Using integrated weed management to minimize production and environmental impacts in grasslands: an Australian perspective

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Abstract. This paper reviews the impacts of weeds that threaten either pasture production or native grassland biodiversity values. It then reviews weed management strategies in grasslands to control weeds. We describe differing perceptions of grassland weeds and the associated societal values underlying these perceptions that present challenges for weed management decision making. A short potted history of grassland weed management is presented with some recent examples of long-term effective weed management programs based on biological control. We argue that only integrated weed management based on grazing strategies and where appropriate biological control for high impact alien weeds will lead to effective weed management in grasslands. We also describe current and continuing research challenges for effective weed management in grasslands, including; biological control of grasses, effective IWM strategies in pastures, grazing strategies based on mixed livestock systems, weed management in rangelands and automated approaches using new technologies.

Keywords: Grassland biodiversity, IWM, grazing strategies, biological control, pasture management, invasive alien plants, rangeland management.

Introduction

Weeds have been a feature of grasslands from the start of pastoral agriculture and have become the most costly threat to livestock production after animal disease (Pimentel *et al.* 2010). Pastoral agriculture is generally more extensive (low stocking rates over wide areas) than cropping, because it is more cost effective to run livestock on poorer soil types and in drier climates and the only sensible agronomic use of rangelands (Grice 2000). This lower economic return per hectare in most grazing systems in turn makes costly chemical-based weed control rarely affordable. Even in dairy and high quality beef intensive production systems, where lethal herbicide applications might be economic, grazing management should still the underling basis of weed management. Here as in cropping systems, herbicide resistant weeds are nonetheless an increasing problem (Sindel 2000). The most extensive grazing systems are based on largely native grasslands. However where possible to optimize production, native pastures are "improved" by manipulating composition through addition of high value usually exotic perennial grasses and legumes. This has massively reduced the distribution and extent of native grasslands except on the poorest soils where pasture improvement remains uneconomic (Steffen *et al*. 2009). As such from a biodiversity standpoint many productive native grassland are now threatened ecological communities worldwide and are themselves being increasingly threatened by exotic invasive grassland plants.

In this paper we review the impacts of weeds and weed management strategies in grasslands to control weeds that threaten either pasture production or native grassland biodiversity values. In the following sections we describe differing perceptions of grassland weeds and the associated societal values underlying these perceptions. We then describe in more detail weeds of grasslands and the production and environmental impacts. This is followed by a short potted history of grassland weed management and then some examples of long-term effective weed management programs based on biological control that have more recently been augmented by integrating different strategies. We finish by looking at current research challenges for effective weed management in grasslands.

Weed perceptions

In grasslands weed perceptions are driven by multiple values through the role of grasslands for both animal production and biodiversity conservation. For production systems weeds are species that reduce livestock productivity either through reduced palatability or toxicity or because of a low capacity to provide sustained forage. These weeds include toxic plants, plants that have a low nutrient value or are unpalatable or plants that out-compete more desirable species in pasture systems and include native and exotic species. They include many species across the spectrum from annual herbs to perennial woody shrubs. Indeed forests and scrublands are perceived as weeds in this context given land clearing of trees is a common prerequisite for pastoral agriculture. In the context of grassland biodiversity preservation, weeds are any non-native species that is having a detrimental impact on a native species in that system, covering a broad range of plant types and species. As such, weed perceptions conflict between these two value sets as many highly productive pastoral grasses and legumes are deliberately introduced non-native species selected to increase productivity of local grassland systems for grazing.

The biodiversity benefits from native grasslands represent more of a broad environmental public benefit, while the productivity benefits in pastures are a local economic industry benefit. The associated cultural benefits from native grasslands and the social benefits for local livelihoods from a vibrant pastoral industry add complexity to the values behind weed management decision making.

Weeds of grasslands and their production and environmental impacts

Weeds are both a symptom and cause of grassland degradation. Degraded grasslands allow opportunities for weeds to invade and, once present, the weeds resist re-establishment of desirable species (Friend and Kemp 2000). There is therefore a need to remove the weed "symptom" as well as closing the sward gaps; "the cause". Just controlling the weed will not provide sustainable management.

Grasslands and therefore grassland weeds come in many different forms as grasslands have high agricultural usage and are present across the full range of climates. Native grasslands naturally dominate on low productivity soils and/or in dry/cold climates. Where grasslands dominate on productive soils in wet environments, this is due to water logging, frost prevention of woodland formation or the presence of large grazing herbivores (*e.g.* elephants) to keep woodland formation in check. Most grasslands, however, are now man modified through both the clearing of native tree and scrub layers for pastoral grazing production systems or through the introduction and often encouragement of non-native species. As a consequence human modified grasslands generally experience high levels of disturbance, including grazing pressure, making them more susceptible to domination by disturbance adapted and grazing tolerant weeds. Many of these are exotic grassland plants that have also been introduced or encouraged. Weed types vary with climate and soil conditions and can be either native or exotic.

The tropical savannas are the most extensive grassland type around the world covering vast areas in many variants. Such rangelands include tussock and hummock grasslands as well as arid and semi arid savannas, many of which exist as open woodlands (Grice 2000). Weeds in these systems vary widely from space filling annuals at relatively low grazing pressure through to woody perennials at high grazing pressure. In pastoral situations the woody weeds cause the greatest problems, but toxic herbs can also be important. C4 grasses predominate in such systems as they grow well at high temperatures and low moisture.

In the drier Mediterranean climates with more seasonal rainfall, grasslands are dominated by annual grasses and herbs, including many legumes (Dowling *et al.* 2000). Production weeds in these conditions include most of the annuals as these can be highly competitive, toxic and or gap fillers failing to provide year round forage. In colder temperate higher rainfall conditions pasture weeds tend to be mainly short and long-lived perennials. Many of these are unpalatable or toxic broadleaf weeds often adapted to particular pastoral conditions. For example, invasion by classic pasture weeds like thistles is linked to high soil nutrients and overgrazing in livestock camp areas. High grazing pressure also encourages unpalatable grasses like serrated tussock (*Nassella trichotoma*), but some other grasses also become unpalatable if not actively grazed like African love grass (*Eragrostis curvula*). Loss of the shrub suppressing herb layer to heavy grazing also leads the conversion of grasslands to scrublands.

Environmental weeds in grasslands are any exotic species that displace the native species (Grice 2000). Some impacts are obvious such as the transformation of treeless grasslands into woodlands following the invasion of prickly acacia (*Acacia nilotica*). The impacts attributed to these weeds in rangelands are only starting to be understood and quantified but sometimes the impacts on flora and fauna are obvious (Grice 2000). In native grasslands introduced palatable grasses are also a problem. This is where controversy arises, as beneficial introduced palatable grasses, not considered weeds in pasture situations, can have dramatic impacts on native flora and fauna (Grice *et al.* 2012). When ungrazed, gamba grass (*Andropogon gayanus* Kunth) introduced from Africa for pastoral agriculture in northern Australia builds into thick highly flammable fuel loads that are changing the frequency and intensity of the natural fire regimes causing open savanna woodland to change into near monocultures of gamba grass (Rossiter *et al.* 2003). Similarly buffel grass (*Cenchrus ciliaris* L.) in central Australia is invading relatively undisturbed native savanna communities and also significantly altering species composition, including food plants important to indigenous peoples (Marshall *et al.* 2011). Both these grasses are altering the grass-fire cycle that drives many savanna ecosystems (D'Antonio and Vitousek 1992). Managing widespread invasions of such ecosystem altering weeds into native grasslands is a huge regulatory challenge when in managed pasture systems the same species are valued (Grice *et al.* 2012).

Potted history of grassland weed management

In early pastoral agriculture, native pastures were simply the resource for animal production and their management consisted only of altering stocking rate. In most extensive rangeland areas this is still the case. As pastoral agriculture connected around the world, however, climate-specific high productivity forage species were recognized and introduced into new areas leading to many species that are now common to grazing systems worldwide. This in turn allowed pasture composition to be manipulated for higher production through both the widespread sowing of such high productivity forage mostly exotic species combined with fertilizer application. Such "improved" pastures have lower species composition than native pastures, as the native species are poor competitors on the higher fertility soils (Dowling *et al.* 2000). These highly tailored fertile pastures may show higher productivity, but are also less resilient to droughts. Under harsh conditions and high grazing pressure they degrade quite quickly. This provided an ideal opportunity for weed invasion and many highly competitive pasture weeds responded after having been accidentally introduced around the world, with the movement of livestock and forage species (Mack 2001).

With pastures as mixtures of exotic desirable pasture species and weeds, pastoralists needed to learn how to sustain a productive pasture composition under their local conditions while at the same time reducing weed impacts. This led to a number of approaches. The first was based on moving away from continuous grazing (Friend and Kemp 2000). Deferring grazing to encourage perennial grass growth followed by crash grazing, where high livestock stocking rates are applied for short periods, can reduce weed biomass. Graze-topping, intensely grazing weeds when in flower, can also be effective at reducing seed production. From this rotational or cell grazing (also called time controlled grazing) was developed; applying a short period of high grazing pressure within small fenced paddocks. This has been widely touted as a way of both maximizing pasture productivity while managing weeds (Savory 1983). At high grazing pressure grazing becomes less selective so unpalatable and toxic weeds are as affected as the palatable species by grazing and trampling pressure. In practice this grazing-only approach has only been practically successful for certain types of pasture composition, following low initial weed density and only in intensive managed grazing systems. Poor practice and droughts, when forage is low, still allows toxic, unpalatable and woody weeds to establish and increase in abundance.

As weeds have been moved around the world their impacts on grazing systems have become increasingly evident. Free to proliferate under grazing pressures to which they are perhaps better adapted than native species and usually introduced from their native ranges without their own natural enemies, some such weeds have had massive outbreaks. One of the first such outbreaks was the spread and infestation in Australia over 24M ha grazing country by prickly pear cactus (*Opuntia stricta*) from India in the early 19th century (Dodd 1940). To combat this problem, scientists developed classical biological control as an ecological basis for weed suppression, where the natural enemies specific to the weeds imported from their native range were introduced to suppress the weeds in the invaded range. Such strategies require international research and collaboration to be effective, but the rewards have been substantial in terms of outstanding and long-term control successes. In the prickly pear story, since the introduction of natural enemies of prickly pear into Australia, this weed is no longer a significant weed of Australian pastures as infestations collapsed and have never recovered. Many other pastoral weeds have also been effectively controlled in this way (Julien *et al.* 2012; Coombs 2004).

Only with the availability of herbicides could pasture composition between the desirable and undesirable species be more directly managed. Pasture improvement strategies were based on chemical removal of undesirable weeds and over sowing of desirable pasture species. Although chemical weed management in theory provides a one stop weed management solution, in practice grazing strategies always play a role. Furthermore herbicide costs have prevented widespread use at lethal dose rates in extensively grazed landscapes. Even in highly productive pasture systems, the increasing tide of herbicide resistant weeds is now undermining a simple chemical approach.

In extensive rangelands used for grazing where the impacts come from complexes of many weed functional types, high cost strategies are uneconomic. The complex and heterogeneous semi natural systems found in rangelands are compounded by increasing but often locally occurring native woody plants. There are also many widespread exotic rangeland weeds including prickly acacia, parkinsonia (*Parkinsonia aculeata*), mesquite (*Prosopis* spp.) and rubber vine (*Cryptostegia grandiflora*) and toxic shrubs like belly ache bush (*Jatropha gossypiifolia*) for which biological control programs have been developed. In rangelands, fire is a frequent pasture management tool, especially in the dry season to encourage new perennial grass growth when the rain comes.

The management of weeds in a biodiversity conservation context has had to be based on grassland ecology and an integration of strategies. Management of the exotic species in native grasslands is dependent more on localized use of herbicides to remove or contain exotic weed infestations, combined with biological control to suppress such weeds at a much broader scale.

Examples of long-term effective sustained weed management using biological control

Classical weed biological control remains the only effective means for managing widespread alien invasive plants in grasslands, for the reasons described above. Biological control has a mantra of high risk to agriculture and the environment, because it involves the importation and release of more exotic organisms to control the weed and such releases are largely irreversible. This risk is managed through an internationally recognized process of risk assessment and the use of only very highly specific natural enemies (herbivorous arthropods and plant diseases) as biological control agents. Classical biological control of weeds is a whole research field which we do not have the space to analyze here. Suffice it to say that negative impacts have been rarely harmful (Palmer *et al.* 2010). We will focus here therefore on its history of success in reducing weed impacts in grasslands from both a production and environmental perspective.

Australia has long been a strong proponent of classical biological control of weeds (Palmer *et al*. 2010). Since the first attempts at finding agents for prickly pear, *O. stricta*, as early as 1908 and lantana, *Lantana camara* L., in 1916 there have been several outstanding successes. Substantial and widespread control has now been achieved against a range of grazing productivity impactful weeds including Paterson’s curse (*Echium plantagineum*), nodding thistle (*Carduus nutans*) and docks (*Rumex* spp.) in temperate/ Mediterranean grasslands and rubber vine, spinyhead sida (*Sida acuta*), parthenium weed (*Parthenium hysterophorus*) and groundsel bush (*Baccharis halimifolia*) in subtropical and tropical grasslands (Julien *et al*. 2012). Since 1997 Australia has released 35 biological control agents (including 3 pathogens) against 16 alien invasive non-grass weeds of grasslands. Most weed biological control programs globally have targeted and continue to target grassland weeds and historically these programs were largely against pasture weeds, but are now increasingly against weeds of native grasslands (Van Driesche *et al.* 2010). Active biological control programs against exotic leguminous shrubs of native grasslands, such as giant mimosa (*Mimosa pigra* L.) in flood plain grassland communities of northern Australia and Scotch broom (*Cytisus scoparius* (L.) Link) in upland native grasslands in southern Australia, are examples of this.

Broader effective IWM strategies in pastures

As grazing management is the primary driver of pasture condition more weed control in pastures occurs from grazing than any other weed control method. Combining this with herbicide applications was the first step in integrated weed management (IWM; Dowling *et al.* 2000). However the cost and increasing resistance to herbicides as led to biological control and grazing as the main basis for grassland IWM (Huwer *et al.* 2005). IWM in pastures recognizes grazing strategies will always be part of the mix and this requires producers to understanding pasture composition and the life cycle and growth characteristics and contributions to digestible biomass throughout the year of the dominant pasture plants and target weeds. Most weed management is reactive to the presence of a neglected weed infestation and herbicides are the usual basis of the initial response. However IWM is aimed at a preventative approach of maintaining a sustainable pasture with minimum weed presence that is as far as possible tailoring the actual botanical composition of each paddock. IWM in pastures achieves this by trying to maintain a dense mat of perennial grass. Lower than label rates of herbicide application are also used in combination with crash grazing strategies for undesirable heavy grazing susceptible weeds. Strategic use of fertilizer and other mineral applications, resowing or over sowing with desirable pasture species are also other options available. The effectiveness of an integrated approach is driven more by an understanding of weed ecology than an herbicide "kill rate" approach. This together with biological control has brought plant ecology and grassland community ecology to the fore as the basis of pasture weed management.

Integrated weed management strategies can be very varied and are usually both weed and environment context specific. There are many options for varying grazing pressure in space and time deferring it when weeds are most susceptible to herbicides or when biocontrol agents are most active. IWM has also started to include the complexities of herbicide strategies aimed at reducing the proliferation of herbicide resistance. In general each weed or at least each weed functional type needs to have an IWM strategy developed for it. In general, an adaptive management approach, where different combinations of management options are combined in an experimental way by the farmer until the best IWM strategy emerges, will offer the most likely long-term benefits.

Research challenges

Biological control of grasses

As already mentioned in Australia the worst grassland/rangeland weeds are exotic grasses. Applying biological control to perennial grass weeds is still only a recent development due to historical concerns about risks to cereal crops. To date few agents have been released globally. More research is needed to know whether biological control of grass weeds will be as equally successful as against broadleaf weeds.

More effective IWM in pastures

Dowling *et al.* (2000) stated that "Integration of weed management methods in Australian pastures has not been widely researched, developed and practiced". IWM is increasingly required because of the high costs of re-establishing degraded perennial pastures. Lack of progress in developing effective sustainable pasture management has also resulted in premature weed invasions into resown pastures. Effective strategies need to operate and be profitable under local (and future) climates, relatively simple to apply, biologically and technically feasible, compatible with other farm operations and be able to avert environmental impacts. The problem is to give up short-term lethal herbicide applications for solutions that only provide effective control in the long term and when droughts can delay effectiveness. Herbicide applications need to be combined with competitive species, grazing (deferred, heavy) and alternative livestock types. The other challenge is to incorporate biological control into all of this, especially as it is now proving effective against a number of grassland weeds (Julien *et al.* 2012). Where IWM information is available, it has not been readily taken up by producers. This is because farmers are nervous about applying complex long-term solutions when short-term benefits may be slight. IWM also needs better economic evidence for long term effectiveness given the often short pastoral grazing business cycle.

Grazing strategies based on mixed livestock systems

With grazing strategies recognized as the main mechanism for sustaining good pasture productivity in pastoral systems, there is a need to expand understanding for their use to suppress specific weeds or weed functional types. This will vary with pasture environment (*e.g.* climate and soil type) and the major desirable pasture species present. The key elements are when, how much, and the type of available livestock (Friend and Kemp 2000). As grazing is by its very nature selective, its management requires reducing selectivity against the weed and targeting grazing when the weed (often in the early growth stages or at flowering) will be more impacted than the desirable grasses and legumes. Weed control is also best achieved where it is possible to have mixed stocking systems. Compared to cattle, sheep are less selective and less susceptible to toxic weeds and goats are the most effective against woody weeds. Research is therefore required that develops and optimizes grazing strategies within the context of other requirements of the production system such as the nutrient needs of the livestock.

Weed management in rangelands

Management of weeds in rangelands is still very sporadic. Managing the livestock grazing patterns in these systems is challenging. Furthermore the widespread existence of feral cattle and goat populations and their impacts on native vegetation illustrates the impacts uncontrolled grazing strategies can have for grassland biodiversity. Effective weed management in rangelands requires an ecological understanding of the factors like weed dispersal, competition and disturbance that drive weed abundance.

Vegetation change in rangelands generally results from episodic events such as land use change or good rainfall events rather than from continuous processes, although the impacts of climate change are likely to be a new over-arching continuous driver. The principles have been identified by Grice (2000). There need to be strategies to prevent weed introductions into new areas, including forage grasses known to reduce native species diversity. There is a need for cost efficient ways of detecting new weed infestations. Also strategies are needed for early intervention when weeds appear in a new region at high risk of invasion. Management strategies are also needed that can operate at relevant spatial scales and so this will often require strategies that are relevant for different types of weed, rather than for specific weed species. Rangeland weed management needs to integrate fire as a management tool where appropriate as fire can also exacerbate weed infestations. Given the scale of infestation of weeds in rangelands, weed management strategies must coordinate efforts across properties and different tenures. Biological control, where appropriate should underpin weed management efforts (van Wilgen *et al.* 2013).

Automated approaches

A number of different technological advances are being made in automated agriculture and remote sensing that should assist grassland weed control. Firstly in rangelands electronic capsules implanted to livestock are being used that can remotely control animal movements. This "virtual fence" technology could allow more effective grazing management of weeds in extensive grazing systems. Remote sensing of quite short-term vegetation change in landscapes may also prove useful for both detecting the status of pasture cover for effective pasture management and also as a low cost detection of new weed infestations that will allow weed management to get in early and be more preventative in approach. Other technologies like satellite based geo-location can speed up effective follow up treatments.

Conclusions

In this paper we have presented a rapid overview of weeds and their management in grasslands and offered a few areas where research and development is needed to increase effective control strategies. One of the key strategies is biological control, however this approach is receiving less investment than a decade ago, because of the high initial research start up costs and the long time frames to success (Sheppard *et al.* 2013). Unfortunately effective weed management in grasslands requires investing for the long-term and so it will be increasingly important that such research and development is also supported for the long term outcomes.

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