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1 Introduction

Grasslands, defined here as ecosystems in which graminoids, forbs and shrubs form a relatively continuous herbaceous layer of vegetation (Veldman et al. 2015), cover some 40% of the Earth's land surface, extending over large areas on all continents except Antarctica. The development of grasslands, their species composition and challenges in their sustainable management for production and conservation vary considerably across regions (Olson et al. 2001). In many parts of the world, such as in North America, Central Asia and Sub-Saharan Africa, primary grasslands dominate. These 'old-growth' grasslands (Veldman et al. 2015) often occur where tree growth is limited by shallow soils, low soil moisture availability, low temperature, frequent fires or herbivory by large grazers. While Eastern European steppes are considered to be a climax vegetation, large parts of temperate grasslands in western and central Europe are associated with human activity, and their origin and maintenance are mostly linked to forest clearing and subsequent management such as mowing, grazing by domestic livestock or fire. Due to their anthropogenic origin, these grasslands are called secondary grasslands (Bredenkamp et al. 2002).

While primary and secondary grasslands in temperate zones are often important in terms of biodiversity, the pressure to increase animal production has

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led to grassland intensification by increasing cutting and/or grazing frequency, reseeding, herbicide and fertilizer application, resulting in high-intensification grasslands and a corresponding loss of diversity. In contrast, it is estimated that some 40% of the subtropical and tropical grasslands and savannas in Sub-Saharan Africa are degraded due to overgrazing, fire, climate change or other factors, usually resulting in a reduction of herbaceous vegetation cover and diversity (Le et al. 2016).

Problems with undesirable, weedy plant species are known from all grassland types, but the type of weeds, the nature of the problem and thus options for their management vary considerably (Plate 1). For example, the vast majority of grassland weeds in the Prairies in North America are invasive non-native plants (INNPs), both grasses and forbs that have been brought in as seed contaminants with forage grass species from Eurasia. Weeds in arid and semi-arid savannas of Sub-Saharan Africa vary widely, from space-filling annuals to woody or other non-palatable perennials; they are mostly introduced but are sometimes also native species. In contrast, most grassland weeds in Europe are native plant species that are toxic or unpalatable to livestock; these may benefit from nutrient input and from vegetation gaps due to trampling or other mechanical disturbance.

Until recently, the reliance on herbicides has been high in intensive grasslands in most regions of Europe. In low-yield grasslands in, for example, the northwestern United States or Australia, classical biological control by importing antagonists from the weed's native range has been successfully used for more than 50 years to control INNPs in a relatively cheap and sustainable way. However, the concept of integrated weed management (IWM), that is, the

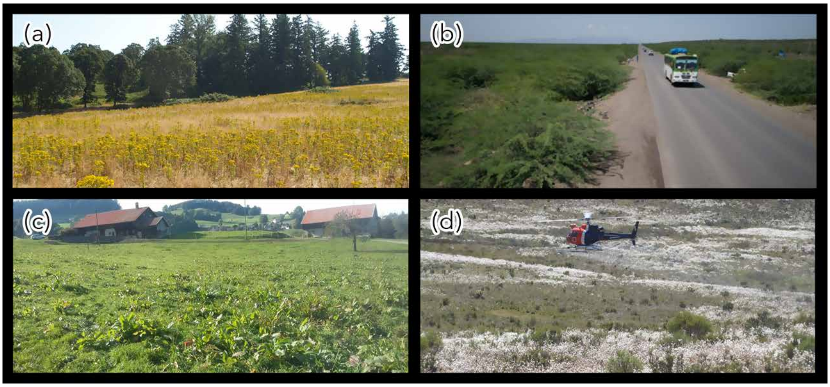

Plate 1 Examples of grassland weeds. a: Tansy ragwort, *Jacobaea vulgaris*, in Oregon, USA; b: *Prosopis juliflora* in Afar region, Ethiopia; c: *Rumex obtusifolius* in Kt Zürich, Switzerland; and d: *Leucanthemum vulgare* in Kosciuszko National Park, New South Wales, Australia. Photo credits: a: Marianna Szucs, b: René Eschen, c: Julie Klötzli, d: Andrew McConnachie.

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combined use of complementary weed management practices, such as grazing, herbicide application, land fallowing or biological control (FAO 2021), remains largely understudied. The evolution of herbicide resistance, environmental concerns regarding the large-scale application of herbicides in grasslands and the fact that weed management strategies based on single control options often fail to manage weeds at the landscape level are likely to foster a truly IWM approach in grasslands across the globe, although the focus on particular components of weed management options may differ among regions and ecosystems. In particular, an IWM approach is considered critical for managing herbicide resistance in weeds (Norsworthy et al. 2012) and may offer options of low-cost, environmentally friendly and sustainable weed management in low-yield grasslands or in protected grasslands.

Here, we describe the current status of IWM for grasslands by adopting a conceptual approach proposed by Kudsk et al. (2020). Its focus is on management practices available to influence transitions

1 from the soil seed bank to seedling establishment;
2 from the seedling stage to the mature plant; and
3 from the mature plant to the soil seed bank.

The latter includes export and import of propagules from and to the grassland as well as selecting well-adapted species/variety/genotype assemblages, when establishing the grassland community (Fig. 1). We thus provide a conceptual approach to illustrate how management practices available in IWM affect different transitions in a weed's life cycle and then provide examples of how weed management practices have been integrated so far. As weed management in grasslands differs considerably among geographic regions and among the type of weed species, we discuss examples of integration of weed management practices from across the globe. We end with an outlook for possible ways to promote increased uptake of IWM in grasslands.

2 The weed management toolbox for grasslands: prevention, cultural, physical, chemical and biological control

While the conceptual approach of IWM outlined in the study of Kudsk et al. (2020) is applicable to all major agricultural systems, weed management in perennial grasslands differs from weed management in annual cropping systems in a number of aspects. First, grasslands tend to form a perennial competitive environment, which, if well managed, only offers a few microsites for weeds to recruit from invading seeds or the soil seed bank (Fig. 1, transition

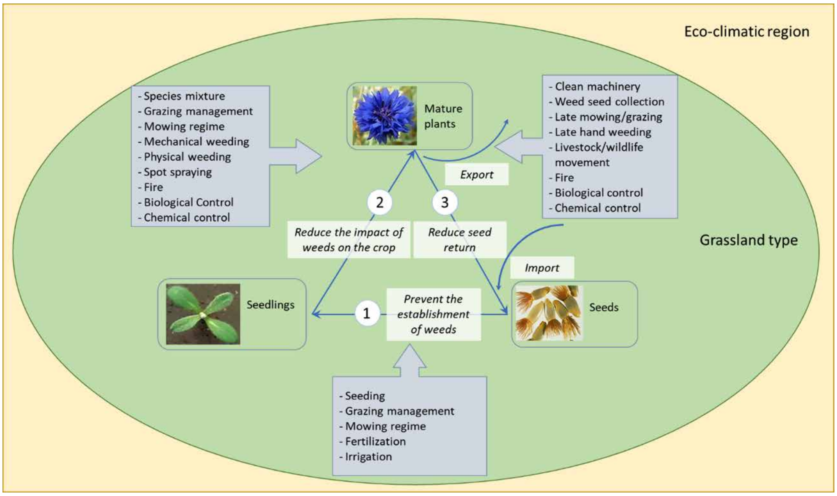

Figure 1 Integrated weed management (IWM) framework for grasslands, consisting of tools that 1) limit seedling establishment in grassland from the soil seed bank or subterranean vegetative organs, 2) limit competition for resources such as light, nutrients and water by removing weeds or reducing their competitive impact, and/or 3) limit return of seeds or vegetative organs to the soil seed/vegetative organ bank or their export to or input from other grasslands. Suitable tools may depend on grassland type and eco-climatic region (adapted from Kudsk et al. 2020).

1). In addition, this competitive environment can affect the whole life cycle of weeds, reducing their growth rate and size (Fig. 1, transition 2) and consequently their seed production or fitness (Fig. 1, transition 3). Secondly, weed problems in grasslands are often caused by one or a few problematic species, while annual cropping systems are confronted with a diverse community of weedy species (Müller-Schärer et al. 2018). Thirdly, grasslands, particularly in semi-arid and arid regions, tend to generate relatively low short-term economic benefits, which sometimes are lower than the costs of chemical weed control (Griffith and Lacey 1991). Thus, weed management strategies in grasslands may be built on different management practices than those in annual cropping systems. In the following sections, we briefly describe individual weed management practices as potential components of IWM, that is, prevention and cultural, physical, chemical and biological control measures.

2.1 Prevention

We understand prevention as any measure that prevents the transfer of weed propagules (primarily seeds) to areas where the weed has not yet established. In the context of INNPs, prevention measures may be implemented at the national border (e.g. control of goods or passengers at the port of entry).

In the case of native weeds or INNPs already established locally, prevention measures include activities that help avoid the transfer of weed propagules from an invaded to an uninvaded grassland. Practices that can prevent invasion of uninvaded grassland include controlled moving of livestock, cleaning of machinery or the use of weed seed-free fodder or seeding material. As most weeds are spread by seed, prevention can be described as the spatial component of the transition from mature plants to the soil seed bank (Fig. 1). Moreover, weed seeds may also be deliberately introduced if the weed species are sold as ornamentals or as components of commercial seed mixtures (Reichard and White 2001).

2.2 Cultural control

The aim of cultural control practices is to establish or maintain a competitive, well-managed sward, an essential component of weed management in grassland. Weed management must therefore be closely linked with adapted grazing management, as overgrazed grassland with an open sward is likely to be more susceptible to weed invasion compared with unstocked or well-managed grassland. On the other hand, undergrazing strongly increases selective foraging by the animal, resulting in a competitive advantage of less-grazed weedy species over heavily grazed forage species. Accordingly, Suter et al. (2007) observed 12 times higher relative risk of *Jacobaea vulgaris* Gaertn. (syn. *Senecio jacobaea* L.) problems in pastures with low stocking rates as compared to well-managed rotational grazing or cutting management.

Besides the prevention measures described above, cultural control measures primarily attempt to reduce the transition from the soil seed bank to the seedling establishment or seedling survival (Fig. 1), but grazing can also be used to reduce growth and seed set of established weeds (e.g. Samuel et al. 2004). Cultural measures include rotational grazing, stabling livestock during wet days to reduce trampling damage, fire, overseeding and restoration of diverse grasslands. In general, multi-species, well-managed swards consisting of species with complementary functional traits have higher biomass production and prevent the establishment of unsown species more effectively than species-poor swards (Connolly et al. 2018; Suter et al. 2017). Fire, which can be used to reduce the transition from seedlings or saplings to adult plants, and reduce the survival and fitness of adult plants, is often used to manage invasive grasses or trees. Other cultural control measures, such as targeted grazing of weeds, also aim to reduce the transition from the seedling to the adult stage as well as to seed set; for example, sheep grazing is used to reduce densities or standing biomass of leafy spurge (*Euphorbia esula* L.), an important grassland weed in the Northwestern United States (Masin et al. 2018).

2.3 Physical control

Physical control measures include manual, mechanical and thermal (e.g., flaming, hot water) practices for weed control in grassland. Manual control comprises the uprooting of plants by hand pulling or using, for example, a spate, a hoe or a garden fork, or by removing the above-ground parts of a plant with an axe or a machete. It may also include ring- and strip-barking of woody weeds. Mechanical control may involve the use of machinery, for example, bulldozers or tractors, and involves, among others, chaining of larger plants, stick-raking or blade ploughing. Mechanical control is often used to remove dense stands of woody weeds but can be expensive and may lead to disturbance of the grassland sward, thereby increasing its susceptibility to re-invasion by the same or other weeds from the soil seed bank.

2.4 Chemical control

Chemical control is the use of naturally occurring or synthesized herbicides that alter the metabolic processes of a weed, so the plant is either killed or suppressed. Post-emergence herbicides, which are applied to weeds after they have emerged, are most frequently used to manage grasslands. Dense infestations with herbaceous weeds are often treated with foliar applications, and low densities are treated with spot spraying of herbicides that selectively control broadleaf species; the advantage of spot spraying is the reduced damage to non-target species, but the cost of application can be high. Chemical control of invasive alien tree species invading grasslands is usually based on foliar application, cut-stump treatment, basal bark treatment or stem injection; the latter two treatments allow selective application of non-selective herbicides with little risk to other plants growing nearby. Herbicides are labelled to indicate which weeds are susceptible to the herbicide, the habitats in which they may be applied, and the appropriate application method.

A major difficulty of herbicide application in grassland is the multi-species nature of the non-targeted grassland sward. This makes it difficult to find a herbicide that is selective enough to only/mainly affect the weed species. It is thus difficult to chemically control unwanted grass species in grasslands that are generally grass dominated. In addition, treating dicot weeds may kill also dicot forage plants, resulting in gaps in the sward that facilitate the establishment of new weed species from the soil seed bank. Finally, herbicide treatments against dicot weed species often also kill leguminous species, which are highly advantageous in grassland systems (Lüscher et al. 2014; Suter et al. 2021). Repeated use of the same herbicide or other herbicides with the same mode of action will favour the development of resistant weed populations, a driving force for the adoption of IWM.

2.5 Biological control

Three methods of biological weed control can be distinguished based on targeted weed, origin of the control agent and the amount of initial inoculum used (Müller-Schärer and Schaffner 2008). These three methods are

- classical biological control;
- inundative biological control; and
- conservation biological control.

Classical biological control (CBC; also called importation biological control) aims to control invasive non-native weeds by the introduction of specialist control organisms, usually insects, mites or fungal pathogens, from the weed's native range. The inundative or bioherbicide method uses periodic releases of an abundant supply of a native or exotic control agent over the entire weed population to be controlled. Such biological agents, generally, are manufactured and registered as biological control products. The third approach, which is called the conservation or system management approach, aims to enhance the effectiveness of resident natural enemies by manipulating their environment to increase their survival or performance.

Grasslands rank among those habitat types with the longest and most successful history of classical biological weed control against non-native weeds (Winston et al. 2014), particularly in regions Europeans emigrated to between the sixteenth and nineteenth century. Several myco-herbicides have been developed against weeds, including members of the genus *Taraxacum*, *Isatis* and woody invasive alien species, but this inundative biological control approach has been hardly applied in grasslands (Table 1; Triolet et al. 2020, Hasan et al. 2021). Similarly, the use of commercial products consisting of herbivorous insects to manage grassland weeds has only been tested in a few cases so far (Vitelli 2000; Hahn et al. 2016).

3 Integrated weed management practices in grasslands

As has been repeatedly emphasized, in the case of grasslands, there is a need to manage the whole plant community rather than just manage individual weed species or populations (Dietl 1982; Grice and Brown 1996). The challenge of weed management in grasslands is to be effective, provide minimal negative environmental impacts and be economically sustainable. While there are examples where CBC of INNPs achieves all of these goals at the landscape scale, sustainable weed management in grasslands often requires an integrated management approach that combines management practices related to one or several transitions of the conceptual model as shown in Fig. 1.

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Table 1 Bioherbicides for use against weeds in grasslands and lawns (Triolet et al. 2020; Hasan et al. 2021)

Agent	Target	Commercial name	Country developed	Year developed/ first registered
Acremonium diospyri (Crand.) W.Gams	*Diospyros virginiana L.*		USA	1960
Alternaria destruens E.G.Simmons, strain 059	*Cuscuta* spp.	Smoulder®	USA	2005
Xanthomonas campestris (Pammel) Dowson, pv. poae	*Poa annua* L.	Camperico™	Japan	1997
Puccinia thlaspeos C.Shub., *'strain woad'*	*Isatis tinctoria* L.	Woad Warrior®	USA	2002
Sclerotinia minor Jagger, strain IMI 344141	*Taraxacum officinale* L.	Sarritor®	Canada	2007
Streptomyces acidiscabies strain RL-1101, non-viable cells	Broadleaf weeds, e.g. *Taraxacum officinale, Senecio* spp., *Plantago* spp.	Opportune™	USA	2012
Cylindrobasidium laeve (Pers.) Chamuris	*Acacia* spp.	Stumpout®	South Africa	2008
Colletotrichum acutatum J.H. Simmonds	*Hakea sericea* Schrad. & J.C.Wendl	Hakatak	South Africa	1999 (not registered)
Pinus radiata D.Don, oil	*Ochna serrulata* Walp.	BioWeed™	Australia	?
Cymobopogon sp., oil	Broadleaf weeds and weedy grasses	GreenMatch EX	USA	?

Promoting an appropriate combination of individual management practices to tackle weed problems in grasslands (and in other habitats) often requires developing context-dependent solutions. For example, in their native range, the build-up of high population densities of *J. vulgaris* in grasslands can largely be prevented by implementing cultural management practices that avoid sward damage from continuous extensive grazing on grassland with low nitrogen fertilization (Suter et al. 2007). In contrast, in their invasive range in North America, cultural management needs to be combined with biological control to achieve long-term control of this weed, as the resident community in the invaded range appears to be less competitive than that in the native range (see above; McEvoy et al. 1993). In a study comparing different combinations of management practices against three different INNPs, Huwer et al. (2005) found a trend towards a more favourable pasture state in all cases when at least two practices were combined in an IWM system. However, the results suggested that the order in which the IWM components should be applied depended on the initial perennial grass content at the study sites. Thus, to assist farmers to maintain healthy pasture systems, the IWM approach must be sufficiently flexible so that selection of practices and the order of the IWM components can be arranged depending on initial grassland conditions and biogeographic and eco-climatic settings (Fig. 1).

The development of IWM strategies should also be based on the management objectives of the invaded grasslands, for example, whether the grasslands should be primarily managed for forage production, wildlife habitat improvement, restoration of native vegetation complexes, or recreational land maintenance (DiTomaso et al. 2006; Firn et al. 2013). To increase forage production and reduce densities of invasive forbs, IWM management in the Northwestern United States sometimes includes overseeding with perennial, competitive European grass species (Miller 2016), a practice that should be avoided in areas managed for wildlife habitat improvement or restoration of native grasslands.

4 Integrating weed management practices: case studies

In the following sections, we discuss strategies to integrate weed management practices in grasslands using case study examples listed in Table 2. We then end the chapter with an outlook on future developments and challenges related to sustainable weed management in grasslands.

4.1 Tackling multiple transitions in the weed's life cycle

A possible way to integrate weed management practices consists of combining a practice that reduces the establishment of seeds from the soil seed

Table 2 Examples of integrated weed management of grassland weeds

Target weed	Region	Type of integration	Agents and substances	Effect	References
Rhaponticum repens (L.) Hidalgo					
Carduus nutans L.	North America	BC/plant competition	*Rhinocyllus conicus* Frölich		Tipping (2001)
Bromus tectorum L.	North America	Grazing/fire	Cattle		Diamond et al. (2012)
	North America	CC/grazing	Sheep		Lehnhoff et al. (2019)
	North America	BC/CC	*Pyrenophora semeniperda* (Brittleb. & D.B. Adam) Shoemaker; imazapic		Ehlert et al. (2014)
Cirsium arvense (L.) Scop	Europe	BC/cutting	*Puccinia punctiformis*		Kluth et al. (2003)
	Europe	BC/CC	*Hadroplontus litura*, *Pseudomonas syringae pv. Tagetis*; glyphosate	synergistic	Sciegienka et al. (2011)
		BC/plant competition	*Cassida rubiginosa* Muller		Ang et al. (1994)
	North America	CC/fertilization	Picloram and 2,4-d	+	Grekul and Bork (2007)
Centaurea s stoebe L.	North America	BC/plant competition	*Agapeta zoegana* (L.); native vegetation		Müller-Schärer (1991)
Centaurea solstitialis L.	North America	CC/fire	Clopyralid		DiTomaso et al. (2006)
Echium plantagineum L.,	Australia	BC/CC/grazing/plant competition	*Mogulones larvatus* (Schultze)	multiplicative	Huwer et al. (2005)
Taraxacum officinale (L.) Weber ex F.H.Wigg.	North America	BC/CC	*Sclerotinia minor* Jagger; 2,4-D		Schnick et al. (2002)
Various invasive alien plant species	North America	Grazing/fire	Cattle		Delaney et al. (2016)
Rosa bracteate J.C. Wendl.	North America	Mowing/CC	Various herbicides		Enloe et al. (2013)
Euphorbia esula L.	North America	BC/fire	*Aphthona nigriscutis* Foudras;	+	Fellows and Newton (1999)
	North America	BC/CC	*A. nigriscutis*		Nelson and Lym (2003)

	North America	BC/grazing	*Aphthona spp.*; sheep	+	Samuel et al. (2004)
	North America	BC/CC	*Hyles euphorbiae* L.; 2,4-D	ns	Lym (1998)
	North America	BC/CC/reseeding	*Aphthona spp.*, imazapic, grasses		Richardson et al. (2008), Joshi (2008)
Ranunculus acris L.	New Zealand	Mowing/BC	*Sclerotinia sclerotiorum* (Lib.) de Bary		Green et al. (1998)
Jacobaea vulgaris L.	North America	BC/plant competition	*Longitarsus jacobaeae* (Waterhouse)		McEvoy et al. (1993)
Onopordum spp.	Australia	BC/CC/plant competition	*Larinus latus* Herbst. *Lixus cardui* Olivier		Huwer et al. (2005)
Opuntia stricta (Haw.) Haw.	South Africa	BC/CC	*Cactoblastis cactorum* (Berg)		Hoffmann et al. (1998)
Mimosa pigra L.	Australia	BC/CC/physical control/ fire	*Acanthoscelides puniceus* Johnson, *Carmenta mimosa* Eichlin & Passoa, *Chlamisus mimosae* Karren, *Coelocephalapion pigrae* Kissinger, *Neurostrota gunniella* (Busck)		Paynter and Flanagan (2004)
Hypericum perforatum L.	Australia	BC/fire	*Aphis chloris* Koch, *Chrysolina quadrigemina* (Suffrian)		Briese (1996)
		BC/plant competition	*Aculus hyperici* Liro	additive	Willis et al. (1998)
Rumex crispus L.	Europe	BC/BC	*Gastrophysa viridula* Degeer; *Uromyces rumicis* (Schum.) Wint.	+	Hatcher et al. (1994)
Rumex obtusifolius L.	Europe	BC/CC	*Gastrophysa viridula* Degeer; asulam	ns	Speight and Whittaker (1987)
	Europe	BC/BC	*Gastrophysa viridula* Degeer; *Uromyces rumicis* (Schum.) Wint.	ns	Hatcher et al. (1994)
		Mowing/fertilizer	Cattle slurry, NPK fertilizer	ns, -	Niggli et al. (1993); Hopkins and Johnson (2002)
Isatis tinctoria L.	USA	BC/CC	*Puccinia thlaspeos* C. Shub.		Phatak et al. (1983)

BC = biological control; CC = chemical control.

bank (transition 1 in Fig. 1) with a practice that kills plants before they start setting seeds (transitions 2 or 3; Fig. 1). McEvoy et al. (1993) could show that establishing a competitive sward to reduce both seedling establishment in combination with biological control by the leaf beetle *Longitarsus jacobaeae* Waterhouse 1858, which kills established plants, had the highest impact on the population dynamics of the European plant *J. vulgaris* in the invaded range in Oregon, United States. Similarly, Grekul and Bork (2007) found a strong synergistic effect of fertilization on the herbicide treatments for *Cirsium arvense* (L.) Scop. control, which was at least partly attributed to enhanced competition from the increase in grass vigour and biomass of the fertilized forage sward. To manage the invasive yellow starthistle, *Centaurea solstitialis* L., DiTomaso et al. (2006) first applied prescribed burning to kill established plants; the efficacy of prescribed burning was significantly increased when it was followed by chemical control, probably due to a decreased recruitment from the remaining soil seed bank.

A combination of practices reducing the performance of established plants and reducing the input of seeds into the soil seed bank also appears promising. In short-lived weeds, this may be achieved by combining practices that target the transitions from the seedling to the adult stage and the transition from the adult plant to the soil seed bank (Huwer et al. 2005). In long-lived weeds, particularly in woody species, both practices may target the adult plants, that is their survival and their reproductive output. For example, mechanical removal of established trees and releases of biological control agents led to the successful control of the tree *Hakea sericea* Schrad. & J.C.Wendl. (Proteaceae), which invaded fynbos and grassland ecosystems in South Africa. The seed-feeding biological control agents reduced seed output by more than 95%, which significantly reduced the weed's population growth rates (Le Maitre et al. 2008). Modelling analyses conducted by Buckley et al. (2004) indicated that the most successful strategy for suppressing the invasive tree *Mimosa pigra* L. involved a combination of herbicide application, mechanical control, burning, a reduction of small-scale disturbances and the use of insect biological control agents.

4.2 Vertical and horizontal integration of weed management practices

The integration of weed management practices can be viewed as a vertical integration of various management practices against a single weed species or as a horizontal integration across different weed species in one crop (Müller-Schärer and Collins 2012). In grassland, horizontal integration mainly involves practices that aim to establish or maintain competitive vegetation that offers as few microsites for weed recruitment or growth as possible. Practices for horizontal integration thus include grazing and mowing practices

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or practices to prevent the import of seeds through machinery or livestock. Vertical integration of weed management practices can be implemented by separating the individual practices spatially or temporally, depending on weed densities or location relative to the invasion front or by fully integrating the different practices locally. For example, Chalak-Haghighi et al. (2008) suggested a combination of chemical control and intensified grazing at low density of *C. arvense*, while mowing in late summer plus chemical control and targeted grazing management techniques at high density of *C. arvense*. Grice et al. (2011) proposed a spatially explicit management strategy against the INNP *Hymenachne amplexicaulis* (Rudge) Nees in Australia that considers the stage of invasion and the assets to be protected. They developed a map that distinguished zones with different management objectives and thus different sets of suitable management practices. The study by Grice et al. (2011) provides a nice example of a spatially explicit management strategy against an INNP, focusing on better local integration of management practices. Paynter and Flanagan (2004) showed that the impact of biological control on the invasive tree *M. pigra* can be maximized by integrating it with other management practices locally, rather than by separating the practices spatially or temporally.

4.3 Integrating grazing and mowing practices in integrated weed management

As overgrazing is one of the main factors promoting problematic weeds in grasslands, integrating grazing/mowing management practices is often key for long-term sustainable weed management in grasslands. For example, Suter and Lüscher (2011, 2012) found that herbicides and mowing once a year reduced the density of *Jacobaea aquatica* (Hill) G. Gaertn. & al. in Swiss grasslands by almost 90% in the short term. However, after 3 years, weed densities had recovered again if no site-adapted mowing or grazing management was implemented, as gap formation in the vegetation and increased availability of light on bare soil facilitate weed recruitment from the soil seed bank. This study exemplifies the primary importance of the soil seed bank in a weed species' life cycle. *J. aquatica* is biannual, meaning that in a stable population every year 50% of the plants die and are replaced by new plants recruited from the soil seed bank. If a herbicide is applied and kills all established weed plants, some 50% of the original population will re-establish in the first year and another 50% in the second year, resulting in the loss of the herbicide effect.

The example of control of *J. aquatica* highlights two important issues:

- For an effective IWP, it is important to know the weed's biology; and
- Preventing the build-up of a large soil seed bank is a key factor for successful and sustainable weed control.

Adjusting livestock stocking rates to or below the carrying capacity and implementing cultural grazing practices such as rotational grazing should be considered in numerous weed management projects on grassland; they also help restoring or conserving ecosystem services such as soil organic carbon stocks or flood protection (Baer et al. 2015). Targeted grazing practices can also increase the efficacy of other weed management practices. For example, leaf beetles of the genus *Aphthona* have been shown to be more effective when used in sequence with livestock grazing than either strategy used alone (Samuel et al. 2004). When contrasting herbicide treatments with environmentally more sustainable management practices, Pywell et al. (2010) concluded that lenient grazing in spring and autumn was sufficient to give long-term control of *C. arvense* in lowland and upland grasslands in the United Kingdom; herbicide wiping was the most effective control measure, but effects were lost rapidly. These examples illustrate the importance of implementing an appropriate mowing frequency or grazing rate as part of IWM in grasslands. One should consider, though, that mowing and grazing may have differential effects on the spacing and genetic structure of grassland weeds and thus affect prospects of other management practices (e.g. biological control; Kleijn and Steinger 2002).

4.4 Weeding with invertebrates and pathogens in combination with other management practices

Specialist invertebrate herbivores or pathogens have been repeatedly used in IWM of INNPs, in combination with either chemical control, physical control, prescribed burning or grazing (Fig. 1; Table 2). For example, Paynter and Flanagan (2004) found that herbicide application, bulldozing and fire alone were not effective in the management of the woody INNP *M. pigra*, but they enhanced the impact of invertebrate CBC agents (Buckley et al. 2004). Importantly, integrating CBC with other management can also significantly reduce management costs (Paynter and Flanagan 2004). While CBC is based on the deliberate introduction of specialist natural enemies to control INNPs, the use of native pathogens to control INNPs has also been considered. For example, Ehlert et al. (2014) proposed a two-pronged approach to control the INNP *Bromus tectorum* L. combining inoculation with the soil-borne generalist fungal pathogen *Pyrenophora semeniperda* (Brittlebank and Adam) Shoemaker with post-emergent application of the herbicide imazapic to limit the invasion of this weed in grasslands of western North America.

In contrast to integrated management of pests, the use of native herbivores has rarely been considered in IWM, neither in inundative nor conservation biological control. *Rumex obtusifolius* L. and other European dock species are problematic grassland weeds in their native range as well as in the introduced range in Australia (Scott and Sagliocco 1991a). For biological control of invasive

Rumex species in Australia, two closely related European clearwing moths, *Pyropteron chrysidiforme (*Esper) and *P. doryliforme* (Ochsenheimer), were examined as potential control agents (Scott and Sagliocco 1991a,b). Ultimately, *P. doryliforme* was released in Australia where it significantly decreased densities of invasive *Rumex* populations (Strickland et al. 2012).

Based on this successful CBC project, a research project has been initiated to assess the feasibility of using *P. chrysidiforme* for inundative BC in the native European range of the insect and the target weed. Based on a field experiment assessing different application techniques, Hahn et al. (2016) proposed that mass releases of *P. chrysidiforme* may be a valuable approach to control *R. obtusifolius* in the native range by biological means. However, the considerable variation in infestation and subsequent impacts detected under experimental field conditions call for long-term studies to assess the full potential and efficacy of *P. chrysidiforme* for inundative BC of *R. obtusifolius*. Intuitively, the development of commercial inundative BC products using native invertebrate herbivores or pathogens (Kluth et al. 2003) and their integration in IWM holds considerable promise, but the proof of concept has yet to be established.

5 Future trends

IWM of weeds in grasslands is based on a good understanding of the biology and population dynamics of the target weed, particularly of site-specific transitions between stages of the weed's life cycle where particular management techniques can be effective (Fig. 1). Furthermore, the composition of the grassland, soil nutrient status and top-down pressure by natural enemies must be considered in IWM. The examples in Table 2, and discussed earlier, illustrate that targeted integration of different weed management practices can help to successfully reduce reliance on herbicides and result in more environmental friendly and sustainable management practices when tackling weed problems in grasslands across the globe. However, because the most suitable IWM strategies are context-dependent, developing new strategies often requires well-designed field experiments, which run for sufficiently long periods to allow community responses to develop. Moreover, successful implementation of IWM in grasslands requires careful planning that includes capacity building among stakeholders, prevention programs and dissemination of validated strategies (Liebman et al. 2016).

In long-term perennial systems like grassland, understanding the competitive ability of the grassland sward relative to that of the weed species is a key factor for long-term success in weed management. The reason for weed dominance in a grassland is that growth conditions may give the weed a strong competitive ability relative to the grassland sward. In such a situation, any intervention that affects the weed only for a short time span – independent whether the measure is of chemical, physical or biological manner – will only treat the symptom but not the fundamental cause of infestation. Several studies show that weeds come back immediately after a short-term control measure stops. To sustainably manage weeds in grasslands, the challenge is to adapt growth conditions in a way that the competitive ability of the grassland sward is increased or that of the weed species reduced or both.

Species composition and productivity of grasslands are linked to climatic conditions. Weed management strategies should therefore take climate change into account, potential warming and the increasing prevalence of extreme weather conditions due to climate change. It has been suggested that such changes may affect population dynamics of weeds by affecting physiological seed dormancy, germination and emergence pattern, morphological characteristics (e.g., tougher plants) and resulting in reduced herbicide efficiency, and thus, their competitive ability and, in turn, the grassland community (Ziska 2016). Climate change is also expected to directly influence herbicide effects via changing herbicide uptake, translocation and metabolism (Varanasi et al. 2016) and to break herbicide selectivity (Jursík et al. 2020). Few studies have investigated such climate change effects, although they create a need for adapted control strategies as part of mitigation planning (Sun et al. 2021). Rapid increases in herbicide resistance have further highlighted the ability of weeds to undergo rapid evolutionary change. This also has been rarely studied so far but most likely does occur with consequences for the distribution, community composition and herbicide efficacy. It remains to be further explored how the recipient communities may also be affected by climate change, either directly (e.g., drought stress) or indirectly (e.g., change in land use), which in turn will affect their susceptibility to or impact on weeds (e.g., Sandel and Dangremond 2012). As a key prediction and observation of climate change is a shift in species ranges, a resilient weed management strategy should also take changes in the composition of desirable grassland and weed species into account (Catford et al. 2019).

The expected accelerated evolution of herbicide resistance under climate change, increased herbicide regulations (e.g., the ban of numerous acting ingredients of herbicides) and a reduction in the discovery of new active ingredients of herbicides are further moving the field from herbicide-dominated weed management to IWM.

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