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REVIEW ARTICLE

# Biology and management of *Avena fatua* and *Avena ludoviciana*: two noxious weed species of agro-ecosystems

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**Abstract** *Avena fatua* and *Avena ludoviciana* are closely related grass weed species infesting a large number of crops around the world. These species are widely distributed in diverse agro-ecosystems from temperate to sub-tropical regions due to their unique seed traits, successful germination ecology, high competitive ability, and allelopathic potential. *A. fatua* is more widespread, adaptable, and problematic than *A. ludoviciana.* Both these species infest major winter and spring crops, including wheat, oat, barley, canola, maize, alfalfa, and sunflower, causing up to 70% yield losses depending on crop species and weed density. Chemical control has been challenged by large-scale herbicide resistance evolution in these weed species. *A. fatua* is the most widespread herbicide-resistant weed in the world, infesting about 5 million hectares in 13 countries. The use of alternative herbicides with different modes of action has proved effective. Several cultural practices, including diverse crop rotations, cover crops, improved crop competition (using competitive cultivars, high seed rates, narrow row spacing, altered crop geometry), and allelopathic suppression, have shown promise for controlling *A. fatua* and *A. ludoviciana.* The integrated use of these cultural methods can reduce the herbicide dose required, and lower dependency on herbicides to control these grasses. Moreover, integrated management may successfully control herbicide-resistant populations of these weed species. The use of integrated approaches based on the knowledge of biology and ecology of *A. fatua* and *A. ludoviciana* may help to manage them sustainably in the future.

**Keywords** Wild oats · Cereals · Weed management · Herbicide resistance · Crop competition

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## Introduction

Several *Avena* species are listed among the most widespread, noxious, and problematic weeds in modern-day agriculture (Holm et al. 1977). *Avena fatua* L. and *Avena ludoviciana* Durieu are the most important weeds of this genus (Aibar et al. 1991; Barroso et al. 2004; Qasem 2007; Heap 2014a; Harker et al. 2016). *A. fatua* and *A. ludoviciana* are popularly known as wild oats and sterile oats, respectively (Holm et al. 1977). They are tall-growing, annual grasses which seriously affect cereal crops around the world (Holm et al. 1977; Fernandez-Quintanilla et al. 1990). *A. ludoviciana* is the most common sub-species of *Avena sterilis* L. and is usually reported as a separate species (Baum 1991; Del Arco et al. 1995; Qasem 2007). Both species are widely distributed in subtropical and temperate areas, particularly in Asia, Australia, Europe, the USA, and Canada (Holm et al. 1977; Balyan et al. 1991; Fernandez-Quintanilla et al. 1990; Beckie et al. 2012a; Ahmad-Hamdani et al. 2013; Harker et al. 2016). Although these two species are quite similar in their morphological appearance, there are some differences which can be used to distinguish them from each other (Thurston 1951; Holm et al. 1977; Mennan and Uygur 1996). The similarities and differences are discussed in this manuscript to provide a better understanding of the biology of these species.

*A. fatua* and *A. ludoviciana* have remarkable biological features, including high seed production, dormancy enabling them to persist in seed banks for several years, vigorous growth, tall stature, extensive root systems, phenotypic variation, and the ability to germinate under a wide range of environmental conditions (Holm et al. 1977; Qasem 2007; Owen and Powles 2009; Beckie et al. 2012a). Seeds of *A. fatua* commonly shatter before crop harvest, and are then incorporated into the soil upon plowing (Almaghrabi 2012). *A. fatua* seeds can remain dormant but viable for several years in the seed bank and may germinate upon exposure to favorable conditions (Khan et al. 2008). For these reasons, this weed species is very difficult to control and maintain below acceptable economic thresholds. *A. fatua* is far more widely distributed than *A. ludoviciana*, contributing to substantial crop losses around the world. Hence, there is less published information on *A. ludoviciana,* which is often ignored as a separate weed. It is important to study the biology of both these species separately in order to devise effective and species-specific management options.

*A. fatua* and *A. ludoviciana* resemble certain winter cereal crops, which make them more difficult to identify and control at the early growth stages. Both these species are highly competitive in nature. *A. fatua* and *A. ludoviciana* competition causes significant losses in wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), rye (*Secale cereal* L.), pea (*Pisum sativum* L.), canola (*Brassica napus* L.), lentil (*Lens culinaris* Medikus), alfalfa (*Medicago sativa* L.), sunflower (*Helianthus annuus* L.), sugarbeet (*Beta vulgaris* L.), maize (*Zea mays* L.), potato (*Solanum tuberosum* L.), and soybean [*Glycine max* (L.) Merr.] (Dew and Keys 1976; Torner et al. 1991; Walia et al. 2001; O'Donovan et al. 2000; Daugovish et al. 2002; Watson et al. 2006; Khan et al. 2008; Beckie et al. 2012b; Adamczewski et al. 2013). The extent of yield loss depends on the density of *A. fatua* and *A. ludoviciana.* These weed species also infest grasslands, pastures, and non-cropped areas (Beckie et al. 2012a, b). *A. fatua* has been found to be highly responsive to fertilizers, particularly nitrogen (Balyan et al. 1991). *A. fatua* is a highly allelopathic weed species, releasing allelochemicals such as phenolics in its rhizosphere (Schumacher et al. 1983; Pérez and Núnez 1991; Ahmad et al. 2014). Usually, such allelochemicals not only suppress crop growth but also affect soil microbes in a way which is favorable for weed growth yet damaging for crop growth and nutrient cycling (Jabran et al. 2010; Farooq et al. 2013; Bajwa 2014).

Different management strategies are used to control *A. fatua* and *A. ludoviciana*, with varying degrees of success depending on weed densities, crop, and local conditions. Prevention and clean cultivation are the most effective ways to deal with these noxious species (Beckie 2006; Beckie et al. 2012b; Harker and O'Donovan 2013). Numerous herbicides have been used to successfully control these species in the past (Terry 1984; Balyan 2001; Qasem 2007). Unfortunately, both these species have become resistant to a large number of herbicides in several countries (Uludag et al. 2007, 2008; Owen and Powles 2009; Adamczewski et al. 2013; Heap 2014a). *A. fatua* is one of the three worst herbicide-resistant weed species globally (Heap 2014b). Certain new herbicides have been found effective in controlling herbicide-resistant populations of *A. fatua* and *A. ludoviciana* (Zand et al. 2007; Scursoni et al. 2011). Cultural strategies can be used to successfully manage both susceptible and herbicide-resistant populations of *A. fatua* and *A. ludoviciana* (Walker et al. 2001; Beckie and Kirkland 2003). The use of competitive cultivars, high seed rates, modified crop rotations, and cover crops may be more effective when used along with herbicides (Anderson 2003; Beckie 2006; Harker et al. 2009). Studies have also shown the potential of allelopathy to manage these *Avena* species; however, this area needs extensive research and field evaluation (Batish et al. 2002; Turk and Twasha 2003). Reliance on any single weed control option is unlikely to be successful. Suitable integrated weed management packages based on the best options for a specific region may help in controlling *A. fatua* and *A. ludoviciana* effectively (Beckie 2006; Qasem 2007; Harker et al. 2009, 2016). Therefore, the successful management of these species will depend on the careful selection of combinations of chemical and cultural control methods.

*A. fatua* and *A. ludoviciana* are important weed species as they cause significant yield losses to major crops. Although a lot of published material is available on *A. fatua*, the information on *A. ludoviciana* is very limited. Moreover, a single manuscript covering the biology and management of *A. fatua* and *A. ludoviciana* with a comparative approach is lacking. This review covers the salient biological features, distribution, and management of these two species. The implications of biological traits and adaptations for current and potential management strategies are discussed, and research gaps highlighted along with key findings. This review is intended to provide up-to-date information on the biology and management of *A. fatua* and *A. ludoviciana* in modern-day agriculture, where herbicide resistance and changing weed behavior challenge successful crop production.

## Global distribution and habitat

*Avena* species are documented as weeds throughout cereal growing areas of the world. *A. fatua* is native to Asia, and has been reported as a major grass weed in the USA, Canada, and the United Kingdom (UK; Baum 1968, 1991). It has naturalized in several countries across Europe, and in China, Australia, and India (Mustafee 1989; Tang and Lamerle 1996). *Avena* species cause significant crop yield losses in Canada (Beckie et al. 1999), and *A. fatua* has become a major weed in grain growing regions of Australia (Holm et al. 1977). It is mostly found in cooler and wetter climates, and compared with other *Avena* species, *A. fatua* is favored by higher altitudes and rarely exists in coastal areas. *A. fatua* can flourish in areas receiving annual rainfall of 375 to 750 mm (Holm et al. 1977). *A. fatua* is well adapted to rainfed as well as irrigated areas (Almaghrabi 2012). It can grow on diverse soil types and has the ability to germinate and grow at pH as low as 4.5 (Holm et al. 1977). However, it grows best on heavy, fertile soils where its seed production ability increases.

*A. ludoviciana* is native to southern Europe and the Mediterranean region (Torner et al. 1991; Stace 1997). Turkey has been reported as the center of diversification for this weed species (Phillips et al. 1993). It is common in semi-arid, temperate, and sub-tropical regions all over the world (O'Donnell et al. 2002). It has naturalized in north, south, and central America; eastern, northern, and southern Africa; the Middle East; southeastern and central Europe; Australia; and India. *A. ludoviciana* prospers on heavier soils (Stace 1997). It is widely distributed in Mediterranean environments and causes significant yield losses in cereals. Temperate and sub-tropical climates, with either summer or winter dominant rainfall, are suitable for *A. ludoviciana* (Thurston 1957). O'Donnell et al. (2002) found that *A. ludoviciana* is widespread in northern areas of Australia. In eastern Australia, *A. ludoviciana* emerges in wheat during mid-winter, and it is also a dominant weed of winter cereals in the UK (Chancellor and Froud-Williams 1984; Fernandez-Quintanilla et al. 1990). The prevalence of *A. ludoviciana* is attributed to its winter emergence and cold-hardiness (Thurston 1961). *A. fatua* grows best in cold and moist conditions, whereas *A. ludoviciana* can grow under relatively lower soil moisture (Thurston 1951, 1957). Both these species have the potential to spread widely into new areas due to changing climate. For instance, Chile, southern UK, the Pacific Coast of the USA, and parts of Argentina have become suitable for *A. ludoviciana* infestation. Similarly, Mediterranean regions where cereals are sown in late winter or spring are suitable for further spread of *A. fatua* (Fernandez-Quintanilla et al. 1990). A short growing season, high winter temperatures, and low rainfall are climatic features which support geographical distribution of *A. fatua* (Paterson 1976).

Such widespread distribution of these two species clearly show their adaptability and invasiveness. Future research must be oriented towards tracking the dispersal mechanisms and then controlling these species through preventive measures. Moreover, further studies should be conducted to estimate the current and future distribution patterns considering the modeling approaches. It will help for early detection and potential containment of these problematic *Avena* species.

## Biology

### Botanical description

*Avena* species have little variation in appearance and it is difficult to distinguish them on a morphological basis, except during the reproductive growth stages. *A. fatua* has a growth habit and life cycle similar to winter cereals; however, it shows great flexibility in life cycle according to environmental conditions (Edgar 1980; Medd 1996). *A. fatua* causes more losses in cereals as compared to other *Avena* species because it matures early, shattering panicles and shedding seeds on the ground before crop harvest. Despite similarity with wheat and barley, *Avena* species can be distinguished by their collar region before flowering. Florets of *A. ludoviciana* look similar to those of *A. fatua*, with hairy, bent, and twisted awns (Edgar 1980).

Plants of *A. fatua* are up to 1.5 m tall with loose, drooping panicles and open branches bearing spikelets, whereas *A. ludoviciana* plants grow up to 2 m with spreading and loose panicles (Edgar 1980). *A. fatua* is an annual grass with relatively broad leaves, and closely resembles cultivated oats (Ivens 1989; Medd 1996). The stem is stiff and straight, without branching, rooting at the nodes. The leaf blade is 6–14-mm-wide and 60-cm-long membranous, with a 2-mm-long ligule. The inflorescence is a 15–45-cm-long and 8–25-cm-wide panicle, commonly one-sided, with spikelets bearing two to five florets. The glumes are usually 30–50 mm long, and the lemmas are 15–40 mm long (Ivens 1989; Stace 1997).

The panicles of *A. ludoviciana* are less heavy because the spikelets bear fewer and smaller florets (Edgar 1980). In *A. ludoviciana*, the ligule is more than 5 mm long, the spikelets have three to five florets, and the lemma and glume are 25–33 and 32–45 mm long, respectively (Stace 1997). The glume is lengthy (25–30 mm) in *A. ludoviciana* as compared with *A. fatua* (18–25 mm) (Stace 1997). In both these species, the first and second seeds in a spikelet are awned; however, the awn is absent on the third seed in *A. ludoviciana* but present in *A. fatua* (Moss 2015). The stem of *A. fatua* is upright and has few tillers, while in *A. ludoviciana*, the stem is prostrate with many tillers at the maximum tillering stage (Thurston 1957). The seeds of *A. fatua* separate from the spikelets at maturity and are shed singly, whereas in *A. ludoviciana*, the spikelets are hard and do not break easily, and the seeds remain within the spikelet at maturity and are shed in units of 2 or 3 (Moss 2015).

Keeping in view the above-mentioned facts, it is very important to distinguish these species based on their botanical features to devise suitable management strategies. Further studies should be carried out to investigate the morphological and physiological attributes of *A. ludoviciana* as those are relatively less explored. It is likely that the differences in biological features of *A. fatua* and *ludoviciana* may also contribute to their differential distribution and geographical spread. However, further research is needed to these hypotheses.

## Propagation and seed dispersal

Both these *Avena* species propagate exclusively through seeds (Holm et al. 1977). They are highly autogamous, so that isolated populations can yield seeds. *A. fatua* is an obligate inbreeding temperate plant with high seed producing capacity—up to 1000 seed per plant (Rauber 1977). In the case of *A. ludoviciana*, a single plant produces up to 400 seeds (Fernández-Moreno et al. 2016). Flowering in *A. ludoviciana* occurs earlier compared to *A. fatua* (Holm et al. 1977; Stace 1997), with seeds shattering 2–3 weeks before wheat is harvested (Balyan and Malik 1989). Seeds of *A. fatua* are large, elongated, and hairy. Natural dispersal by wind or water is not reported for *A. fatua*. In most cases, cultivation of cereal crops is the cause of *A. fatua* seed dispersal around the globe. In a weed dispersal study, it was revealed that patches of *A. fatua* normally progress by 1–3 m in a single year, but this can increase up to 30 m in cultivated lands (Wheeler et al. 2001). Anthropogenic dispersal has great importance for *A. ludoviciana*, which was introduced to Europe through contaminated wool and seed (Stace 1997).

High seed production and viability, long retention period in seed bank, and efficient dispersal mechanisms allow these species to establish successfully in agro-ecosystems. Further studies are required to estimate the seed production ability of both these species in different cropping systems. Moreover, seed longevity in soil seed bank should be extensively studied to devise some ecologically based management options.

## Germination ecology

Germination of *A. ludoviciana* is favored more by low temperature as compared to that of *A. fatua* (Fernandez-Quintanilla et al. 1990). *A. fatua* exhibits high germination in relatively warm conditions. *A. ludoviciana* is also better adapted to limited soil moisture as compared to *A. fatua* (Fernandez-Quintanilla et al. 1990). *Avena* species can germinate at a wide range of temperatures (5–30 °C) and solute potentials (−0.025 to −1.4 MPa). In one study, the germination rate was similar for both species up to 10–18 °C. However, germination of *A. fatua* was higher than *A. ludoviciana* above 20 °C, but the opposite was found below 10 °C (Fernandez-Quintanilla et al. 1990). In the northern hemisphere, germination of *A. fatua* generally takes place in spring (Jones 1976; Davies 1985; Wilson 1985). The optimum temperature for germination is 15–20 °C (Davies 1985; Wilson 1985). Hassanein et al. (1996) reported that the germination rate of *A. fatua* was maximum at 20 °C, while maximum length of plumule and dry weight of seedlings were attained at 25 °C. Minimum, maximum, and optimum temperatures for *A. ludoviciana* germination were 2, 30, and 10 °C, respectively (Uremis and Uyagur 1999). Other studies have reported 15 °C (Mennan and Uygur 1996) and 25 °C (Hassanein et al. 1996) as the optimum germination temperatures for *A. ludoviciana*. Optimum emergence of *Avena* species was observed at the temperature range of 9–20 °C, and low temperatures delayed their emergence (Aibar et al. 1991). The emergence time of both species differ with respect to space and time (Aibar et al. 1991). For instance, in northern and central Europe, emergence of *A. fatua* mainly takes place in spring, whereas *A. ludoviciana* emerges in winter and autumn conditions (Thurston 1957). In southern Europe, *A. fatua* and *A. ludoviciana* emerge at the same time, in August (Aibar et al. 1991). In countries with long and cold winters (e.g., Norway and Canada), *A. fatua* emerges in spring (Sharma and Vanden Born 1983).

The seeds of both *Avena* species may remain viable in the soil in a dormant condition for several years. It is difficult to generalize about the dormancy behavior of *A. fatua* because of its various environmental interactions and high genetic variability (Holm et al. 1977). It has been reported that the extent of dormancy is greater at low temperatures and is released with increased temperature (Fennimore et al. 1998). Dormancy helps *A. fatua* to persist longer in the soil seed bank under conditions unfavorable for the seedling (Wu and Koetz 2014). Miller and Nalewaja (1990) reported that seed viability of *A. fatua* was reduced by 80% soon after burial; however, up

**Table 1** Yield losses caused by *Avena fatua* and *Avena ludoviciana* in different crops

| Crop | Weed species | Weed density (plant $m^{-2}$) | Yield reduction (%) | References |
|---|---|---|---|---|
| Wheat | *A. fatua* | 100 | 50–60 | Walia et al. (2001) |
| Wheat | *A. fatua* | 500 | 54 | Stougaard and Xue (2004) |
| Wheat | *A. ludoviciana* | 146–162 | 17–62 | Balyan et al. (1991) and Dhima and Eleftherohorinos (2001) |
| Wheat | *A. fatua* | 8 | 14 | Wimschneider et al. (1990) |
| Wheat | *A. ludoviciana* | 10 | 30–40 | Walia et al. (2001) |
| Wheat | *A. ludoviciana* | | 35 | Walia and Brar (2001) |
| Wheat | *A. fatua* | 49 | 30 | Khan et al. (2008) |
| Wheat | *A. ludoviciana* | – | 17–62 | Balyan et al. (1991) |
| Wheat | *A. ludoviciana* | 3 | Up to 15 | Walia et al. (2001) |
| Wheat | *A. ludoviciana* | 40 | 16 | Balyan and Malik (1989) |
| Wheat | *A. ludoviciana* | 160 | 46 | Balyan and Malik (1989) |
| Barley | *A. ludoviciana* | 120 | Up to 67 | Dhima et al. (2000) |
| Barley | *A. fatua* | 170 | 40 | Morishita and Thill (1988) |
| Barley | *A. fatua* | 70 | 25 | Scursoni and Satorre (2005) |
| Barley | *A. fatua* | – | Up to 63 | O'Donovan et al. (2000) |
| Barley | *A. fatua* | 70 | Up to 79 | Watson et al. (2006) |
| Barley | *A. ludoviciana* | 20–80 | 10 | Torner et al. (1991) |
| Barley | *A. ludoviciana* | 300 | 50 | Torner et al. (1991) |
| Barley | *A. fatua* | 150–170 | 29–40 | Morishita and Thill (1988) |
| Maize | *A. fatua* | 27 | 25 | Castillo and Ahrens (1986) |
| Maize | *A. fatua* | 9 | 14 | Castillo and Ahrens (1986) |
| Pea | *A. fatua* | – | 30 | Adamczewski et al. (2013) |
| Canola | *A. fatua* | 100 | 32 | Dew and Keyes (1976) |
| Sugarbeet | *A. fatua* | – | 90 | Adamczewski et al. (2013) |

to 7% of the seeds remained viable 9 years after they were buried, and a small proportion were viable even 14 years after burial. In contrast, another study reported that less than 1% of *A. fatua* seeds were viable only 5 years after burial (Conn 1990). Seed viability and persistence have been linked with soil conditions and other environmental factors (Demo 1999). Burial depth and surface residues have significant impact on the germination ecology of *A. fatua* and *A. ludoviciana*. Miller and Nalewaja (1990) claimed that seed loss is increased with burial depth.

Special morphological features, high seed production, effective seed dispersal, and a unique germination ecology render *A. fatua* and *A. ludoviciana* suitable to a wide range of environmental conditions. These species quickly adapt to climatic and other changes in their environment. So, it is important to study the biological and ecological responses of these species in relation to changing climate and crop management practices. An updated knowledge of weed ecology will help to devise suitable management practices for these problematic species.

## Interference

*A. fatua* and *A. ludoviciana* strongly interfere with crop production. Both these species are highly competitive in terms of resource acquisition. Studies have also shown that *A. fatua* has great allelopathic potential which adds to its strong interference ability. Due to strong competition and allelopathic effects, these species cause substantial crop yield losses.

## Competition

Crop yield and quality losses due to *Avena* species interference, and their control costs, are of great concern across the world (Jabran et al. 2010). *A. fatua* and *A. ludoviciana* cause significant yield reductions in several crops (Table 1). Infestation by both these species is common in cereal crops, pasture lands, and vineyards (Thurston 1957, 1961). These crops differ in their ability to compete with *Avena* species, resulting in variable yield losses (O'Donovan et al. 2000). Among the different winter cereals, barley was found to be a better competitor with *A. fatua* and *A. ludoviciana* (Dew 1972; Dew and Keyes 1976). Yellow mustard was a better competitor than canola against *A. fatua* (Daugovish et al. 2002). Canola was revealed as a poor competitor with *A. fatua*, as it suffered due to severe competition in the early growth stages (Chow and Dorrell 1979). Compared with wheat, *A. fatua* has greater capacity to acquire and utilize resources, including nutrients and water (Lalelo et al. 2008). Competition begins soon after emergence of the wheat crop, and competition during the first 6 weeks following crop emergence contributes the most to yield loss (Ahmad et al. 2014). Up to 70% yield reduction in cereal crops were reported due to *A. fatua* interference (Beckie et al. 2012b). In wheat, yield losses varied between 10 and 60% depending on weed density, crop cultivar, and agronomic practices (Carlson and Hill 1985; Cudney et al. 1991; Kirkland and Hunter 1991). In Australia, Pannell and Gill (1994) reported that *A. fatua* was two times more competitive than annual ryegrass (*Lolium rigidum* Gaud.) in wheat crops. Interference of *A. fatua* with barley, oat, and wheat was found to be more from root competition compared to shoot (Pavlychenko and Harrington 1934; Satorre and Snaydon 1992). The rooting ability of *A. fatua* was found to be better than wheat (Lalelo et al. 2008). Due to high uptake of nitrogen and phosphorus, *A. fatua* develops a big root system compared to wheat (Haynes et al. 1991). The nutrient use efficiency of *A. fatua* was found to be higher than wheat (Kirkland and Beckie 1998).

*A. ludoviciana* competes with arable crops and causes substantial yield reductions (Stace 1997). It is very difficult to control *A. ludoviciana* because of its long emergence time (Qasem 2007). *A. ludoviciana* closely resembles wheat plants and uses large amounts of water and nutrients (Dhima et al. 2000; Gonzalez-Ponce and Santin 2001). *A. ludoviciana* grows rapidly, establishes extensive and deep root systems, and efficiently responds to high levels of nitrogen (Balyan et al. 1991). *A. ludoviciana* competition can cause up to 35% loss in wheat yield (Walia and Brar 2001). *A. ludoviciana* reduced grain and straw yield of wheat by 19 and 23%, respectively (Qasem 2007). Similarly, growth and yield of barley was reduced by *A. ludoviciana* competition, as it reduced the number of fertile tillers, particularly in dry conditions (Torner et al. 1991). The type of cropping system may affect the competitive ability of *A. ludoviciana*. Infestation is higher under conventional cropping compared to organic systems. Dhima et al. (2000) reported significant variation in the competitive ability of barley cultivars against *A. ludoviciana*. This study revealed that early-maturing cultivars yielded equal and more economic yield in weed-free and weedy situations, respectively, than the late-maturing and mid-maturing cultivars. Barley was found to be more competitive than wheat, and also reduced seed production by *A. ludoviciana* (Walker et al. 2001). Therefore, inclusion of barley in the crop rotation could be an effective management strategy against *A. ludoviciana*. A study on competition of wheat and barley with *A. ludoviciana* revealed that competition at the vegetative growth stages was more damaging as compared with the reproductive stages (Walker et al. 2001).

Compared with *A. fatua*, fewer studies are available on yield losses caused by *A. ludoviciana* in different crops. It is important to evaluate the extent of competition and yield losses caused by *A. fatua* and *A. ludoviciana* separately. Moreover, the critical weed-crop competition period for both these species should be determined across a range of crops, keeping in view the cropping system, climate, and management practices.

## Allelopathic effect

*Avena* species release important allelochemicals into the environment (Schumacher et al. 1983; Pérez and Núnez 1991; Zhang et al. 2006). Most of these allelochemicals have negative effects on the growth of cereal crops (Beckie et al. 2012a). The majority of allelopathic research has been conducted on cultivated species of *Avena* rather than wild species (Fay and Duke 1977). Wheat seed germination, root, and shoot length were considerably decreased by aqueous extracts of *A. fatua* (Jabran et al. 2010; Ahmad et al. 2014). Higher concentrations were more phytotoxic. Schumacher et al. (1983) identified vanillic acid and scopoletin as major phytotoxic compounds in the *A. fatua* root exudates. These root exudates decreased the leaf and root biomass of spring wheat. Pérez and Núnez (1991) identified hydroxybenzoic acid, coumarin, and vanillic acid as the allelochemicals in root exudates of *A. fatua* responsible for inhibiting seedling growth of wheat. Zhang et al. (2006) also found that the aqueous extract of *A. fatua* had a suppressive impact on wheat. Recently, Liu et al. (2016) isolated five potent allelochemicals (syringic acid, syringocide, tricin, acacetin, and diosmetin) from aerial parts of *A. fatua*, which reduced the germination and root and shoot growth of wheat by up to 50%.

There is little information available on the allelopathic potential of *A. fatua* and *A. ludoviciana.* Field evidence for the role of their allelopathic effect in crop interference is lacking. To determine the nature of impacts on crop growth and development, further research is required on the allelopathic potential of living tissues and residues of these species.

## Management

Various cultural, mechanical, and chemical approaches have been reported to control *A. fatua* and *A. ludoviciana*. Herbicides have been and still are the major control method for these species. However, the evolution of resistance in *A. fatua* and *A. ludoviciana* against several herbicides have made their management much difficult. Following are the different management options being used for these weeds in different situations.

## Cultural strategies

Crop rotations, use of competitive crops and cultivars, tillage, manipulated row spacing, increased seed rates, delayed sowing, and fertilizer management are important cultural practices to manage both susceptible and herbicide-resistant *A. fatua* and *A. ludoviciana* populations (Martin and Felton 1993; Thill et al. 1994; Boerboom 1999; Nalewaja 1999; Beckie et al. 2002, 2012a). Delayed crop sowing, pre- and post-sowing tillage, summer fallowing, legume and forage grass-related rotations, and fall sowing of winter cereals are valuable cultural strategies to control *A. fatua* (Brown 1953; Harker et al. 2016). Terry (1984) reported that cultivation before sowing encouraged rapid germination of *Avena* species. Control of the emerged seedlings was achieved through uprooting the plants by cultivation or hand pulling at the time of sowing. Hand weeding to remove *A. ludoviciana* at 3 and 4 weeks after sowing the crop also gave effective control (Sharma et al. 1989). Tine cultivation before crop sowing proved effective in reducing the seed bank of *A. fatua*, achieving a more rapid reduction compared to plowing (Wilson 1985). Soil solarization using polyethylene sheets has also been used to effectively control *A. fatua* and *A. ludoviciana*, with better results in moist soil compared to dry soil (Arora and Yaduraju 1998). In Canada, a high seed rate of barley provided better suppression of *A. fatua* compared to the recommended seed rate (O'Donovan et al. 2001). In Australia, Walker et al. (2002) found that seed production of *A. ludoviciana* was significantly reduced in barley as compared with wheat at reduced doses of herbicides. Increased planting density of wheat suppressed the growth, biomass production, and fecundity of *A. fatua* and *A. ludoviciana* (Radford et al. 1980). Harker et al. (2009) reported that tall cultivars, crop rotation, and double seeding rates inhibited emergence, density, and seed production of *A. fatua*.

Targeting the seed banks of these *Avena* species by inhibiting seed return to the seed bank is another promising control strategy (Wu and Koetz 2014). However, seed biology plays an important role in seed bank dynamics. For instance, *A. ludoviciana* germinates only in cool conditions and a summer fallow will not reduce the soil seed bank (Thurston 1957). *A. ludoviciana* seedlings are small compared to cereal crops at the initial growth stages, and therefore can be controlled effectively early in the cropping phase by a competitive crop stand (Thurston 1957, 1961). Residues of pea and wheat promoted germination and seedling growth of *A. ludoviciana* (Purvis et al. 1985), indicating that crop residue management might play a vital role in *A. ludoviciana* management. In other research, delayed crop sowing increased the mortality of *Avena* species through intraspecific competition, and suppressed the infestation by up to 80% (Gonzalez-Ponce 1988; Aibar et al. 1991).

Cultural strategies have been shown to be effective in controlling susceptible and herbicide-resistant populations of *A. fatua* and *A. ludoviciana* in different cropping systems. However, further research is needed to explore the potential of these practices under a wide range of environmental conditions. Moreover, the integrated use of different cultural and other weed management options should be emphasized.

## Allelopathy

Allelopathy could be an effective weed management strategy if properly explored in an agro-ecosystem (Farooq et al. 2013; Bajwa 2014; Bajwa et al. 2015a, b). Several studies have reported the allelopathic suppression of *A. fatua* by different allelopathic species in laboratory bioassays and field experiments. However, the allelopathic suppression of *A. ludoviciana* has not been studied to date. Germination and seedling growth of *A. fatua* were significantly suppressed by allelopathic extracts obtained from different plant parts of black mustard (*Brassica nigra* L.) (Turk and Twasha 2003). Extracts of *Parthenium hysterophorus* L. delayed the germination of *A. fatua* and reduced seedling growth (Marwat et al. 2008; Bajwa et al. 2013). These responses might be due to phytotoxicity caused by several potent allelochemicals present in *P. hysterophorus* (Bajwa et al. 2016a). Batish et al. (2002) also reported that parthenin (a sesquiterpene lactone allelochemical present in *P. hysterophorus*) suppressed germination and growth of *A. fatua*. Allyl glucosinolate exuded from Indian mustard (*Brassica juncea* L.) inhibited the emergence of *A. fatua* (Handiseni et al. 2011). Pérez and Núnez (1993) reported that hydroxamic acids exuded from rye inhibited the growth of *A. fatua* in field conditions.

Allelopathic extracts of sorghum [*Sorghum bicolor* (L.) Moench], mulberry (*Morus alba* L.), winter cherry (*Withania somnifera* L.), and barnyard grass [*Echinochloa crusgalli* (L.) Beauv.] were found suppressive against *A. fatua* (Jabran et al. 2010). The degree of suppression in *A. fatua* was mulberry > winter cherry > barnyard grass > sorghum (Jabran et al. 2010). In another study, Almaghrabi (2012) reported ferulic acid, salicylic acid, hydroxyl-benzoic acid, and hydroxyl-phenyl acetic acid as the major phenolic compounds that were inhibitory to *A. fatua*. Ferulic acid completely inhibited the germination of *A. fatua* at a concentration of 3.0 mM (Almaghrabi 2012). Azania et al. (2003) reported various allelochemicals from sunflower which suppressed the germination and seedling growth of *A. fatua*. Leaf extracts of red-stem wormwood (*Artemisia scoparia* Waldst. & Kit.) and African rue (*Peganum harmala* L.) have also been shown to reduce the germination and seedling growth of *A. fatua* (Singh et al. 2009; Sodaeizadeh and Van Damme

**Table 2** Herbicides used to control *Avena fatua* and *Avena ludoviciana*

| Herbicide | Dose (g a.i. $ha^{-1}$) | Time of application | Weed species controlled | Crop | References |
|---|---|---|---|---|---|
| Fenoxaprop | 81 | POST | *A. fatua* | Barley | O'Donovan et al. (2013) |
| Pinoxaden | 40 | EPOST | *A. fatua* | Wheat, barley | Scursoni et al. (2011) |
| Fenoxaprop-p-ethyl | 55 | EPOST | *A. fatua* | Wheat, barley | Scursoni et al. (2011) |
| Clodinafop-propargyl | 36 | EPOST | *A. fatua* | Wheat, barley | Scursoni et al. (2011) |
| Iodosulfuron + metsulfuron methyl | 3 + 3.75 | EPOST | *A. fatua* | Wheat, barley | Scursoni et al. (2011) |
| Imazamethabenz | 125 | POST | *A. fatua* | Barley | Harker et al. (2009) |
| Tralkoxydim | 100 | POST | *A. fatua* | Barley | Harker et al. (2009) |
| Difenzoquat | 840 | POST | *A. fatua* | Wheat | O'Donovan et al. (2003) |
| Metribuzin | 247 | POST | *A. fatua* | Wheat | Mueen-ud-Din et al. (2011) |
| Diclofop | 900 | POST | *A. ludoviciana* | Barley | Fernandez-Quintanilla et al. (2006) |
| Imazamethabenz | 750 | POST | *A. ludoviciana* | Barley | Fernandez-Quintanilla et al. (2006) |
| Isoproturon | 750 | POST | *A. ludoviciana* | Wheat | Balyan et al. (1991) |
| Pinoxaden | 100 | EPOST | *A. ludoviciana* | Wheat | Travlos et al. (2011) |
| Mesosulfuron + iodosulfuron | 7.5 + 7.5 | EPOST | *A. ludoviciana* | Wheat | Travlos et al. (2011) |
| Tralkoxydim | 250 | POST | *A. ludoviciana*, *A. fatua* | Glasshouse study | Aibar et al. (1991) |

*POST* post-emergence, *EPOST* early post-emergence

**Table 3** Some herbicide resistance cases in *Avena fatua* and *Avena ludoviciana*

| Herbicide | Weed species | Country | References |
|---|---|---|---|
| Diclofop-methyl | *A. fatua* | Australia | Owen and Powles (2009) |
| Diclofop-methyl | *A. fatua* | USA | Seefeldt et al. (1994) |
| Fenoxaprop-P-ethyl | *A. fatua* | Poland | Stokłosa and Kieć (2006) |
| Flamprop | *A. fatua* | Canada | Friesen et al. (2000) |
| Pinoxaden, sulfometuron | *A. fatua* | Poland | Adamczewski et al. (2013) |
| Sethoxydim | *A. fatua* | Canada | Heap et al. (1993) |
| Fenoxaprop-p | *A. fatua* | Canada | Friesen et al. (2000) |
| Difenzoquat | *A. fatua* | Canada | Beckie et al. (2008) |
| Triallate | *A. fatua* | Canada | O'Donovan et al. (1994) |
| Flucarbazone | *A. fatua* | USA | Nandula and Messersmith (2001) |
| Imazamethabenz | *A. fatua* | USA | Nandula and Messersmith (2000) |
| Difenzoquat | *A. fatua* | USA | Kern and Dyer (1998) |
| Clodinafop-propargyl | *A. ludoviciana* | Greece | Papapanagiotou et al. (2012) |
| Tralkoxydim | *A. ludoviciana* | Greece | Papapanagiotou et al. (2012) |
| Glyphosate | *A. ludoviciana* | Spain | Fernández-Moreno et al. (2016) |
| Diclofop-methyl | *A. ludoviciana* | Greece | Travlos et al. (2011) |

2009). Aqueous extracts of wheat and pea have also been reported to suppress *A. fatua* (El-Khatib and Hegazy 1999; Marles et al. 2010). Foliage applied aqueous extracts of sorghum and sunflower also suppressed *A. fatua* within a wheat crop (Jamil et al. 2009). Pyrenophorin, a compound exuded from *Drechslera avenae* (fungus), inhibited germination and growth of *A. fatua* (Hetherington and Auld 2001). Costunolide and parthenolide are sesquiterpene lactones separated from the bark of southern magnolia (*Magnolia grandiflora* L.), which also negatively affect the biomass of *A. fatua* (Abdelgaleil et al. 2009).

Although allelopathy has potential for *A. fatua* and *A. ludoviciana* control, the evaluation of different means of allelopathic application under field conditions is challenging. Inclusion of allelopathic crops and/or cultivars in rotation, use of allelopathic mulches, and the use of allelopathic extracts could provide effective control of these species in combination with other options. Further field-based research is needed to evaluate the potential of allelopathy to manage these species.

## Chemical control

Herbicides are the most important method of control for *Avena* species (Beckie et al. 2002). Several herbicides have been effectively used to control *A. fatua* and *A. ludoviciana* over the years (Table 2). Effective control of these species depends on early post-application of acetyl-CoA carboxylase (ACCase) and aceto-lactate synthase (ALS) inhibitor herbicides (Owen and Powles 2009). Aryloxyphenoxypropionate (APP) and cyclohexanedione (CHD) herbicides have also been broadly used to suppress *A. fatua* and *A. ludoviciana* (Burton et al. 1989). A range of herbicides including glyphosate, barban, difenzoquat, chlorfenprop, linuron, metribuzin, monolinuron, and metoxuron have proved effective for control of *A. fatua* and *A. ludoviciana* (Terry 1984). Pinoxaden, a new phenolpyrazoline graminicide, has been shown to provide effective control of *A. ludoviciana* (Zand et al. 2007; Scursoni et al. 2011). Singh and Gosh (1992) reported that application of pendimethalin and isoproturon before emergence provided maximum control of *A. ludoviciana*. Elsewhere, it has been reported that diclofop-methyl, metoxuron, and isoproturon, alone or along with a non-ionic surfactant, improved the phytotoxicity to *A. ludoviciana* (Malik et al. 1989). Efficient control of *A. ludoviciana* has also been demonstrated using imazamethabenz-methyl, alone or blended with tralkoxydim and isoproturon, with 21.4% improvement in grain yield (Qasem 2007). *A. ludoviciana* may emerge after the crop, but it has a faster growth rate, so applications of pre-emergence (PRE) herbicides may not be effective (Thomas and Yaduraju 2000). Moss et al. (2001) reported that the application of different herbicides at recommended doses showed maximum control at the two to three leaf stages, while delayed applications gave poor results. Isoproturon can provide complete control of *A. ludoviciana* (Balyan 2001), and no resistance has been found against this herbicide (Moss et al. 2001).

Although a range of herbicides has provided excellent control of *A. fatua* and *A. ludoviciana* over the years, the evolution of widespread herbicide resistance in these species have reduced the scope of chemical control.

### *Herbicide resistance*

Evolution of herbicide resistance in weeds is becoming a major threat to crop production (Heap 2014a, b). More than 250 weed species have evolved resistance, against 161 different herbicides in 91 crops across 67 countries, and about 32% (1/3) of these resistant weed species are grasses (Heap 2016). *A. fatua* and *A. ludoviciana* have evolved resistance against several herbicides belonging to different modes of actions across the globe. To give the readers an idea of this widespread problem, but without significant repetition of the data available from other sources, only a few select cases are provided in this paper (Table 3). Full details can be found on the website for the International Survey of Herbicide Resistant Weeds Database (http://www.weedscience.org). *A. fatua* is the most widespread herbicide-resistant weed in the world, infesting 48,000 sites on 5 million hectares in 13 countries, with resistance against herbicides from five different modes/sites of action (Heap 2014b). About 52 cases of herbicide resistance in *A. fatua* have been reported to date, out of which 16 were from the USA and 14 from Canada (Heap 2016). *A. fatua* populations are also evolving multiple resistance in other countries. The first case of herbicide resistance in *A. fatua* was reported from Western Australia in 1985, where it developed resistance against diclofop-methyl in a wheat crop (Heap 2016). On the other hand, only seven cases of herbicide-resistant *A. ludoviciana* have been documented so far, with three each from Australia and Iran (Heap 2016). Overall, 14 cases have been reported for *A. sterilis*, which also includes sub-species other than *ludoviciana*. Both target-site and non-target-site herbicide resistance mechanisms prevail in these two species (Powles and Yu 2010). Both these species are highly resistant to ACCase and ALS inhibitor herbicides (Heap et al. 1993; Tal et al. 2000; Adamczewski et al. 2013).

Screening of over 100 biotypes of *A. ludoviciana* revealed that about 89% of them were susceptible against diclofop (Travlos et al. 2011). Owen and Powles (2009) reported that numerous populations of *A. fatua* were more resistant against diclofop-methyl than APPs. In another study, Beckie et al. (2008) reported that resistance of *A. fatua* populations was less common against cyclohexanedione herbicides, while other authors (Valverde 2007; Uludag et al. 2008) found that many populations of *A. fatua* had cross resistance against APPs and cyclohexanedione herbicides. Some *A. fatua*

**Table 4** Integrated management options for *Avena fatua* and *Avena ludoviciana*

| Crop | Integrated approach | Control | Reference |
|---|---|---|---|
| Barley | Tall cultivar (AC Lacombe) + high crop density (400 plants m$^{-2}$) + diverse crop rotation (barley–canola–barley–pea–barley) + A 50% reduced dose of herbicides | Reduction in biomass of *A. fatua* and a 40-fold reduction in its seed production | O'Donovan et al. (2013) |
| Barley | Competitive cultivar + A 50% reduced dose of recommended herbicides | Reduction in biomass and seed production of *A. ludoviciana* | Walker et al. (2001) |
| Barley | Tall cultivars + double seed rate + diverse crop rotation (barley–canola–barley–pea) | Effective control of *A. fatua* resulting in high crop yield | Harker et al. (2009) |
| Barley | Tall and late maturing variety (Albacete) + A 50% reduced dose of recommended herbicides (tralkoxydim, diclofopand, imazamethabenz) + higher seed rate (200 kg ha$^{-1}$) | Reduction in biomass and seed production of *A. ludoviciana* resulting in high crop yields and economic returns | Fernandez-Quintanilla et al. (2006) |
| Barley | Higher seed rate (175 kg ha$^{-1}$) + reduced rates of tralkoxydim + narrow row spacing (11 cm) | Effective control of *A. fatua* resulting in high crop yield | Kirkland (1993) and O'Donovan et al. (2001) |
| Barley | High seed rate (200 kg ha$^{-1}$) + competitive varieties (AC Lacombe and Seebe) | Reduction in biomass and seed production of *A. fatua* resulting in high crop yields | O'Donovan et al. (2000) |
| Wheat | High crop density (150 plants m$^{-2}$) + reduced doses of herbicide | Reduction in biomass and seed production of *A. ludoviciana* | Walker et al. (2002) |
| Wheat, canola | Competitive cultivars + high seeding rates | Growth suppressed of *A. fatua* | Lemerle et al. (1996) |
| Canola, barley, wheat, pea, rye | Diverse crop rotations involving cereals and legumes + high seed rates + cover crops | Reduction in biomass and seed production of herbicide-resistant *A. fatua* resulting in high crop yields and economic returns | Harker et al. (2016) |
| Wheat | Higher seed rate (160 kg ha$^{-1}$) + taller competitive cultivars | Effective management of *A. fatua* | Balyan et al. (1991) and Khan et al. (2008) |

populations showed multiple resistances to imidazolinones and sulfonyl ureas (ALS-inhibiting herbicides) and ACCase inhibitors (Friesen et al. 2000; Beckie et al. 2008). Some biotypes of *A. ludoviciana* showed high resistance to diclofop-methyl herbicide as compared with ACCase inhibitors (Maneechote et al. 1997). Moreover, *A. ludoviciana* biotypes showed resistance to APPs and fenoxaprop-p-ethyl, and low resistance to cyclohexanedione herbicides (Uludag et al. 2007).

Given increasing herbicide resistance in *A. fatua* and *A. ludoviciana*, their effective control has become a challenge. A multi-faceted approach is required to control these weed species.

*Chemical options to manage herbicide resistance*

Alternative and rotational use of herbicides has been very effective in controlling herbicide-resistant populations of *A. fatua* and *A. ludoviciana* (Gressel and Segel 1990). The use of herbicides having very different modes of actions in rotation has restricted the evolution of resistance by reducing selection pressure (Gressel and Segel 1990; Boerboom 1999). The practice of using reduced doses of herbicides has been proposed as an effective way to reduce the evolution of target site-based herbicide resistance in these weed species (Christoffers 1999). However, it is crop specific, and may indeed promote metabolically based herbicide resistance if not wisely done. For instance, a 75% reduction in the herbicide dose provided good control of *A. ludoviciana* in barley, but not in wheat (Walker et al. 2001).

Very little research has examined the relationship between crop competitiveness with these weed species, and the effectiveness of low herbicide rates (Beckie and Kirkland 2003). This is another potential dimension for research relating to herbicide-resistant *A. fatua* and *A. ludoviciana* management.

### Integrated management

Integrated weed management is the most appropriate and effective strategy to control weeds in modern-day agriculture (Harker and O'Donovan 2013; Bajwa 2014; Bajwa et al. 2016b, c). Although herbicides remain the core part of any integrated package, the inclusion of several cultural and mechanical options may provide excellent weed control. Non-chemical options which can be effectively used in IWM package for *A. fatua* and *A. ludoviciana* include tillage, manual weeding, mechanical control, crop rotation, mulching, crop competition, manipulation of seeding dates, and allelopathic suppression (Boerboom 1999; Nalewaja 1999; Thill et al. 1994). Rather than exclusive dependence on herbicides, *A. fatua* could be managed in an integrated manner, and its competitiveness and seed production can be alleviated through the integration of different approaches (O'Donovan et al. 2000). *A. fatua* and *A. ludoviciana* have been effectively controlled on several occasions using compatible combinations of different management options (Table 4). The use of integrated approaches has been reported to decrease weed biomass of these two species by up to 90% (Anderson 2003; Blackshaw et al. 2008; Harker et al. 2009). The use of IWM strategies has also proved very effective in reducing and managing the herbicide resistance problem in these two species (Beckie 2006). Improving the competitiveness of crops by integrating multiple approaches, including competitive cultivars, increased seed rates, altered row spacing, and manipulated planting geometry, has proved successful in controlling *Avena* species and other weeds in major field crops (Bajwa et al. 2016c). So, the adoption of suitable IWM packages could be the key to successful management of *A. fatua* and *A. ludoviciana.*

## Conclusions and future perspective

*A. fatua* and *A. ludoviciana* are serious threats to crop production in different parts of the world. The biological attributes of these weed species enable them to survive harsh conditions and successfully complete their life cycles in a wide range of environments. These species produce a large number of seeds, which are well suited to achieve long-distance dispersal, and may remain in a dormant but viable condition for several years in the soil seed bank, contributing to their persistence in agro-ecosystems. The ability to germinate under a wide range of climatic and edaphic conditions, efficient resource (light, water, nutrients) acquisition and utilization, high competitiveness, and allelopathic expression enable *A. fatua* and *A. ludoviciana* to cause substantial yield losses in field crops. Sole reliance on herbicides is no longer effective for control of these weed species due to evolution of herbicide resistance against a large number of herbicides. However, integrated approaches involving cultural weed control methods, such as diverse crop rotations, improved crop competition and allelopathic suppression, and judicious herbicide use, provide better control of these weed species.

Changing climate and crop production methods have a significant impact on the biology and ecology of *A. fatua* and *A. ludoviciana.* For example, the sole dependence on herbicides to control these species in conservation tillage systems has resulted in a herbicide resistance problem. Similarly, changing temperature and rainfall patterns may also promote a change in the biology of these species in order to adapt to such conditions. Environmental factors also influence the dynamics of these weed species in different cropping systems. So, it is essential to study the biology and ecology of *A. fatua* and *A. ludoviciana* under different conditions before devising a management strategy. Further research on germination ecology, seed bank persistence, competitive ability, economic thresholds, and allelopathic effects of normal as well as herbicide-resistant populations of *A. fatua* and *A. ludoviciana* should be conducted in the future. The development of new herbicides with novel modes of action may also help to deal with herbicide resistance in these two weed species. Integrated use of multiple cultural and biological weed control strategies should be focused on different cropping systems. Improving crop competitiveness by using competitive cultivars, high planting density, narrow row spacing, and altered sowing geometry has provided effective weed control in recent years. This may also be explored to manage *A. fatua* and *A. ludoviciana.* In the future, the use of integrated management strategies may reduce reliance on herbicides, improve crop yields, and protect the environment.

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