Vulpia myuros, an increasing threat for agriculture

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Summary

Vulpia myuros is an annual grass species of Mediterranean origin, which has achieved a global distribution. It is a fast-growing species, with high colonisation and competitive abilities. This species is considered an invasive weed in most countries where it has been introduced, with highly negative economic impact where it now dominates. It is increasingly found to be a problematic weed in winter cereals, especially in no-till and reduced tillage systems, across Europe, United States and Australia. Seeds of *V. myuros* have reduced germination potential when buried. However, where tillage interventions are reduced, ideal conditions for *V. myuros* are created. Minimum and no tillage practices are increasing worldwide, with a concomitant increase in the spread and abundance of *V. myuros*. Effectiveness of herbicides is mostly suboptimal, in particular for well-established populations forming dense swards, even though no herbicide resistance has yet been identified. An integrated management approach, increasing crop diversification combined with management adaptations, possibly including herbicides is suggested as an effective control strategy. Despite increasing research on *V. myuros*, more information is needed to optimise the management of this weed. Based on the species' Mediterranean origins and adaptation to warm and dry environments, an increase of its global importance may be expected with climate changes. It is thus paramount to increase the awareness around this species, improve its identification in the field, and monitor its spread before it becomes a concern of similar magnitude to grass weeds like *Alopecurus myosuroides* or *Lolium rigidum*.

Keywords: grass weed, winter annual, conservation agriculture, no-till, pastures, herbicide resistance

Introduction

Vulpia myuros (L.) C.C.Gmel. (rattail fescue) is an annual grass (Figure 1), present on all continents (Figure 2). It has become a relatively common weed of winter cereal production systems across Europe, Australia and the United States (Tozer, 2004; Ball *et al*., 2008; Melander *et al*., 2013). It is a winter annual, whose life cycle closely mimics the cycle of winter crops. It produces numerous small seeds that germinate in autumn and can form dense vegetation mats hampering the growth of the crops (Figure 1D).

Vulpia myuros has been mentioned among the most problematic weeds associated with reduced tillage systems (Melander *et al*., 2013). Worldwide, no-till or reduced tillage is being promoted for soil conservation and labour/energy cost reduction purposes. Such promotion is expected to result in an increase in *V. myuros* presence in the future. In addition, as a species with a Mediterranean origin, and hence adapted to warm and dry temperate climates, *V. myuros* could be favoured by future climate changes, in temperate areas. While this species is currently considered of lesser economic importance compared to other grass weeds such as black grass (*Alopecurus myosuroides*) or ryegrass (*Lolium* spp.), the combination of expected changes in cultivation practices and climate may render this species a major weed in the near future. This calls for a better understanding of *Vulpia myuros* biology, ecology and control, as well as a more complete overview of the species' current and future distribution.

The aim of this article is to provide a comprehensive review of the current knowledge on the distribution, taxonomy, biology, ecology, management and agronomic impacts of *V myuros*, and to develop a future research agenda on this weed species.

Taxonomy of *Vulpia myuros*

Vulpia myuros is a monocot angiosperm, from the order Poales, family Poaceae. It belongs to the subtribe Loliinae, one of the largest subtribes of temperate grasses, which encompasses about 10 genera, including the large genus *Festuca*, *Lolium* and *Vulpia* (Inda *et al.*, 2008). The genus *Vulpia* is closely related to *Festuca* and has sometimes been considered as a subgenus of *Festuca*, but is most often treated as a genus on its own (Cotton & Stace, 1976; Stace, 1981). *Vulpia* is a polyphyletic genus, which has between 20 and 30 species depending on the sources, with diploid, tetraploid and hexaploid species (Cotton & Stace, 1976). It belongs to the fine-leaved clade of the Loliinae, whose species tend to have coloniser syndromes, i.e. vagile, short-living species (Catalán *et al.*, 2006; Inda *et al.*, 2008). The

Vulpia genus has now been split into four lineages (Catalán *et al.*, 2006, 2007; Inda *et al.*, 2008; Díaz-Pérez *et al.*, 2014; Minaya *et al.*, 2017). Among the *Vulpia* genus, *V. myuros* and *V. bromoides* are considered as problematic weeds (see below).

Vulpia myuros is an allo-hexaploid (2n=42) species, belonging to the '*Psilurus*/*Vulpia* 4x-6x' lineage, together with *Psilurus incurvus* and *Vulpia ciliata* (tetraploid), its closest relative (Torrecilla *et al.*, 2004; Catalán *et al.*, 2006, 2007; Inda *et al.*, 2008; Díaz-Pérez *et al.*, 2014; Minaya *et al.*, 2017). *Vulpia myuros* has also been found to produce natural hybrids with *Festuca rubra* in the wild (nothogenus *xFestulpia* Melderis ex Stace & R. Cotton), even though the intergeneric offspring are sterile (Willis, 1975; Ainscough *et al.*, 1986). Such hybrids have been reported in the United Kingdom, the Netherlands, Czech Republic and recently also in Italy (Ardenghi *et al.*, 2011). Numerous synonyms are listed for *Vulpia myuros*, the most common being *Festuca myuros*, *Vulpia megalura* and *Festuca megalura*. Its main English vernacular names are 'rattail fescue', 'rat's tail fescue' or 'annual fescue', while 'silvergrass' is often used in Australia. *V. myuros*' EPPO code is VLPMY.

Distribution of *Vulpia myuros*

Old world species of *Vulpia* have Eurasian origins (Díaz-Pérez *et al.*, 2014). Their centre of diversification is the western part of the Mediterranean basin, mainly the Italian and Iberian peninsulas and the adjacent parts of North Africa (Cotton & Stace, 1976). *Vulpia myuros* is among the most widely distributed *Vulpia* species. Its naturalisation is ancient in most parts of Europe, where its native versus introduced status is thus unknown for most countries. *Vulpia myuros* has now been introduced in all continents (Figure 2A).

Vulpia myuros is present in almost all western Europe and in the Mediterranean basin. It is also present in North Africa, and has been introduced to South Africa, mainly in southern and eastern Cape region, where it is listed as a problematic grass weed (Bromilow, 2001).

In the United States, the species was probably introduced to California around 1800 and was already well established in the western part of the US one century later (Tarasoff *et al.*, 2013). It is now present on the West coast as well the East coast of the US (Figure 2A). *Vulpia myuros* is listed as invasive in California (Cal-IPC, 2020) and western US (USDA, 2020), and causes problems in the Pacific Northwest region (see below).

In Australia, *V. myuros* was probably accidentally introduced during European settlement in the early 1800s through contaminated forage or grass seeds (Wallace, 1998), and now causes major economic impacts together with other *Vulpia* species (Tozer, 2004). It is mainly restricted to the more temperate areas of Australia, i.e. south east and south west, and is also present in New Zealand (Figure 2A). Japan, China and South Korea all have recorded presence of *V. myuros* as well.

Comparing *V. myuros* distribution with a climatic map allows to highlight the climatic range in which it can thrive (Figure 2B). It is mostly limited to 'temperate' climates (group C) according to Köppen-Geiger climate classification (Beck *et al.*, 2018). It is notably found in the Mediterranean biomes around the World, in California, South Africa and Australia. In tropical countries, the species is found at higher elevation than in temperate areas, based on GBIF observations database (GBIF.org, 2020).

History of impact and use of *Vulpia myuros*

This section gives an historical and geographical perspective of the impact and use of *V. myuros* (see also Supplementary Material Table S1), starting with Australia, the first country where this species was reported as problematic. Mentions of *V. myuros* as being part of the flora of natural ecosystems are not listed here.

Australia – widespread weed in pastures

Vulpia myuros seems to be reported as a weed in pastures in Australia since the 1960s, while references to this species as a weed in winter cereals started later, in the early 1980s (Dillon & Forcella, 1984). Most of the Australian literature thus focusses on pastures. In many Australian studies, the species of *Vulpia* ('silvergrass') are not distinguished: *V. bromoides* and *V. myuros* (and a few other, rarer *Vulpia* species) are often discussed together because of their similarities in impact on pastures. However, *V. myuros* is specifically studied in many of the cited references, and has been shown to be as problematic as *V. bromoides* (Wallace, 1998; Tozer *et al.*, 2009). *Vulpia* spp. in Australian pastures cause a range of problems (see references in Leys *et al.*, 1991), i.e.: 1. competition with other pasture species, 2. low nutritional value for livestock, 3. injury to livestock through their spiky seeds and 4. contamination of wool. *Vulpia* spp. can also be hosts of the nematode vector of a livestock disease called annual ryegrass toxicity (Riley, 1995). The economic impact of *Vulpia* spp. for the wool industry has been estimated at more than $AUS 30 million annually (Sloane *et al.*, 1989). Brennan and Murray (1988) estimated the cost of lost production in winter cereals due to annual weed grasses (including *Vulpia* spp, but its specific contribution is unknown) at $AUS 100 million each year.

In Australia, an extended body of literature has addressed the biology and ecology of *Vulpia* spp. as pointers for the design of control methods (e.g. Dillon & Forcella, 1984; Charles *et al.*, 1991; Tozer, 2004; Hely & Roxburgh, 2005; Loo, 2005). Investigations into herbicide effectiveness have also been conducted (Scott & Blair, 1987; Leys *et al.*, 1991; Leys & Plater, 1993). Most of these studies have been published before 2010, while the last 10 years have seen fewer articles published on *Vulpia* from Australia. In 2019, *V. myuros* was also mentioned as a common pasture weed in New Zealand (Ghanizadeh & Harrington, 2019).

United States – from revegetation to invasive species

In the United States, the first articles specifically mentioning *V. myuros* focus on its usefulness in revegetation programmes in California, owing to its capacity to grow rapidly on disturbed and poor soils. A specific variety named 'Zorro' was distributed for this purpose by the USDA (Kay *et al.*, 1981). This variety was also shown to grow on contaminated mine soils in California (Heeraman *et al.*, 2001). Another use of this species mentioned in the years 1980-2000 is as ground cover in vineyards (Bugg *et al.*, 1996) and orchards, although it has been reported as potentially too competitive against young peach tree seedlings (Meyer *et al.*, 1992). By the end of the 1990s, the perception on this species started to change as negative reports about its invasiveness appeared. These reports pointed at the negative effects of *V. myuros* on establishment of native species and therefore recommended against its inclusion in revegetation seed mixtures (Stylinski & Allen, 1999; Brown & Rice, 2000). Despite these recommendations, its use as ground cover in vineyards continued (Baumgartner *et al.*, 2008) although it was also considered as a potential weed in these systems (Steenwerth *et al.*, 2010). From 2007 onwards, the perception of *V. myuros* in the scientific literature changed drastically, with studies reporting it as a problematic weed in no-till winter cereal systems in the Pacific Northwest region (e.g. Ball *et al.*, 2007, 2008; Jemmett *et al.*, 2008).

Europe – a native species recently spreading in cropping systems

In Europe, where *V. myuros* is considered as a native or naturalised species in most countries, the first articles focussing on this species mainly addressed morphology and taxonomy (e.g. Cotton & Stace, 1976; Auquier & Stace, 1980; Stace, 1981). The next decade saw almost no literature on the subject, while some modern phylogenetic studies were published after 2000 (e.g. Torrecilla *et al.*, 2004; Catalán *et al.*, 2006, 2007; Inda *et al.*, 2008; Díaz-Pérez *et al.*, 2014; Minaya *et al.*, 2017). The first scientific article mentioning *V. myuros* as an agricultural weed in winter crops in Europe (i.e. Denmark) was published in 2009 (Jensen, 2009), around the same time the species starts to attract research attention as a new weed in the US. Since then, most of the articles on *V. myuros* as a weed in European cropping systems come from Denmark, with other contributions coming from the UK (Hull *et al.*, 2011), Romania (Georgescu *et al.*, 2016, 2018), France (Cordeau *et al.*, 2015, 2018) and Switzerland (Büchi et al., 2018). All these articles regard the presence of *V. myuros* as a weed in winter crops (e.g. grass seed crops, winter wheat, winter rapeseed), especially in no-till or conservation agriculture systems. Its presence has also been confirmed in this type of systems in Spain and Belgium (personal communication), and recently in Germany (Augustin & Gehring, 2020). In these countries, it seems to still be a marginal problem compared to other grass weeds like black grass (*Alopecurus myosuroides*) or annual ryegrass (*Lolium rigidum*), but its importance tends to shift from a minor weed 20 years ago to a common and potentially major weed in current days. In contrast to these concerns about the species weediness in agricultural fields, *V. myuros* has been periodically used for revegetation of contaminated sites in the UK (Shaw, 1996) and Spain (Gomez *et al.*, 2016).

Japan and China – a success story as cover crop in orchards?

In contrast to Australia, US and Europe, *V. myuros* is not studied in Japan as a weed problem but as a ground cover in orchards (Ishii *et al.*, 2007, 2008, 2011; Matsumura *et al.*, 2008; Cruz & Ishii, 2012) and vineyards (Motosugi & Terashima, 2008). *Vulpia myuros* is presented as offering a good soil cover, preventing the growth of weed species and providing erosion control. Most of these studies also mention the potential positive effect of *V. myuros* on mycorrhiza and nutrient transfer to the main crop. Similarly, a very recent article presents the many benefits of cultivating *V. myuros* in tea plantations in China (Xianchen *et al.*, 2020).

This historical perspective shows that *V. myuros* is now considered as a weed in three large areas, namely in Australia, United States and Europe, with a recently reported increase in its impact.

Biology and Ecology of *Vulpia myuros*

Morphology

Vulpia myuros is a C3 grass species, usually described as short and prostrated but its height can exceed 1 m in certain environments, especially in competition with crops or established grasses in field margins (Figure 1) (Georgescu *et al.*, 2016; personal observation in wheat fields). Its culms are erect and mostly glabrous. Leaves are fine (1-3 mm wide) and long, with 5-7 pubescent veins on the upper surface, tightly folded. The leaf sheath is split, generally glabrous. The ligule is very short (0.2-0.4 mm), membraneous and denticulate. Auricles are absent. The typical panicle inflorescences, narrow, dense, one-sided, 5-35 cm long, green to purplish in colour, give the species its vernacular and Latin name. The base of the inflorescence is often enclosed in the sheath of the uppermost leaf. Spikelets have short stalks (<1 mm length). They are 5-12 mm long, with lower glume up to 1.5 mm long and upper glume 2.5-5.5 mm long. Spikelets have 3-8 florets. Lemmas are 4.5-6.5 mm long with straight terminal awns of 5-15 mm length, fruits are 3.5-4.5 mm long (Figure 1B).

Identification of *V. myuros* at vegetative stages is difficult, and its appearance resembles *Festuca rubra* and thus could result in misidentification. The presence of hybrids with *F. rubra* is probably also contributing to the difficult identification of *V. myuros* in the field. However, the presence of fine hairs on the veins of the leaf blade allows separation from *Festuca rubra* and *Lolium perenne*, which are both glabrous. The tightly folded prefoliation is also a distinctive character.

Vulpia myuros is generally described as having a shallow, but dense root system (Rossiter, 1966; Moreau *et al.*, 2017). However, in a study presenting a new tool for root monitoring, Jeudy et al. (2016) presented pictures of *V. myuros*' root system, showing a depth of ~50 cm after 51 days growth in pots.

Reproduction and germination

Vulpia myuros is mainly self-pollinating cleistogamous (Cotton & Stace, 1976, 1977), even though observations of intergeneric hybrids suggest at least some events of cross-pollination (Auquier & Stace, 1980). To our knowledge, no studies on seed dispersal have been conducted. The seed shape does not seem particularly adapted to wind dispersal. In nature, dispersal of seeds is mainly assured by animals, thanks to their long pointy awns allowing them to hook on to fur. Their structure and light weight also enable high potential contamination of animal feed or pasture seed mix if produced from infested fields. In agricultural fields, dispersal can probably also occur through machinery, similarly to what has been shown for *L. rigidum* in Spain (Blanco-Moreno *et al.*, 2004). In the UK, dispersal along railway is probable (BRC, 2020).

Vulpia myuros usually germinates in autumn (Ball *et al.*, 2007; Scherner *et al.*, 2017a), in successive cohorts triggered by rainfall events, but winter and spring emergence is also possible (Jensen, 2019). Newly formed seeds require a short dormancy period (‘after-ripening period’) before being able to germinate, the length of which depends on environmental conditions (2-3 months in Dillon & Forcella, 1984; 1-12 months in Ball *et al.*, 2008). Optimum germination temperature was shown to be around 20°C but seems to depend partially on light conditions (Dillon & Forcella, 1984; Ball *et al.*, 2008; Weller *et al.*, 2019). Continuous light induces faster germination and over a wider temperature range than continuous dark conditions (Dillon & Forcella, 1984). *Vulpia myuros* seeds generally have a reduced germination rate when buried in the soil, with optimal placement at or just below the surface (Dillon & Forcella, 1984; Cordeau et al., 2015; Weller *et al.*, 2019). Factors responsible for this effect (e.g. temperature, light, humidity) have not yet been elucidated, but are likely related to the small size of the seeds. Water requirement studies have shown that *V. myuros* can germinate at low water potential and germination of seeds lying on the surface is less affected by hydric stress than other species (Scherner *et al.*, 2017a; Cordeau *et al.*, 2018). Seeds were also shown to be able to germinate over a large range of pH values (see Weller *et al.*, 2019), even if the species is mainly found in soil with relatively low pH.

Life cycle

Vulpia myuros is generally described as a winter annual species, which means it requires a vernalisation period to trigger flowering in spring. However, plasticity in vernalisation needs has been shown. Two US populations of *V. myuros* exhibited different germination rate and fertility depending on vernalisation length and temperature treatments (Tarasoff *et al.*, 2013). And while some studies have shown no seed production for spring germinated individuals (Ball *et al.*, 2008) or in treatments mimicking the absence of a vernalisation period (Tarasoff *et al.*, 2013), others have reported seed production from plants that emerged in spring (Schillinger *et al.*, 2010). This latter study also mentioned possible vegetative regrowth, via re-tillering of *V. myuros* in spring, which would have consequences for its management and thus deserves further investigations. Photoperiod requirements have not been extensively studied but short-day requirement for floral induction has been mentioned (Ball *et al.*, 2008). *Vulpia myuros* is generally known to produce large amounts of seeds in summer, but only few studies have reported quantitative seed production information (Dowling, 1996). Most seeds germinate a few months after dispersal and seeds are rather short-lived. When buried in the soil, seed longevity in seedbank has been reported to be only 2-3 years (Ball *et al.*, 2008).

Abiotic requirements

Vulpia myuros thrives on poor or contaminated soils but tends to be outcompeted on richer soils (Shaw, 1996; Moreau *et al.*, 2013; Gomez *et al.*, 2016). Its Ellenberg value for nitrogen classifies it as an indicator species of infertile soils (Hill *et al.*, 1999; Moreau *et al.*, 2013). It has been shown to be able to grow with low soil phosphorus concentration, because of its higher phosphate absorption capacity (Scott & Blair, 1987), probably linked to its dense root system (Moreau et al., 2017). Its dominance is greater in moderately acidic soils (Rossiter, 1966; Hill *et al.*, 1999). *Vulpia myuros* grows under a large range of rainfall patterns (Loo, 2005). It is generally considered as drought tolerant in Europe and the United states, and is an indicator of dry habitats according to its Ellenberg value for moisture (Hill *et al.*, 1999). In Australia, where the species occupies the cooler areas of the country, it is however described as drought sensitive thus explaining its constrained distribution (Rossiter, 1966).

Competitive ability

Several studies have shown a high competitive ability of *V. myuros*, leading to reduced biomass growth of co-occurring species (Scott & Blair, 1987; Leys & Plater, 1993; Tozer, 2004; Hely & Roxburgh, 2005). It can also outcompete other plants species by forming dense swards (Figure 1C). Densities of up to 43,000 seedlings/m^2 have been reported in Australia (Scott & Blair, 1987). This species has a high colonisation ability as evident from observations of rapid occupation of vegetation gaps in perennial pastures in Australia (Tozer *et al.*, 2008).

Vulpia myuros has also been shown to have phytotoxic properties, due to the allelochemicals produced during decomposition of its residues (An *et al.*, 1997, 2000, 2001a,b). These substances negatively affect the emergence or growth of other species (Kato-Noguchi *et al.*, 2010) and can be responsible for the deterioration of pasture quality (An *et al.*, 2007). In addition, the phytotoxicity observed during residue decomposition means that the species can have a negative carry-over effect on other plant species even after completion of its life cycle (Jemmett *et al.*, 2008).

Fast germination, high vegetative growth rate, competitive and colonisation abilities and its adaptation to a broad range of habitats contribute to the high invasion potential of *V. myuros*.

Management of *Vulpia myuros*

The biology and ecology of *V. myuros* described earlier explain why its control can be difficult, and why the problem must be tackled as soon as it appears in a field and at early stages of plant growth. Results from the past forty years studying *V. myuros* as a weed in pastures and crops also demonstrate the necessity to develop an integrated management programme to ensure the best possible control.

Cropping practices

Since germination mainly occurs in autumn, inclusion of a spring crop in the rotation is a way of improving *V. myuros* control (Ball *et al.*, 2008; Scherner *et al.*, 2016). This creates a longer fallow period between harvest and seeding of the new crop in spring, extending the time window for interventions with herbicides or tillage to destroy *V. myuros* (Figure 3). Alternating dicotyledon and monocotyledon crops also increase the number of possible interventions at the rotational scale and could increase the control of *V. myuros*. The introduction of a cover crop in between crops may outcompete *V. myuros* for light and reduce its growth (Cordeau *et al.*, 2015) and could be a useful tactic to control the species in no-till systems. Delayed drilling in autumn, higher crop seeding rates and using more competitive crop varieties has all been shown to be a successful way to better control the grass weed *A. myosuroides* (Lutman *et al.*, 2013). Similar results have been observed for the management of *Bromus diandrus*, a weed in Mediterranean systems with similar characteristics to *V. myuros* (García *et al.*, 2014). Such insights could provide useful entry points for the development of an integrated management approach towards *V. myuros*.

Mechanical control

Tillage is paramount in the control of *V. myuros*. Buried seeds have low germination rate and adult plants tend not to withstand tillage events. In addition, the seeds, short-lived, seem not to create problems when brought back at the surface by ploughing in the following years. This sensitivity to tillage explains that the recent increase of *V. myuros* has mainly followed the worldwide increasing trend of reduced or no tillage (Dillon & Forcella, 1984; Ball *et al.*, 2008; Schillinger *et al.*, 2010; Melander *et al.*, 2013; Scherner *et al.*, 2016). In Australia, adoption of no-till practices among winter cereal producers has increased from none in the 1960s to around 80-90% in 2008 (Bellotti & Rochecouste, 2014). In the Pacific Northwest region in the US, where *V. myuros* is problematic in winter cereals, reduced or no tillage adoption by wheat growers increased from none in 1975 up to 60% in 2005 (Kok, 2007). In Europe, adoption of reduced or no tillage is comparatively low (26% in 2000 according to Eurostat) but is following an increasing trend (Soane *et al.*, 2012; Kertész & Madarász, 2014). *Vulpia myuros* has been shown to rapidly invade no-till fields after first observation of occurrence (Schillinger *et al.*, 2010; Scherner *et al.*, 2016; Büchi *et al.*, 2018), probably because of a combination of species traits, i.e. higher number of fast germinating seeds, ability to germinate with seed lying on the soil surface (Cordeau *et al.*, 2015) and fast growth and high competitive ability.

Tillage, and especially ploughing, is an obvious control method of *Vulpia myuros*. The use of the stale (or false) seedbed technique in the autumn, where seedbed is prepared without seeding any crop, just to promote weed germination, has also been shown to control *V. myuros* (Jensen, 2010, 2019). Alternatively, and quite in opposition to the previous technique, the high mortality rate of seeds lying at the soil surface means that delaying autumn tillage could reduce the seed pressure in the next crop (Jensen, 2009, 2010). Inter-row cultivation after crop seeding is also an option when the type of crop and the soil conditions allow it (Melander *et al.*, 2005).

In no-till systems, where the absence of soil tillage tends to promote *V. myuros*, an early intervention is necessary; once a dense carpet of *V. myuros* is present, tillage is currently the only really effective method. This would come at the cost of jeopardising the benefits of several years of no-till (Schillinger *et al.*, 2010; Scherner *et al.*, 2016; Blanco-Canqui & Wortmann, 2020). Post-harvest burning, used to control downy brome in the Pacific Northwest of the United States, was reported to be inefficient to control *V. myuros* (Schillinger *et al.*, 2010). New innovative solutions are thus needed to control *V. myuros* in no-till systems.

Chemical control

Since the 80s, several herbicides and combinations of herbicides have been tested against *V. myuros* (Supplementary Material Table S2; Scott & Blair, 1987; Leys *et al.*, 1991; Leys & Plater, 1993; Ball *et al.*, 2007; Jemmett *et al.*, 2008; Hull *et al.*, 2011; Lawrence & Burke, 2014). One of the main problems regarding chemical control of *V. myuros* in pastures and crops is that it is inherently tolerant to some herbicides (acetyl CoA carboxylase ACCase inhibitors) (Leys *et al.*, 1991; Hull *et al.*, 2011). In addition, *V. myuros* has a low sensitivity to glyphosate application at recommended rates; even double doses or sequential applications results in only weak control of *V. myuros* (Leys *et al.*, 1991; Jemmett *et al.*, 2008; Hull *et al.*, 2011; Augustin & Gehring, 2020). This is particularly problematic in no-till systems, which rely heavily on glyphosate to control weeds (Adeux *et al.*, 2019). Generally, pre-emergence herbicides give better results than post-emergence herbicides (Ball *et al.*, 2007; Lawrence & Burke, 2014), and post-emergence herbicides are more effective when applied at an early phenological stage, due to higher sensitivity of young plants. However, the efficiency of pre-emergence herbicides in no-till is still generally low due to adsorption on residues and organic matter. The most recent studies have suggested that a combination of several herbicides, or a sequential application of herbicides (pre and post emergence), provides the best chemical control of *V. myuros* (Table 1; Ball *et al.*, 2007; Jemmett *et al.*, 2008; Hull *et al.*, 2011; Lawrence & Burke, 2014). Field experiments in winter wheat resulted in tangible herbicide recommendations. Ball *et al.* (2007) obtained good results with pre-emergence application of flufenacet alone or followed by post-emergence application of either mesosulfuron/sulfosulfuron, imazamox, or diuron. Jemmet *et al.* (2008) recommended a sequential application of glyphosate or a combination of paraquat and diuron, followed by glyphosate. Lawrence and Burke (2014) confirmed that sufficient control of *V. myuros* is achieved using pre-emergence application of herbicides, in particular flufenacet combined with metribuzin or pyroxasulfone. Hull *et al.* (2011), using pot experiments, confirmed the efficiency of flufenacet in pre-emergence application or a combination of mesosulfuron and sulfosulfuron post-emergence for cereals, or propyzamide in rapeseed.

A sequential application of herbicides in autumn would also address the long period of emergence of *V. myuros* in no-till fields (Scherner *et al.*, 2017b). Hull *et al.* (2011) have shown that *V. myuros* is well controlled by the same type of herbicide combination as used against *A. myusoroides* (black grass), which is currently a major concern in a lot of European countries. This could explain why *V. myuros* has often remained unnoticed so far, but the recent spread and increased records of *V. myuros* as a problematic weed calls for a careful monitoring. Apart from its natural tolerance to ACCase herbicides, no evidence for evolved herbicide resistance in *V. myuros* has been found (Hull *et al.*, 2011). Evolution of resistance is generally slower for self-pollinating species, however recent cases of resistance to simazine in *Vulpia bromoides* has been shown in Australia (Heap, 2020).

A clear disadvantage of chemical control of *V. myuros* is that the species ontogeny, life cycle and physiology closely match that of winter cereals. This excludes the option of using herbicides that target grass species once the crop is established. Thus, alternative or complementary control options would be necessary.

Future research avenues

While *V. myuros* has been recognised as a weed in many countries, representing an emergent problem in Europe and the US, it has not been studied as extensively as other grass weeds such as *A. myusoroides*. More research and information are thus needed to completely understand its biology and ecology and tackle the challenges *V. myuros* is likely to pose in the future.

Biology and Ecology

First, little is known about the genetics and biogeography of *V. myuros*. Different ecotypes are likely to exist in the different continents, due to its early introduction and thus long evolution history, but different ecotypes are also likely to be found within continents. Differences between wild populations and those found in cultivated fields could also occur. Gathering more information about genetic diversity and local adaptation within *V. myuros* would bring interesting insights in terms of the understanding of its colonisation history and invasion potential.

Many claims about the biology of *V. myuros* are not robustly backed up by the literature. In addition, most of the literature on these aspects comes from Australia and may be different for European ecotypes. For example, *V. myuros* is often described as a short grass, but observations of plants >1 m have been made; articles mention the shallowness of the root system though all refer to a unique Australian reference from the sixties; it is supposed to produce high number of seeds, but no study presents extensive data about this. All these aspects would deserve further investigations, especially in a context of competition with a winter crop, as shoot and root growth also respond to inter-specific competition. While reduced germination with depth of *V. myuros* seeds has been shown, the specific factors responsible for this effect have not been elucidated, as light, humidity, temperature and their fluctuations could all play a role. Identifying the main factor at play would then allow to design better control methods. Similarly, a better understanding of key eco-physiological traits could help find new non-chemical control methods. These traits would include for example photoperiod requirements, seed dormancy, germination patterns, seedbank and seedling recruitment and dynamics of seed production during the year.

Schillinger *et al*. (2010) suggested that *V. myuros* is capable of vegetative regrowth. A confirmation of this phenomenon is needed as effective regrowth from partially destroyed stands in cultivated fields would present additional challenges in terms of control.

Investigating the presumed allelopathic ability of *V. myuros* would contribute to improved understanding of its interference mechanisms with other weeds and crops. Allelopathy has been mainly shown for decomposing residues, but allelopathic potential of living *V. myuros* individuals, as well as disentangling the effect of residue biomass versus allelopathy in preventing other species to emerge, needs further investigations.

A better understanding of the mechanisms behind *V. myuros* tolerance to some herbicide classes could also bring interesting insights, as well as testing new herbicides on different *V. myuros* populations, as new molecules become available.

Revisit the management through the lens of integrated weed management

As *V. myuros* is known to be controlled by tillage, challenges for its management arise in no-till cropping systems. A first question that should be addressed is 'how much' or 'how deep' tillage should be to control *V. myuros*. Ploughing has been shown to be effective, but it would be crucial to know if non-inversion or shallower tillage could be effective too, to minimise soil disturbance while achieving good control. Occasional shallow tillage could be an acceptable compromise for some no-till farmers when a *V. myuros* problem occurs (see Blanco-Canqui & Wortmann, 2020, for a review on the effect of occasional tillage in no-till systems). In this case, ploughing could be done once in ten years, such as in organic rotational no-till systems implemented in the USA (Mirsky *et al.*, 2012). This frequency may be enough since the depletion of *V. myuros* seedbank is generally fast. In addition, further work on the species' adaptation to cropping systems should be done. The stale seed bed technique has been mentioned as a promising way to control *V. myuros* (Jensen, 2010, 2019). This has been tested in Denmark, but only by using a 'simulated' stale seed bed; effectiveness of this technique in the field therefore still awaits confirmation. The potential of inter-row cultivation in the established crop also needs testing. Modification of crop rotations to include spring crops, or adaptations of the timing of seeding or tillage interventions are also promising technologies that merit further testing.

In a more direct approach to *V. myuros* management, harvest weed seed control (HWSC) techniques, or chemical and thermal treatments of newly produced seeds lying at the soil surface should also be investigated. Impact mills that destroy weed seeds in seed-bearing chaff after grain crop harvest has been shown to be highly effective in Australian cropping systems, but not tested on *V. myuros* yet (Shergill *et al.*, 2020). Thermal weed control has shown low effectiveness on grass weeds and may not be suitable, while electricity is being tested (Bauer *et al.*, 2020). The role of seed predation by animals on the depletion of *V.*

myuros seedbank could also be studied to provide new insights into the ecology of the *V. myuros* and potential opportunities for sustainable management. The use of cover crops during the fallow period between two main crops is also a promising approach that would deserve further studies (Cordeau *et al.*, 2018; Jensen, 2019), especially in no-till systems. Studies by Cordeau *et al.* (2015, 2018) show an impact of ryegrass (*Lolium multiflorum*) used as cover crop, on weed emergence. Seeding of cover crops even before the harvest of the previous crop (relay cover crop) would provide the cover crop a head start and potentially increase its competitiveness against *V. myuros*. In most European countries, short season cover crops can be cultivated even between two winter crops, for 2-3 months, and achieve high biomass and weed control in this short period. Büchi *et al.* (2018) showed partial control of *V. myuros* in infested no-till winter wheat plots by a field pea cover crop (*Pisum sativum*), owing to its high biomass production compared to the other cover crops tested. Increased control by cover crops could be envisaged with optimal choice of cover crop species or mixtures, seeding rates and termination methods considering characteristics of the local conditions.

In addition, studies estimating yield loss at different *V. myuros* densities are necessary to allow the identification of thresholds for intervention and the design of management recommendations. In contrast to other weed species, the agronomic and economic impact of *V. myuros* has not yet been thoroughly assessed, especially in Europe, and this lack of knowledge needs to be addressed. Then, bioeconomic models, integrating a decision support system, could be developed (such as that developed for *L. rigidum* in Australia by Pannell *et al.*, 2004). In all cases, a landscape approach to *V. myuros*, including headland and field margin management is paramount, as it is naturally present in these environments and can therefore represent a continuous source of seeds for neighbouring fields if not managed properly.

Facing future changes

All these proposed future studies would need to be performed in different pedoclimatic conditions and cropping systems, to be able to evaluate future impact of *V. myuros* in a changing agricultural landscape and climate. *Vulpia myuros* is a Mediterranean species with a world-wide presence, spanning a large array of soil and weather conditions. In Europe, summers are likely to become hotter and drier, and winters wetter (Figure 2C), which could favour Mediterranean species. The future projection of the climatic map shows indeed that *V. myuros* is likely to extend its future range in Europe and in the United States. By contrast, in

Australia and Africa, where *V. myuros* is already restricted to the coolest areas, the species is likely to regress as the climate could become too hot (Figure 2BC). Most of these potential changes are conditional on *V. myuros* drought tolerance level during its growing period. A proper assessment of the drought tolerance profile of *V. myuros*, ideally including a range of ecotypes, is thus paramount to be able to predict changes in its distribution.

The potential emergence of herbicide-resistant biotypes is also a future threat that needs monitoring. Evolved herbicide resistance has been observed in many grass weeds, including *A. myusoroides* (Menchari *et al.*, 2006) and *V. bromoides* (Heap, 2020), and could appear in *V. myuros* with time if the species invades more cropping systems and is increasingly targeted by herbicide treatments.

Without good control solutions, *V. myuros* may limit the further promotion of no-till or conservation agriculture systems. Despite some drawbacks, these systems do bring benefits in terms of soil health and conservation which could in turn be jeopardised by a future uncontrolled spread of *V. myuros*.

Vulpia myuros monitoring network

In order to allow a monitoring of *V. myuros* distribution and spread, and to build species distribution models to better predict future changes, we suggest here to launch and coordinate a '*Vulpia myuros* monitoring network' to build a database for Europe. First, awareness about *V. myuros* and help with its identification at early stages would need to be set up. Then, we would like to encourage scientists, extension services practitioners and farmers to send us records of *V. myuros* presence, specifying the GPS coordinates or locality where the species has been found together with a picture and information about the crop in which it has been found, crop rotation, tillage system and soil type. An excel form is supplied in the Supplementary Material (Form S1) for this purpose. This database would be used to answer some of the questions raised in this review pertaining to changes in abundance, colonisation of new habitats, mapping future distribution, as well as the identification of successful management practices.

Conclusions

Vulpia myuros is a grass weed that has proven in Australia to have a very high invasion potential and agricultural and economic impacts. Still an emergent problem in cropping systems in Europe and the United States, it has potential to become more problematic in the future due to changes in climate and cropping practices (e.g. progression of no-till). In addition, the species seems to be well adapted to parts of South America that are currently under intensive agricultural production with a large and increasing area under no-till practices. More information on the spread of *V. myuros* is thus needed, and a close monitoring will hopefully allow mitigation of its impact on agriculture before the problem escalates.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1 History of the studies published on *Vulpia myuros*, excluding studies about the taxonomy and phylogeny of the species, and records of flora. The colours indicate in which area of the world the studies were performed. In the ‘weed’ columns, some studies appear twice, to better describe them both in terms of system (natural, pasture, crop) and focus.

Table S2 Summary of the studies on herbicide effect on *Vulpia myuros*. When several active ingredients where tested in the same class, they were grouped together in one entry, and the full list of tested active ingredients is given as foot notes. A: the herbicide was tested alone, in single application, C: the herbicide was tested in combination with another one, S: the herbicide was tested in a sequence with another herbicide. Head rows: reference of the study, pot or field tests, target species (herbicide tested directly on *Vulpia myuros* alone, or with a crop; clover stands for subterranean clover, wheat stands for winter wheat, rapeseed for winter rapeseed).

Form S1 Excel form template to record and send observations of *Vulpia myuros*.

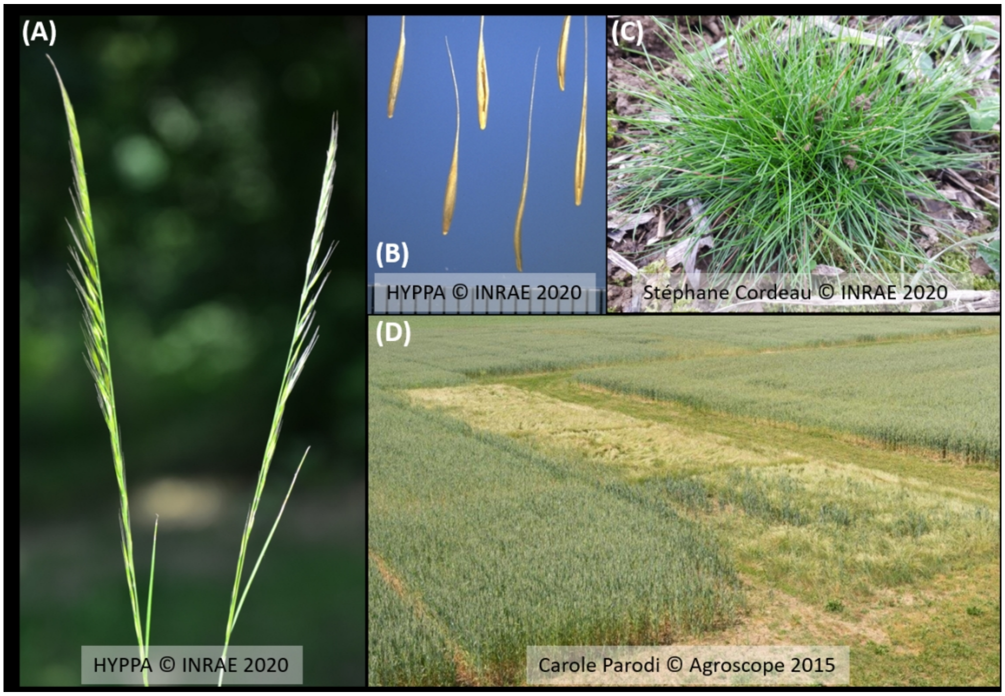
Figure legends

Fig. 1 Illustration of *Vulpia myuros* morphology and stand. (A) reproductive stage (HYPPA @ INRAE 2020) (B) fruits (HYPPA @ INRAE 2020), (C) vegetative stage (Stéphane Cordeau @ INRAE 2020), and (D) invaded wheat field in a no-till treatment in a long term experiment in Switzerland (Carole Parodi @ Agroscope 2015).

Fig. 2 (A) World distribution of *Vulpia myuros*, according to CABI compendium (CABI, 2020), literature records and GBIF database (GBIF, 2020). *Vulpia myuros* is present in the countries indicated in green. The black dots represent individual observations from the GBIF database. (B+C) Climatic map according to Köppen-Geiger classifications for (B) the present days (1980–2016), and (C) the future climate (2071-2100), both from Beck *et al.* (2018), under Creative Common license 4.0. The ovals in (B) represents the main areas of *V. myuros* presence, corresponding to temperate climates (green-yellow colours). The future climate map (C) allows to estimate where *V. myuros* distribution is likely to spread or shrink in the future.

Fig. 3 Illustration of (A) a winter crop cycle compared to (B) the introduction of a spring crop in a rotation, in parallel to *Vulpia myuros* life cycle.

Table 1 Summary of the mode of action and active substances of herbicides tested as successful on *Vulpia myuros*. See Supplementary Table S2 for more detailed information.



HYPPA © INRAE 2020

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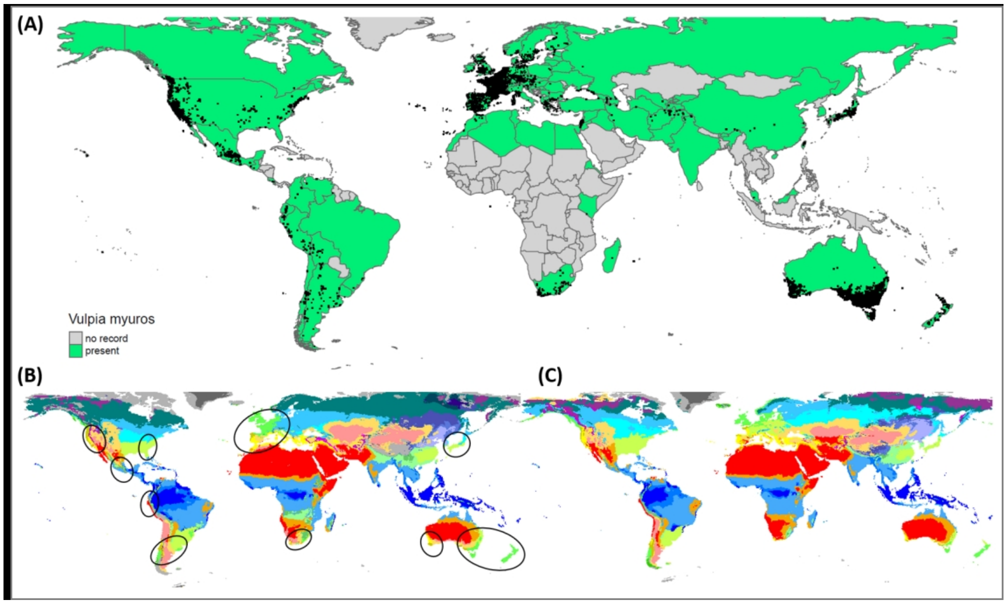
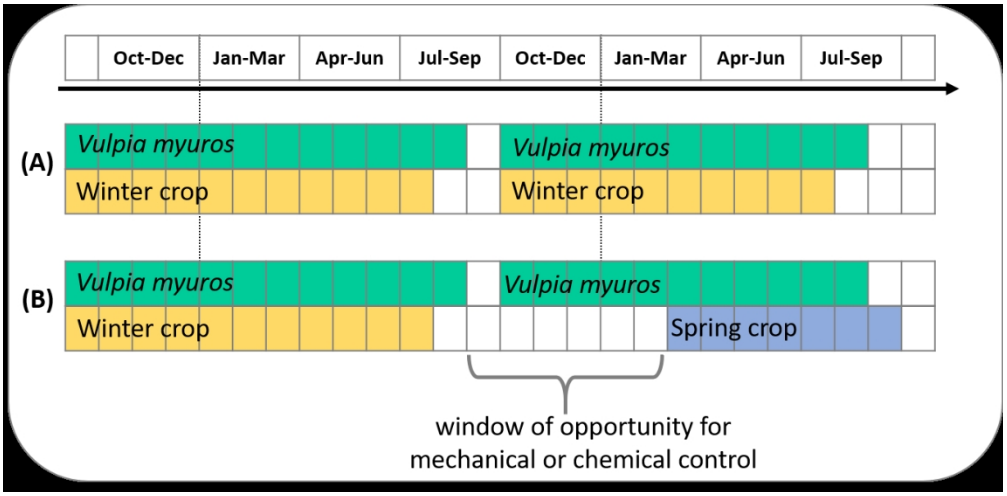
Carole Parodi © Agroscope 2015


(A)
Vulpia myuros
no record
present
(B)
(C)


Oct-Dec
Jan-Mar
Apr-Jun
Jul-Sep
Oct-Dec
Jan-Mar
Apr-Jun
Jul-Sep
(A)
Vulpia myuros
Winter crop
Vulpia myuros
Winter crop
(B)
Vulpia myuros
Winter crop
Vulpia myuros
Spring crop
window of opportunity for
mechanical or chemical control

Mode of action	Site of action	Chemical family
PRE-EMERGENCE		
Photosynthesis inhibitors	Photosystem II inhibitors	Triazinone
Seedling shoot growth inhibitors	Long-chain fatty acid inhibitors	Oxyacetamide
Seedling shoot growth inhibitors	Long-chain fatty acid inhibitors	Pyrazole
POST-EMERGENCE		
Amino acid synthesis inhibitors	ALS inhibitors	Sulfonylurea
Amino acid synthesis inhibitors	ALS inhibitors	Imidazolinone
Amino acid synthesis inhibitors	EPSP synthase inhibitor	Organophosphorus
Photosynthesis inhibitors	Photosystem II inhibitors	Urea
Cell membrane disrupters	Photosystem I electron diverter	Bipyridylium
Seedling root growth inhibitors	Microtubule inhibitors	Benzamide

* Paraquat has been banned from EU since 2007

Active ingredients	**References**
Metribuzin	Lawrence & Burke, 2014
Flufenacet	Ball et al., 2007 / Hull et al., 2011 / Lawrence & Burke, 2014
Pyroxasulfone	Lawrence & Burke, 2014
Mesosulfuron, Sulfosulfuron	Ball et al., 2007 / Hull et al., 2011
Imazamox	Ball et al., 2007
Glyphosate	Jemmet et al., 2008
Diuron	Ball et al., 2007 / Jemmet et al., 2008
Paraquat*	Jemmet et al., 2008
Propyzamide	Hull et al., 2011

Table S1 Chronological sum up of the studies published on *Vulpia myuros*, excluding studies about the taxonomy and phylogeny of the species, and records of flora. The colours indicate in which area of the world the studies were performed. In the 'weed' columns, some studies appear twice, to better describe them both in terms of system (natural, pasture, crop) and focus.

Europe
United States
Australia
New Zealand
Japan
China

	Useful plant		Weed							
	ground cover	revegetation	natural ecosystem	pastures	crops	biology/ecology	management	herbicides	allelopathy	disease host
<1981				genus *Vulpia*						
1981-1985		Kay et al., 1981								
				Dillon & Forcella, 1984		Dillon & Forcella, 1984				
1986-1990				Scott & Blair, 1987		Scott & Blair, 1987		Scott & Blair, 1987		
1991-1995	Meyer et al., 1992			Riley & McKay, 1991		Charles et al., 1991		Leys et al., 1991		Riley & McKay, 1991
				Charles et al., 1991						
				Leys et al., 1991						
				Cocks, 1994	Leys & Plater, 1993			Leys & Plater, 1993		
				Riley, 1995						Riley, 1995
1996-2000	Bugg et al., 1996	Shaw, 1996	Stylinski & Allen, 1999						An et al., 1997	
			Brown & Rice, 2000						An et al., 2000	
2001-2005		Heeraman et al., 2001		Kelman et al., 2003					An et al., 2001a	
				Vere et al., 2003					An et al., 2001b	
				Tozer, 2004		Tozer, 2004	Tozer, 2004			
				Hely & Roxburgh, 2005		Hely & Roxburgh, 2005				
				Loo, 2005		Loo, 2005				
2006-2010	Ishii et al., 2007				Ball et al., 2007	Tozer et al., 2008a	Tozer et al., 2008a	Ball et al., 2007	An et al., 2007	
	Baumgartner et al., 2008				Jemmett et al., 2008	Ball et al., 2008		Jemmett et al., 2008		
	Ishii et al., 2008			Tozer et al., 2008a	Ball et al., 2008	Tozer et al., 2009a				
	Matsumura et al., 2008		Skinner et al., 2009	Tozer et al., 2009a	Jensen, 2009	Tozer et al., 2009b	Tozer et al., 2009b			
	Motosugi & Terashima, 2008			Tozer et al., 2009b	Jensen, 2010	Jensen, 2009				
					Schillinger et al., 2010	Jensen, 2010			Kato-Noguchi et al., 2010	
					Steenwerth et al., 2010					
2011-2015	Ishii et al., 2011				Hull et al., 2011			Hull et al., 2011		
	Cruz & Ishii, 2012			Borger et al., 2012						
					Jensen & Kristensen, 2013					
					Moreau et al., 2013	Moreau et al., 2013				
					Tarasoff et al., 2013	Tarasoff et al., 2013		Lawrence & Burke, 2014		Smiley et al., 2014
					Lawrence & Burke, 2014					
					Smiley et al., 2014					
					Cordeau et al., 2015					
2016-2020		Gómez et al., 2016			Georgescu et al., 2016	Georgescu et al., 2016		Georgescu et al., 2016		
					Scherner et al., 2016	Scherner et al., 2016				
					Moreau et al., 2017	Moreau et al., 2017				
				Piltz et al., 2017	Scherner et al., 2017a	Scherner et al., 2017a				
					Scherner et al., 2017b	Scherner et al., 2017b				
					Büchi et al., 2018	Cordeau et al., 2018				
					Cordeau et al., 2018	Georgescu et al., 2018				
				Ghanizadeh & Harrington, 2019	Georgescu et al., 2018					
		Navarro-Cano et al., 2019		Weller et al., 2019	Jensen, 2019	Weller et al., 2019	Jensen, 2019			
	Xianchen et al., 2020									

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				Scott & Blair, 1987	**Leys et al., 1991**	**Leys & Plater, 1993**	**Ball et al., 2007**	**Jemmet et al., 2008**	**Lawrence & Burke, 2014**	**Hull et al., 2011**			**Mathiassen, 2016[1]**			**ACTA factsheet[2]**	
Mode of action	**Site of action**	**Chemical family**	**Active ingredients**	**Pot lucerne**	**Field clover**	**Field clover**	**Field wheat**	**Field wheat**	**Field wheat**	**Pot vulpia**	**Pot vulpia**	**Pot vulpia**	**Pot vulpia**	**Field vulpia**	**Field red fescue**	**wheat**	**rapeseed**
			PRE														
Photosynthesis inhibitors	Photosystem II inhibitor	Triazinone	Metribuzin						C / S								
Pigment inhibitor	DOXP synthase inhibitor	Isoxazolidinone	Clomazone										A	A			
Seedling root growth inhib	Microtubule inhibitors	Dinitroaniline	Pendimethalin				A / S			A			A				
Seedling shoot growth inh	Lipid synthesis inhibitor	Thioacarbamate	Prosulfocarb							A			A				
Seedling shoot growth inh	Long-chain fatty acid inhi	Oxyacetamide	Flufenacet				A / S		C / S	A			A				
Seedling shoot growth inh	Long-chain fatty acid inhi	Pyrazole	Pyroxasulfone						A / S								
			POST														
Lipid synthesis inhibitors	ACCase inhibitors	Aryloxyphenoxypropionate (fops)	*6-8 active ingredients*			A / C					A		A			A	A
Lipid synthesis inhibitors	ACCase inhibitors	Cyclohexadione	Tralkoxydim								A		A				
Lipid synthesis inhibitors	ACCase inhibitors	Cyclohexanedione (dims)	*2 active ingredients*									A					A
Lipid synthesis inhibitors	ACCase inhibitors	Phenylpyrazolin	Pinoxaden								A		A			A	
Amino acid synthesis inhib	ALS inhibitors	Imidazolinone	Imazamox				A / S										
Amino acid synthesis inhib	ALS inhibitors	Sulfonylaminocarbonyltriazolinones	Propoxycarbazone								A		A				
Amino acid synthesis inhib	ALS inhibitors	Sulfonylurea	*5 active ingredients*				A / S		A		A / C	C	A / C	C	A / C	C	
Amino acid synthesis inhib	ALS inhibitors	Triazolopyrimidine	*2 active ingredients*						A / C / S		C		C			A	
Amino acid synthesis inhib	EPSP synthase inhibitor	Organophosphorus	Glyphosate					A / S			A		A	A			
Growth regulators	T1R1 auxin receptors	Carboxylic acid	Fluroxypyr						C / S								
Photosynthesis inhibitors	Photosystem II inhibitor	Triazine	Simazine		A	A / C											
Photosynthesis inhibitors	Photosystem II inhibitor	Urea	*3 active ingredients*				A / S	C / S								A	
Pigment inhibitor	DOXP synthase inhibitor	Isoxazolidinone	Clomazone										A	A			
Cell membrane disrupters	Photosystem I electron c	Bipyridylium	*2 active ingredients*			A / C		C / S					A	A			
Seedling root growth inhib	Microtubule inhibitors	Benzamide	Propyzamide								A		A	A			A
Seedling root growth inhib	Microtubule inhibitors	Dinitroaniline	*4 active ingredients*							A			A		A		
Seedling shoot growth inh	Lipid synthesis inhibitor	Thioacarbamate	*2 active ingredients*							A			A		A	A	
Seedling shoot growth inh	Long-chain fatty acid inhi	Oxyacetamide	Flufenacet				A / S			A	A	A	A			A	
		Carbamate	Carbetamide		A												A
			SEED COATING														
Lipid synthesis inhibitors	ACCase inhibitors	Aryloxyphenoxypropionate (fops)	Diclofop-metyhl	A													
Seedling root growth inhib	Microtubule inhibitors	Benzenedicarboxylic acid	Chlorthal-dimethyl	A													
Seedling root growth inhib	Microtubule inhibitors	Dinitroaniline	*3 active ingredients*	A													
Seedling root growth inhibitors		Alkanamide	Napropamide	A													
Seedling shoot growth inh	Lipid synthesis inhibitor	Thioacarbamate	EPTC	A													
Seedling shoot growth inh	Long-chain fatty acid inhi	Chloroacetamide	Alachlor	A													
		Organochlorine	2,2-DPA (Dalapon)	A													

A: alone ; C: combined ; S: sequence

Sulfonylurea: Flupyrsulfuron, Foramsulfuron, Iodosulfuron, Mesosulfuron, Sulfosulfuron
Triazolopyrimidine: Florasulam, Pyroxsulam
Bipyridylium: Diquat, Paraquat
Aryloxyphenoxypropionate (fops): Clodinafop, Diclofop (-metyhl), Fenoxaprop-p, Fluazifop-p (-butyl), Propaquizafop, Quizalofop-d-methyl
Cyclohexanedione (dims): Clethodim, Cycloxydim
Urea: Chlortoluron, Diuron, Isoproturon
Dinitroaniline: Benfluralin, Oryzalin, Pendimethalin, Trifluralin
Thioacarbamate: Prosulfocarb, EPTC

[1] Mathiassen, SK (2016). Strategies for control of *Vulpia myuros* . Proceedings on the 7th International Weed Science Conference: Weed Science and Management To Feed the Planet, 2016, p. 543-543

[2] http://www.florad.org/moodle/pluginfile.php/832/mod_resource/content/1/fiche%20vulpie%20FINALE%20compl%C3%A8te.pdf (accessed 15.05.2020)