Annual Ryegrass (Lolium rigidum)

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Annual ryegrass (Lolium rigidum Gaud.), traditionally utilised as a pasture species, has become the most problematic and difficult-to-control weed across grain production regions in Australia. Annual ryegrass has been favored by the adoption of conservation tillage systems due to its genetic diversity, prolific seed production, widespread dispersal, flexible germination requirements and competitive growth habit.

Keywords: grain production ; herbicide resistance ; rigid ryegrass ; weed biology ; integrated weed management

1. Introduction

Australia was once one of the world's largest wool producers. In recent decades, sheep production has markedly decreased and has been replaced with continuous grain production systems, mainly wheat (Triticum aestivum L.) across Australia. Unfortunately, this industry replacement of sheep with continuous grain production systems made a popular pasture species, annual ryegrass (Lolium rigidum Gaud.) an unwanted plant/weed [1]. Annual ryegrass is native to Mediterranean regions of southern Europe, the Indian sub-continent, northern Africa and western Asia [2]. This species had been widely cultivated across Australia in pastures and, was distributed and widely naturalised prior to the production shift to widespread grain production [3]. With continuous production in dairy and livestock industries, annual ryegrass continues to be planted as a pasture species, in spite of the problems it causes to grain cropping.

Australian cropping systems are among the most productive and innovative in the world [4]. Fundamental to this efficiency is the widespread adoption of conservation agriculture systems [5]. Australian growers were among the first to adopt conservation tillage; realising its resource efficiency, soil conservation potential and economic benefits [6]. The adoption of conservation tillage removed the use of cultivation and burning practices for weed control and consequently led to a reliance on herbicides [7]. A reliance on selective herbicides for in-crop weed control and non-selective herbicides for pre-seeding and fallow weed control quickly led to widespread herbicide resistance in the annual ryegrass populations that are endemic in Australia's cropping regions.

Annual ryegrass has become the most problematic weed species in the country thanks to its widespread evolution of multiple resistance mechanisms that confer resistance to most herbicide modes of action used to control this weed. Currently, the majority (>60%) of Australian annual ryegrass populations are resistant to one or more herbicide modes of action [8]. A recent survey of Australian growers determined that this weed infests large areas of the cropping region (8 million ha) and is responsible for large yield (0.35 million tons) and revenue losses ($93 million AUD) each year [9]. Annual ryegrass was found in 81% of winter cereals, 16% of canola (Brassica napus L.) and pulse crops, and 3% of fallow fields. Infestations of annual ryegrass predominate in Western Australia (WA) (4.27 million ha), followed by southern Australia (3.42 million ha) [9]. In the northern cropping region, annual ryegrass has less of a presence (0.32 million ha), but it is still ranked in the top 10 weeds due to its high economic impact. About 76% of growers listed annual ryegrass as the weed most difficult and expensive to control in their cropping systems. Additionally, 83% of growers listed it as the most predominant herbicide-resistant weed [9] and this resistance is estimated to cost Australian growers an additional $103 million annually. This illustrates the enormous economic impact of annual ryegrass in Australian crop production and the ongoing need for its effective management.

Although annual ryegrass is an extensively researched weed, a comprehensive review covering major aspects of its biology, ecology and management in the context of phenomenal adoption of conservation cropping systems in Australia is lacking. This review presents an up-to-date account of the biology, ecology and management of annual ryegrass in these cropping systems. We synthesise available literature to extract and summarise key findings to advance our understanding of this weed. Information on the distribution, biology, ecology and interference the weed causes is discussed in such a way that helps establish the links between biological traits, ecological processes and management of the weed. The existing management options are discussed in terms of their relative efficacy and their future potential use to highlight future research needs.

2. Conservation Cropping Practiced in Australia

The practice of conservation cropping varies globally but it is often referred to the switch from inversion tillage to non-inversion tillage [10]. In Australia, the traditional method of cultivation was full disturbance using tynes to a depth of 10 to 15 cm, potentially combined with removal of crop residue [11]. Conservation cropping is defined as either minimum tillage or no-tillage practices, which buries about 90% of weed seeds to varying soil depths whereas zero tillage leaves about 95% of weed seeds on the soil surface (**Table 1**). Obviously, these systems vary widely, in terms of soil disturbance, weed seed burial and crop residue retention. In Australian cropping systems, many growers occasionally include full soil disturbance once every 5 to 10 years to control problematic weeds and address soil constraints (‘strategic deep tillage’) (**Table 1**) [12]. There is often few data available on soil movement and eventually weed seed movement due to these tillage practices and it can vary widely between soil types [12]. There are also very few data on the characteristics of crop residues in varying agronomic systems. Borger et al. [13] found 2430 to 4480 $kg\ ha^{-1}$ of crop residues at Cunderdin, WA, and 1030 to 1690 $kg\ ha^{-1}$ at Wongan Hills, WA, from crops with varying row spacing, harvested at varying heights, in a no-tillage system. However, these are both lower rainfall areas and the study did not compare residue from different crop species or tillage techniques. In southern Australia, over the dry summer fallow, most residue remains on the soil surface until the following cropping season [13]. Soil disturbance and crop residue will impact the environment that weeds require for establishment e.g., soil temperature, evaporation, light availability etc., and pre-emergent herbicide performance (i.e., herbicide incorporation, volatility etc.) [13][14][15]. It is clear that we need greater understanding of soil disturbance, soil characteristics and crop residue characteristics in minimum tillage, no-tillage and zero tillage systems, before we can begin to assess how weeds will respond to the altered agronomic system.

Table 1. Estimated burial depth of annual ryegrass seed, as a percent of total seed currently on the soil surface, by a range of tillage methods.

Purpose of Tillage	Tillage Method	Example	Percentage of Seed at Different Depths (cm)				
			0	0 to 1	1 to 5	5 to 10	10 to 20
Shallow soil cultivation, for burial of seed and crop residue	Rotary harrow	Phoenix Harrow; evenly distributes soil to 5 cm.	15	50	35	0	0
	Autumn tickle	Kelly chain; distributes 90% of surface seeds to a depth of 1 to 5 cm.	10	30	60	0	0
Full disturbance to address soil constraints	Multiple	Soil inversion using a mouldboard plough	1	1	1	1	96
Crop seeding	Minimum tillage	Direct drill with full cut cultivation; tynes cultivate the soil to 5 cm and provide a disturbed seed bed.	10	50	39	1	0
	Zero tillage	Disc seeding: flat discs are used to create an opening in the soils (to 5 cm) which is followed by a tyne to deliver seed and fertiliser into the slot, often followed by a press wheel to close the slot.	95	2	3	0	0
	No-tillage	Knifepoint seeding; narrow tynes commonly referred to as knife points resulting in 5 to 20% cultivation of the soil surface to 5 cm. Knife points will throw a small amount of soil across the surface, effectively burying the surface seed.	10	80	10	0	0

Source: Weed Seed Wizard decision support tool [16].

3. Biology and Ecology

Some populations exhibit low primary dormancy, but all freshly harvested seeds have more stringent germination requirements than those seeds that have lost dormancy through after-ripening. Maximum germination of fresh seeds requires light, with approximately 32 to 85% of the initial non-dormant seed having a light requirement for germination [17]. Maximum germination of fresh seed also requires alternating temperatures, with germination inhibited below 5 °C or above 35 °C [1]. Following after-ripening, germination requirements for seeds without primary dormancy become more flexible. Maximum seed germination can occur in the dark and at a constant temperature (above the base temperature of 5.4 °C), although the optimal temperature for germination is 20 to 26 °C [18][19]. Full hydration of seeds (i.e., sufficient rain in summer to wet seeds followed by hot, dry conditions) increases the rate of dormancy release [20]. Even a partial hydration event (a small amount of rainfall) can increase seed germinability [21]. However, high rainfall at the beginning of summer (December), directly after the seeds reach maturity, can reduce the rate of dormancy loss during after-ripening over the subsequent months [22]. From a practical point of view, in southern Australia, this indicates that little or no rainfall over the summer/autumn fallow period will result in staggered germination during the winter growing season, with lower total germination. In contrast, mid to late summer rainfall events would ensure increased and more rapid germination after the first substantial rainfall event of the winter growing season.

Hydrated seeds that are buried (i.e., seeds in dark conditions) also lose primary dormancy, allowing a higher proportion to germinate when they once again experience conditions with light and variable temperatures [1][23]. However, seeds that lose dormancy during burial, unlike seeds that experience after-ripening on the surface (in warm, dry conditions), still have a light requirement for germination. There is no research on what volume of crop residue (if any) is high enough to equate to ‘burial’, but seeds under dense residue are likely in dark conditions similar to burial and these seeds may be more likely to achieve hydration as the crop residue would reduce evaporation. These seeds may be exposed to light when the residue shifts (i.e., from planting operations) and there is little research on emergence patterns under these conditions.

Annual ryegrass has a short-lived dormant soil seedbank compared to other species, but a small proportion of seed remains dormant for future years [18]. In South Australia (SA), the dormant proportion of seeds produced after 12 months ranged from 4 to 16% [24]. In field conditions in WA, a very small proportion of the seeds (1.5%) persisted up to four years [25]. Seedbank persistence depends on burial depth. Seeds in a no-tillage system in SA, where the only soil disturbance was due to crop planting, had 48 to 60% seed mortality. By comparison, a minimum tillage system, with full cultivation, twice, to a depth of 10 cm prior to crop seeding, had 12 to 39% seed decay per season [14]. For buried seeds, germination plays a greater role in seed loss compared to seeds on the soil surface. For example, emergence in SA was 49% for seeds buried at 1 cm, compared to 16% of seeds on the soil surface [24]. As a result, emergence was greatest in minimum tillage, followed by no-tillage and zero tillage systems [14][15]. The response to burial may impact emergence patterns during the season. Annual ryegrass emergence in SA soils in a minimum tillage system reached 50% a week earlier than seeds in the no-tillage system [14]. If burial in minimum tillage results in high germination, the resulting seedlings can all be controlled with pre-seeding or selective herbicides. In a zero-tillage system, emergence may be more staggered during the cropping season, making in-crop control difficult. More research is required on seed decay and emergence patterns in varying conservation cropping systems, with reference to levels of crop residue.

The annual ryegrass population growth rate is highly dependent on weed control measures. In the absence of herbicide use in a no-tillage (knife points and press wheels) wheat crop at Wongan Hills, WA, from 2016 to 2018, annual ryegrass density and seed production increased from 63 plants and 9137 seeds m -2 to 405 plants and 42,766 seeds m -2 [26]. A rotation of field pea (Pisum sativum L.), wheat and barley (Hordeum vulgare L.) was conducted in SA from 2010 to 2012, using minimum tillage, with varying herbicide treatments. In the field peas in 2010, applications of trifluralin (pre-plant), trifluralin and clethodim (four-leaf) or trifluralin, clethodim and glyphosate (milk to soft dough growth stages) resulted in 98, 12 and 13 annual ryegrass plants m -2 . Following varying herbicide treatments in the 2011 wheat, the final average annual ryegrass density in the three rotations in the 2012 barley was 319, 105 and 32 plants m -2 [27]. This highlights that increased application of herbicides per rotation can reduce annual ryegrass density, but the population density was still increasing under all possible management regimes. In comparison, a minimum tillage trial at Merredin, WA from 2003 to 2013 (using non-selective, pre-seeding and post-emergent herbicides in each year) had annual ryegrass seed production reduced from 324 to 2 seeds m -2 at 9 cm row spacing and from 382 to 171 seeds m -2 at 36 cm row spacing, over the 11 years [28]. Where crop residue was burnt prior to crop seeding each year, the annual ryegrass seed production was reduced to 0 seeds m -2 in row spacings of 9 to 36 cm. Furthermore, modelling with the Weed Seed Wizard decision support tool indicated seed production would have been reduced from 80 to 10 seeds m -2 with HWSC in every alternate year [29][28].

4. Interference with Crop Production

The world’s first case of annual ryegrass resistance to glyphosate (5 enolpyruvyl shikimate-3 phosphate (EPSP) synthase inhibitor) was reported in 1996 from a cropping field in northern Victoria [30][31] followed by another one from an orchard in central New South Wales (NSW) [32]. Glyphosate resistance in annual ryegrass is low in Australia, with 5 to 7% resistance in WA (**Table 2**), indicating that glyphosate is still an effective option for most annual ryegrass populations [33][34][35][36]. The introduction of glyphosate-tolerant crops (cotton; Gossypium hirsutum L. and canola) in Australia enables the use of glyphosate both in-crop and during fallow periods, which could exacerbate the risk of developing resistance to glyphosate. The resistance to another non-selective herbicide, paraquat (Photosynthesis/Photosystem I (PS I) inhibitor) has evolved in the past decade [37]. Paraquat has been successfully used in a ‘double-knock’ strategy (glyphosate closely followed by paraquat in the same season) to control annual ryegrass (especially glyphosate resistant populations) in conservation systems of Australia [38]. A complete picture of resistance status to paraquat and some other herbicides such as prosulfocarb (lipid synthesis inhibitor) and pyroxasulfone (very long chain fatty acids (VLCFA) inhibitor) in annual ryegrass in Australia remains unknown as these herbicides have not been screened in the previous resistance surveys [39][33].

The resistance of annual ryegrass to some other modes of action is currently relatively low (**Table 2**) partly due to the limited use in a narrow range of rotational crops [34]. However, the number of annual ryegrass populations with complex cross and multiple resistance to different herbicides within and between herbicide groups is on the rise, further restricting the effective control options [40]. Multiple resistance to ACCase- and ALS-inhibitors is widespread across the grain growing areas of southern Australia [39][33][34]. Multiple and cross resistance to other herbicide groups (microtubule assembly inhibitors, lipid synthesis inhibitors and VLCFA inhibitors) is also emerging [41][42]. Hence, diversified control programs integrating non-chemical options are needed to slow the evolution of herbicide resistance, thereby extending the commercial life of many valuable herbicides.

Table 2. Incidence of herbicide resistance across five major modes of action herbicide groups in Australia.

Herbicide Group	Subgroup	Resistance (%)
ACCase inhibitors	Aryloxyphenoxypropionates	81 [33], 56 [43], 96 to 98 [34], 18 [44]
	Cyclohexanediones	65 [34], 1 [44]
ALS inhibitors	Imidazolinones	65 [33], 38 [43], 7 [44]
	Sulfonylureas	70 [33], 53 [43], 96 to 98 [34], 24 [44]
Photosystem II inhibitors	Triazines	2 [34], 0 to 1 [33][35][44][45]
Microtubule assembly inhibitors	Dinitroanilines	27 to 33 [35][44], <6 [39][33][44]
EPSP synthase inhibitors	Glycines	5 to 7 [34][36], 4 [45], 0 to 1 [33][44]

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