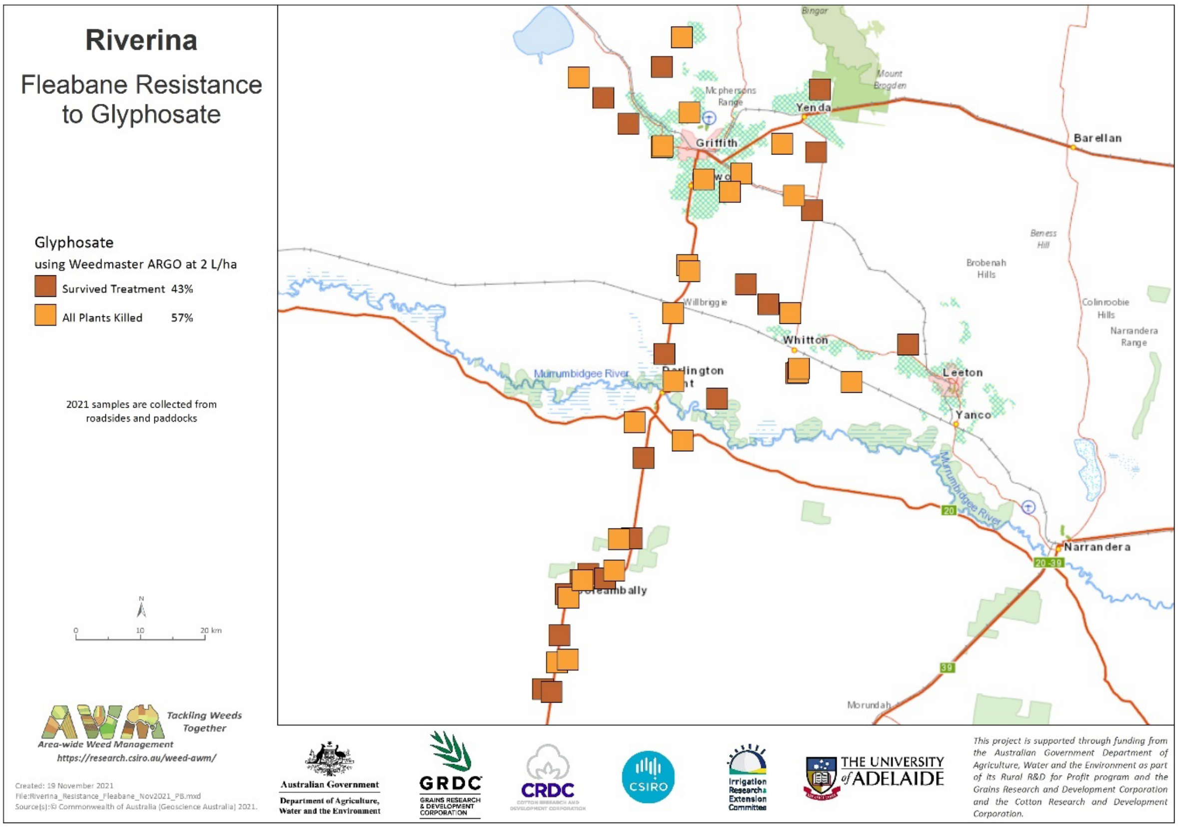


Figure 13. Distribution of glyphosate-resistant (dark symbols) and glyphosate-susceptible (light symbols) of fleabane in the Riverina in 2020 (top) and 2021 (bottom).

In both 2020 and 2021, fleabane was distributed across the region (Figure 13). In 2020, there were more samples collected north of Griffith than in 2021. The area around Hillston only had glyphosate-resistant fleabane in 2020; however, elsewhere, resistant, and susceptible samples were located in close proximity to each other. The Hillston area was not sampled in 2021. The area sampled in 2021 contained a mix of resistant and susceptible samples with resistant samples located close to susceptible samples.

There were 20 samples of annual ryegrass tested in 2020 and 16 samples tested in 2021. In 2020, 65% of annual ryegrass samples tested resistant to glyphosate. This was 81% of the samples tested in 2021. These results show that glyphosate resistance in annual ryegrass is widespread in the Riverina region.

The distribution of glyphosate-resistant annual ryegrass occurred across the region sampled in 2020 (Figure 14). Samples resistant and susceptible to glyphosate occurred in all parts of the region sampled.

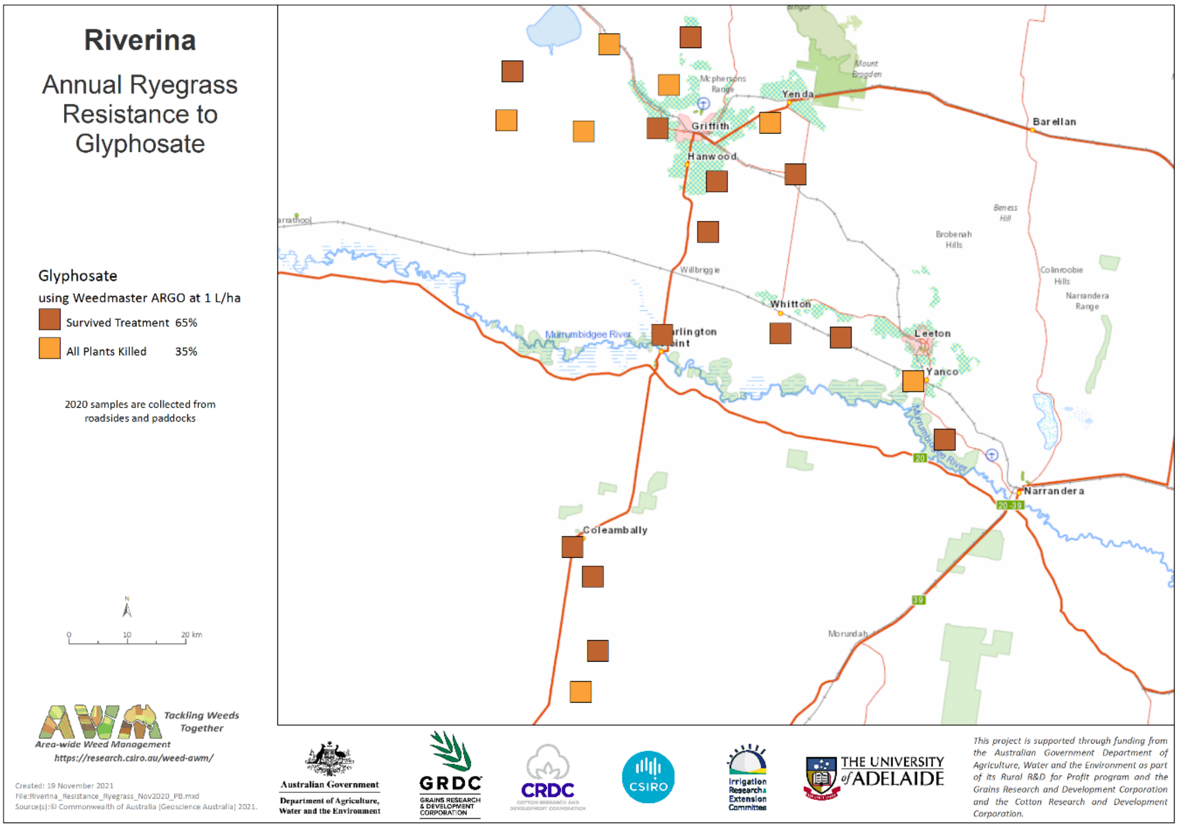


Figure 14. Distribution of glyphosate-resistant (dark symbols) and glyphosate-susceptible (light symbols) of annual ryegrass collected from the Riverina in 2021.

A set of samples of fleabane and silverleaf nightshade were separately collected from vineyards in the Riverina in 2021. Of the 22 fleabane samples, 9 were resistant to glyphosate and none were resistant to paraquat + diquat (see Table 3). The frequency of glyphosate resistance in fleabane samples from vineyards (41%) was similar to that observed in the structured collection across the Riverina.

Darling Downs

In 2021, there were 36 samples of feathertop Rhodes grass collected from the Darling Downs tested for resistance to glyphosate. Of these 18 had survivors to 1080 g ha^{-1} glyphosate and were resistant (see Table 5). In 2023, there were 56 samples of feathertop Rhodes grass tested and 38 were resistant. Glyphosate resistance was present in both years and was common in both 2020 (50%) and 2022 (66%).

Table 5. Results of resistance testing for feathertop Rhodes grass from the Darling Downs to glyphosate in 2021 and 2023.

Year	Samples tested	Resistant to glyphosate
2021	36	18
2023	56	38

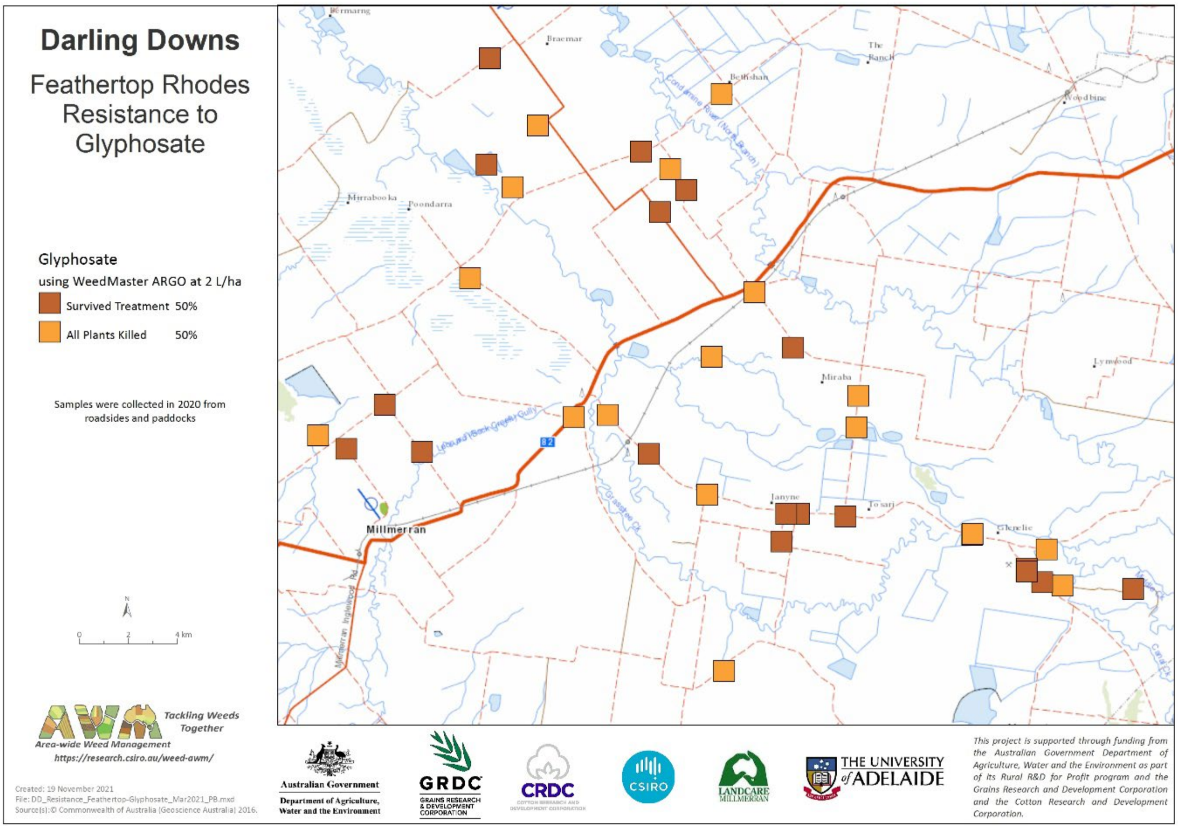


Figure 15. Distribution of glyphosate-resistant (dark symbols) and glyphosate-susceptible (light symbols) of feathertop Rhodes grass from the Darling Downs in 2021.

Summary of resistance status

The results show that resistance to glyphosate was common in fleabane, annual ryegrass and feathertop Rhodes grass. However, there was no resistance to paraquat + diquat in fleabane in either the Sunraysia or Riverina. No resistance to either glyphosate or 2,4-D was identified in common sowthistle. Glyphosate resistance in the weeds tested was spread across each of the regions. The frequency of glyphosate resistance varied between years, in part because of different locations being sampled. However, for fleabane there was also likely some local extinction of populations between years.

Spatial analysis of resistance distribution

Weed samples used in the above analysis were taken from a range of locations in each region which could be in-crop, on roadsides, on non-cropped farm property or, as was often the case, on the edges of such land uses (see Figure below for example of distribution). Where sufficient definition could be achieved in the land use that was the source of the weed and there were sufficient observations, comparisons of resistance frequency could be made. The Table below shows that the frequency of resistance on roadsides is substantial and similar to the overall level of resistance in the region. This is an important finding in the context of the concern expressed by growers in the need for improved management of roadside weeds. It also highlights the potential for awareness raising for local government roadside management.

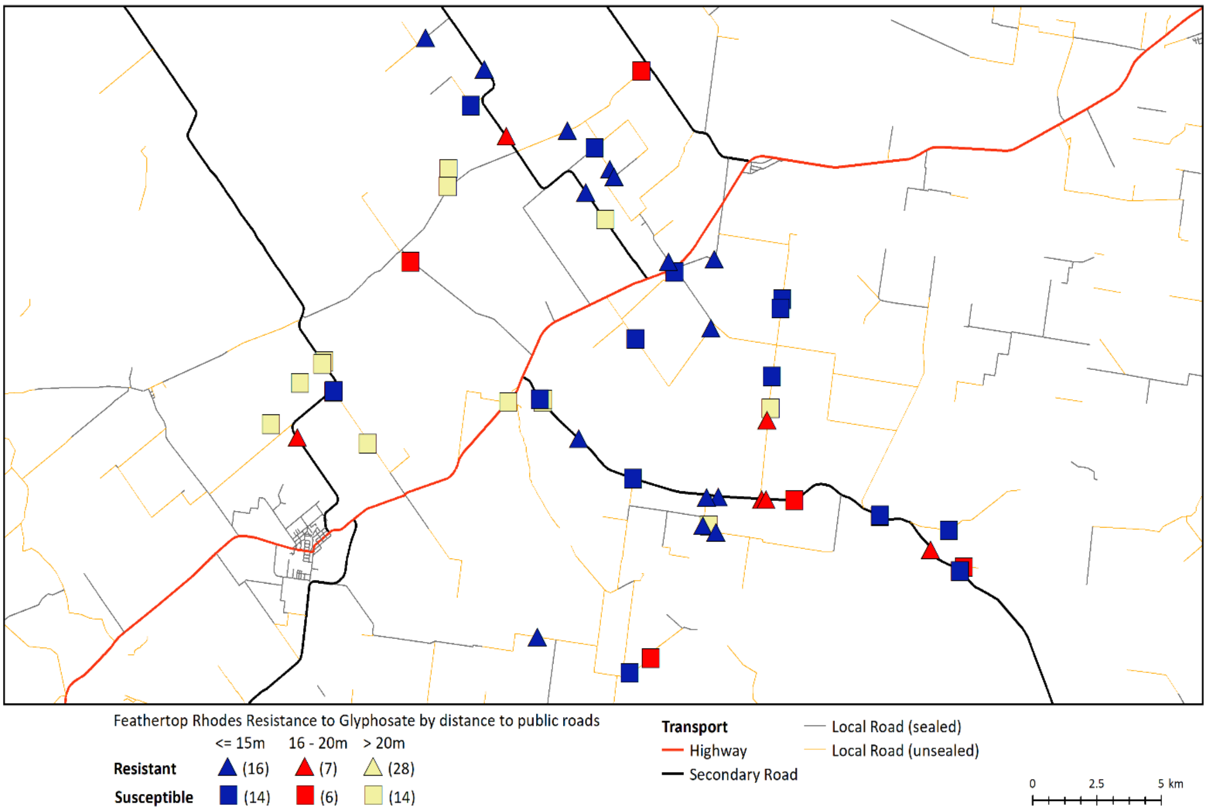


Figure 16. Distribution of glyphosate resistant feathertop Rhodes in the Darling Downs showing proximity of population to roadside

Table 6. Proportion of populations glyphosate resistant (%) on roadsides and away from roadsides.

			Within 20m of road	Greater than 20m from road	All samples
Riverina	Fleabane	Glyphosate	40%	55%	53%
Riverina	Annual Ryegrass	Glyphosate	-	59%	65%
Darling Downs	Feathertop Rhodes	Glyphosate	53%	67%	60%

GIS spatial clustering analysis

An important question when considering resistance mobility is whether the presence of a resistant population makes it more likely that a neighbouring population is resistant. Using the ArcGIS spatial autocorrelation function and Moran's I, the spatial resistance status data was analysed. As can be readily seen in the mapping there was no larger scale grouping of resistance where large areas of a target region had low resistance and others high based on geography or land use. In the case of glyphosate resistant Fleabane in the Riverina the pattern of resistance is found to be random (P=0.9). For glyphosate resistant feathertop Rhodes in the Darling Downs there is evidence of some small-scale local clustering but it is not significant at the 5% level using Anselin Local Moran's Clustering (p=0.06). However, when viewing the spatial clusters and frequency of significance (see Figure 17), there are very few clusters of resistance (High-High) and most are other combinations. For example, susceptibility clustered with resistance is more common than resistance clustered with resistance.

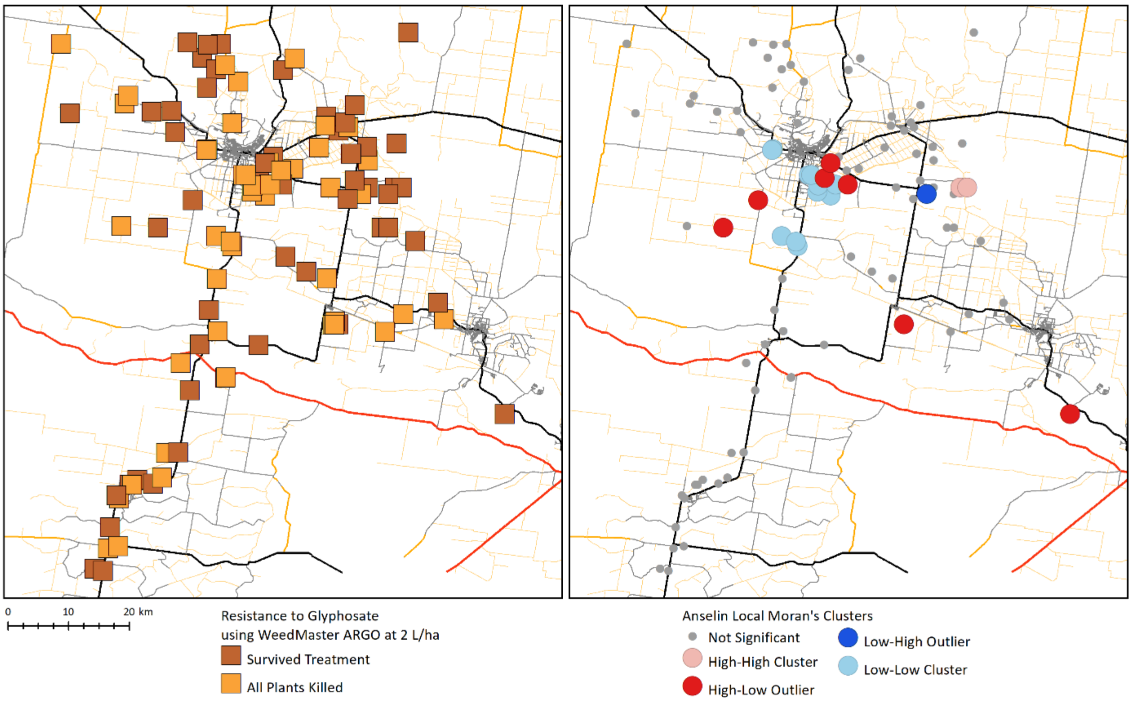


Figure 17. Spatial analysis of glyphosate resistant Fleabane in the Riverina.

Therefore, it can be concluded that for the regions in the study, there was no pattern to the distribution of glyphosate resistance in any of the weeds, suggesting a combination of multiple resistance evolution events and stochastic spread is the main contributor to the distribution of resistant weeds. The results show no potential for sub-regional area-wide action to reduce the risk of glyphosate resistance in these weeds moving from one part of the region to another. Resistance is scattered and common. It is not strongly associated with land use and there are still substantial levels of susceptibility to warrant attention being given to management actions that could maintain susceptibility. The results demonstrate the possibility that populations very nearby to a susceptible population may be resistant or susceptible, making management of near-neighbour weed movement very relevant.

3.2 Contribution to program objectives

The project objective was to identify the benefits, key principles, and practices of successful Area Wide Management (AWM) of weeds in farming systems. AWM involves multiple stakeholders in a coordinated effort to reduce the impact of mobile weeds and the objective of this project was to test this approach in key regions.

The project objective was achieved generating new understanding of the social, bio-physical, geographic, and economic drivers that contribute to area-wide weed management success. The project integrated multi-disciplinary research results with the on-ground testing and experiences from cross-sector regional community partnerships. Approaches to implementing area-wide weed management best able to reduce the negative impact of highly mobile weeds in cropping regions of Australia have been identified through this process.

The project brought together 11 research and industry partners in a multidisciplinary team and formed a network of AWM groups, comprising of representatives from key growers and industries, in three case study regions: Darling Downs, Sunraysia and Riverina.

Activities were conducted in these regions including applied field trials and demonstrations the objective to identify appropriate and effective weed control strategies that reduce weed dispersal as well as test the potential for engagement in AWM effort.

On the Darling Downs, discussions with local government identified differing perceptions of weed species and management issues, legislative barriers to growers controlling roadside weeds, and layers of institutional decision making, all cumulatively impacting the harbouring and/or spread of agricultural weeds from roadsides and community relations. The key achievement in this region was the increased understanding of weed management from a local government perspective.

In the Sunraysia, AWM was achieved across horticulture and grain cropping industries at a neighbourly scale. The dialogue established across industries identified varying weed management capacity and on-ground improvements in weed control. It is expected that the benefits gained by the participating growers and observed will continue to influence others in the region.

In the Riverina, trials were conducted on weed management tactics around irrigation infrastructure and across horticultural industries. The irrigation community were regularly updated through group meetings and research updates. There was strong attendance at field days and evidence of participatory research, with ongoing and responsive evolution of research trials.

In addition to the regional achievements, research was conducted across the regions. There was research on the presence of herbicide resistance, weed genetics, social drivers, and motivations for AWM and economic willingness to pay. The herbicide resistance work was considered by the project team as providing a point of interest for grower engagement and the genetics research results, social research, and economics have all made meaningful contributions to developing an understanding of various aspects of AWM. These results show that AWM of weeds is a concept of potential merit. It is of significant interest to growers, with growers believing there are benefits from improving weed control across boundaries. These research results support the need for ongoing work to develop a working model of AWM as a new way of tackling weeds in the grains industry.

A key finding from the research was that AWM may take many different forms. The project has identified four models of AWM. The 4 models came from earlier work (Graham 2019) and our project has referred to them and adapted them for AWM for weeds.

https://www.sciencedirect.com/science/article/pii/S026483771731339X

- Individual: individual land managers are aware that their actions impact others around them and adjust practices

- Linked: land managers communicate directly or through an intermediary on weed management issues and practices

- Collaboration (together): agreed weed priorities within a geographic area, with a sense of collective action and purpose

- Collaborative coordination (groups): structured coordination with resourcing for shared activities and monitoring

Further work is required to understand the differences between these models including the resourcing and capacity required, and the most appropriate landscape and social contexts for each model.

Finally, a highlight of the project was the use of the relationships established within the project to facilitate the release of a biocontrol for fleabane. The formation of regional network of organisations interested in weed management has proven a useful tool for deploying technology.

Collaboration

The project has established not only extensive new collaborations in the region but also strong new research partnerships between the partner organisations. As described throughout, this has involved not only cross-sector partnerships that extended beyond the initial GRDC-CRDC proponents but to horticulture, viticulture and additional RDC engagement (Wine Australia).

Plans for ongoing collaboration and weed management initiatives are already in place as a result of this project (e.g. WeedSmart cross-sector extension events; local government engagement in identifying best practice).

The extent of new collaborations that were initiated through the efforts of this project are demonstrated in the list of participating organisations listed below:

Key collaborations

Sunraysia

Dried Fruit Association, Almond Board, NuFarm, Frontier Farming Systems, WeedSmart, E.E. Muir & Sons; Nutrano Citrus

Darling Downs

Qld Dept.. Ag & Food (Weeds team and Farming Systems research project team); WeedSmart northern agronomist; University of Sydney.

Riverina

Murrumbidgee Irrigation, Wine Australia, Nutrien, Summit Ag; Ag n Vet Services,

Yenda Producers Co-operative, NSW DPI; Riverina Winegrape Growers; AGnVET

Extension and adoption activities

Extension activities are described in 7.1. Ongoing delivery of results, some of which have only just been finalised (e.g latest resistance, genetic results, national survey results and local government best practice roadside management findings) will have ongoing impact to a potential national audience. Communication materials will be delivered more widely over coming months and partnerships extended. An example of ongoing extension through a high profile established vehicle for grower impact is WeedSmart. The project initiated a partnership with the highly successful national WeedSmart program. Following the successful first ever cross-sector expansion event into horticulture in Sunraysia, there are plans in place for 2 further events in the coming year including new regions. Horticultural partners (e.g EE Muir & Sons) are now also driving this further collaboration.

A major objective of further communications will be to target the awareness and messaging towards the low resource intensity forms of neighbourly AWM. The RDC communications networks will be a key vehicle. As described in this report, this is consistent with the framework for approaching AWM in cropping regions like those involved in this project. It is clearly where the greatest potential for extensive grower impact has been identified and consistent with the level of willingness from growers and likely future resourcing. The project did not find circumstances that is likely to support well resourced coordination of collective regional action, but that is not to say that those circumstances won't arrive through a highly mobile, high cost new weed threat in the future.

A substantial upgrade of the website is budgeted for June once final consolidated and new material included in this report is approved. The aim is that it now shifts from a project-oriented site to an attractive ongoing accessible resource aimed at those (nationally and internationally) seeking information and learnings on area-wide management of mobile weed issues in cropping regions. This includes presenting the recommended steps to determining the most likely effective model and framework for AWM development for the mobile cropping weed management problems being experienced. It also includes providing an ongoing host site (supported by CSIRO) for the substantial project resources produced during the project that are still finding new audiences such as:

- 'Managing hard-to-control weeds along Australian roadsides – guidelines for managers'.
- Area-wide management for cropping systems weeds (overview of key findings)
- Good neighbours work beyond the boundary fenceline to help combat the spread of weeds
- A problem shared is a problem halved when it comes to roadside weeds
- Cross-sector collaboration helps combat herbicide resistance
- Community collaboration supports pilot release of a biocontrol agent for flaxleaf fleabane across the Riverina

Lessons learnt

Area wide management approaches have previously been identified as a continuum of collective action from participatory through to the more resource-intensive coordinated (see Figure 18).

The initial project design expressed Collaborative and Co-ordinated regional collective action as potential paths to AWM adoption. The multi-disciplinary findings and regional experiences has led to a pivot in the project towards Participatory and Linked models for the weed management problems targeted in the project.

Land managers can consciously participate in weed management actions that will benefit neighbours or 'the area' weed management action, not just an individual weed manager in a way that does not involve any substantial information exchange with others. The examples of 'IWM for AWM' presented in this report can be examples of that, where on-farm actions reduce weed set and the weed manager is conscious of potential reductions in the risk of weed or resistance spread. This consciousness and 'neighbourly' perspective can motivate improved implementation of the 'beneficial' weed management practices.

Where highly localised minor levels of collaboration or communication occurs relating to the weed management this can be described as Linked. In this project we have dealt with weed management and resistance scenarios where Participatory and Linked are the most likely actions. The case study highlighted in our video from the Sunraysia mentioned https://youtu.be/4j9t-dg99wo is an example of what is now a Linked action.

At the grower-grower level it is only when greater and more certain relative need or benefit from AWM action is evident that we are likely to see high levels of Collaborative AWM action which can require more extensive social capital and inputs (e.g. organised meetings of multiple parties focused on AWM needs and actions). Our project findings show that the 'good neighbour' approach through Participatory awareness and Linked approaches are most likely to succeed in cropping regions.

However, the project has also demonstrated the potential for Collaborative action and even the more resource-intensive Coordinated action (where parties that would not otherwise interact are brought together, usually with supporting resourcing). It is at the multi-sector representative level where this has substantial potential and value e.g. bringing industry sectors, public land manager and representative industry bodies together to take a regional ('area') approach to shared weed management problems.

These two avenues together, through promoting the 'Linking' of neighbourly growers, facilitated and promoted by 'Collaborative' organisational actions, offer substantial and achievable opportunities to reduce the cost of mobile weeds.

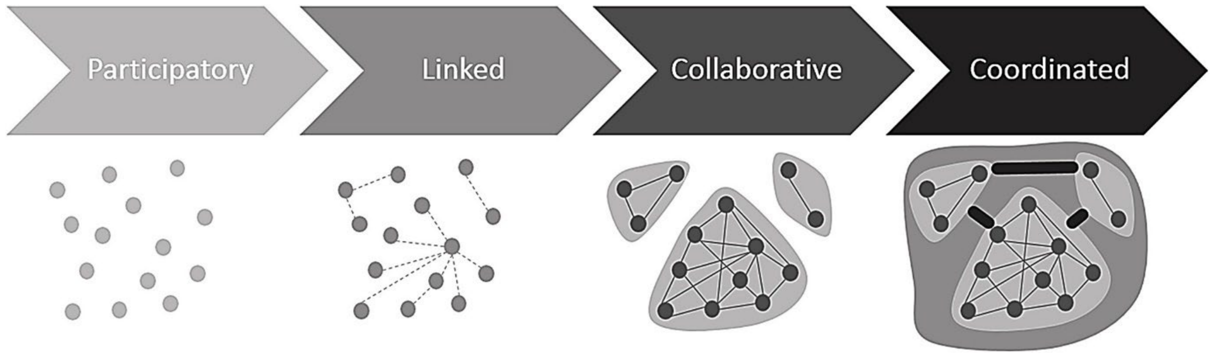


Figure 18. Continuum of collective action models relevant to AWM where dots indicate individual actors involved in IPM, dotted lines indicate weak social bonds, solid lines indicate strong social bonds, and thick solid lines indicate bridging social capital. Grey areas indicate who is involved in collaborative actions. From Graham 2019 (https://www.sciencedirect.com/science/article/pii/S026483771731339X)

Feedback on the program

The multiple major challenges of covid and Murray Darling Basin flooding have already been described above. The flexibility in providing an additional year was much appreciated, and essential if results and impact was going to achieved. However, even in the absence of the major challenges faced with covid extending over most of the original project term, less than 3 years for a project of this nature was always going to limit potential for impact. If a 4- or 5-year project length was offered and could have been planned for there would have been greater potential to expand implementation of the priority strategies that have been identified.

In terms of opportunities to improve the RRD4P program, firstly it should continue. This project has highlighted the need, opportunity and potential for cross-sector coordination at the RDC level through to local collaborations and new partnerships. Weed management in multi-land use regions has a lot to gain from this and all regions, including those entirely dryland broadacre farming, are shown to be looking for greater coordinated effort between farmers and public land managers. Promoting more partnerships between RDCs can be the starting point.

Area-wide Weed Management