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Assessment of current weed control methods relevant to the management of the biodiversity of Australian rangelands

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Abstract. The Australian rangelands contain extensive and often dense populations of a wide variety of weed species. An array of techniques is available for effectively controlling many of these. To achieve long-term weed control, weeds should be targeted objectively and the dependence on the use of single treatments such as herbicides and machinery reduced, with greater adoption of integrated methods. The combination of methods will differ if the primary objective within the rangelands is to restore and maintain biodiversity or to improve forage production for domestic and native animals. Revegetation of sites and exclusion of herbivores from weed treated areas is important in establishing species that will compete with invasive weeds. Due to rangelands being sparsely populated, the necessary equipment, skills and finances to use appropriate control options on extensive weed infestations are often lacking, with landholders requiring the assistance of local, state and federal authorities to assist in managing weeds.

Additional keyword: integrated management.

Introduction

Effective weed control, whether to eradicate, contain or suppress weeds to an acceptable level, requires a strategic approach. In recent years, the focus of weed control has increasingly been on using a combination of methods, a concept known as Integrated Weed Management. Entomologists first used the term 'integrated pest management' during the late 1950s in a bid to overcome problems created by the over-reliance on insecticides (Thill *et al*. 1991). Similarly, Integrated Weed Management is a multi-disciplinary approach encompassing chemical, fire, physical and biological methods of weed management, together with an understanding of ecology, effective education and extension of management components. Each weed control method has advantages and disadvantages and, though individual techniques have become more sophisticated in recent years, no single magic wand has emerged as the ultimate tool for effective weed management at a reasonable cost. However, if various control options are implemented and followed up at appropriate times, effective weed control can be achieved. The choice of options will differ depending on whether the objectives are to restore biodiversity, protect specific endangered species or to increase pasture production for livestock.

Though the use of Integrated Weed Management techniques is vital in maintaining biodiversity within rangelands, there are only a few examples in the literature where the impact of effective weed control options on the biodiversity of Australian rangelands is recorded. The objective of this paper is to review weed control methods that are available for rangelands and consider the implications of these methods for the management of biodiversity.

Prevention and early eradication

The most successful, cost-effective weed management strategy is the prevention of new weed infestations. Movement of livestock, produce and machinery are important factors that could contribute to weed invasion in both pastoral and environmental contexts. Large areas of rangelands can be easily protected from weed invasion by taking care in moving animals, machinery, and produce (e.g. fodder and seed) from infested areas to clean areas. Machinery such as slashers should always be cleaned before moving into weed-free areas. Seeds falling on the slasher deck inevitably drop off the deck and are dispersed. Placing fans or a cover over the slasher deck has reduced the number of accumulated seeds to less than one per cent of seed normally collected (Weeds Australia 2004*c*). Feeding produce to stock in a confined area will

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ensure that any weeds present in the produce will be restricted to that area and not spread throughout the property. Livestock brought into a property for the first time should be placed in a confined area for two weeks to allow any viable weed seeds in their digestive tracts to be expelled. Introducing pest animal control programs can also be effective in minimising weed seed spread. Feral animals such as pigs have proven to be key vectors in both short and long-distance dispersal of weeds throughout the landscape (Lynes and Campbell 2000). Controlling weeds before they go to seed will also prevent their spread.

Effective weed management can be a function of the timing of control practices. Delaying weed control normally leads to higher costs and often decreased efficiency. The weeds increase both in density and number, propagules disperse throughout the landscape, accessibility becomes more problematic and control costs increase as the size of the weed plant increases. Eradicating isolated weed infestations is another cost effective weed management strategy. Seedlings and juveniles appear to be the most susceptible life stages to target for control. They are relatively easy to kill and significant reductions in their numbers will reduce the overall weed abundance of the plant (Kriticos *et al*. 1999). Conversely, locating weeds at the seedling stage can be difficult and time consuming and some seedlings may be missed, requiring follow-up control. Targeting weeds for control at a certain height or age before they become reproductive will achieve effective weed control and minimise new seed input into the soil, opening up the possibility of eradication of that weed from the area.

Local, state and federal authorities are developing and encouraging several programs aimed at prevention or early detection and removal of weed infestations. One such program is the National Weed Detection Project currently being piloted in Queensland. The program aims to build a better early weed detection capability in regional Australia through harnessing state and local government officers and community group members in detecting invasive plants and reporting these plants to state and federal herbaria (Cooperative Research Centre for Australian Weed Management 2004). The Department of Agriculture in Western Australia has compiled and regularly updates a list of plants which are known to be invasive in other parts of the world and could pose a threat to Australian rangelands biodiversity (The Nature Conservancy 2006). Under the National Weeds Program, several wash-down bays have been built in several states to encourage motorists who could be transporting weed seed to wash down their vehicles before moving into weed free areas. In some states, a voluntary Weed Hygiene Declaration form (Weeds Australia 2004*b*) has been established to provide individuals with information on whether any product (e.g. machinery, stock, fodder, seeds used for revegetation programs, soil, water, gravel, grain, or vehicles) they receive is contaminated or free of weeds. The receivers can then make informed decisions and, if necessary, take precautions to prevent new infestations. However, declarations are unlikely to be applied to introduced, perennial grasses such as buffel grass (*Cenchrus ciliaris* L.). Introduced perennial grasses often present a serious threat to biodiversity conservation but are considered beneficial for pastoral production. Declaration of such species is unlikely.

Physical and mechanical control

The physical control techniques used against rangeland weeds include hand pulling (annual weeds and tree seedlings), cutting (vines, shrubs, tree saplings and trees), chaining (trees), mowing/slashing (annuals, tree saplings, grasses, shrubs and vines), tilling (annual weeds, shrubs, and tree seedlings) and hoeing (plants regenerating from underground parts). Hand pulling, and grubbing or hoeing are effective at controlling very small infestations when the soil is moist and friable, enabling the entire plant to be removed easily. These techniques can be extremely effective, minimising damage to desirable rangelands plants, but are generally labour and time intensive and must be followed-up in order to deplete the seed reserve.

Mechanical methods used to control trees, shrubs and perennial vines, such as rubber vine (*Cryptostegia grandiflora* Roxb. ex R.Br.), include the use of stick rakes, front and rear-mounted blade ploughs, chains, discs, roller choppers and grubbers. In northern Australia, where most of the rain falls between January and March, the conventional period for weed control using mechanical methods is June–September. Season, soil texture, soil moisture, depth of operation and weed density can affect root suckering and seedling regrowth and influence cost of control. Best results are achieved when soil is wet enough to allow machinery to work with minimum resistance but dry enough for the root system to desiccate.

Large prickly acacia [*Acacia nilotica* (L.) Willd. ex Del.] do not reshoot or regenerate from underground roots after treating with a stick rake with cutter bars attached to the bottom of the tines (Mackey 1997). Effective control of reshooting species is achieved by pulling a horizontal blade through the soil at a depth greater than 20 cm. Parkinsonia (*Parkinsonia aculeata* L.) can be controlled using blade ploughs with either front or back mounted blades (McKenzie *et al*. 2004). Individual plants can be grubbed out with a front or rear blade attached to a tractor, using identical principles to those of a blade plough or stick rake. A grubber minimises soil disturbance, allows individual plants to be treated, and is ideal for treating isolated infestations of woody weeds. Dense monocultures of mature woody weeds such as prickly acacia and mesquite [*Prosopis pallida* (Humb. & Bonpl. ex Willd.) Kunth] can be controlled using chaining. Increased plant mortality can be achieved by double chaining an area, with the second chaining in the opposite direction from the first. With this method, mortality for prickly acacia ranged from 20% for a single application to 90% for a second application (P. L. Jeffrey, pers. comm.). However, chain pulling is ineffective on seedlings and saplings. Cost of mechanical control can vary from $AU20 (double chain pulling or grubber) to $AU96 (stick-raking) per hectare (McKenzie *et al*. 2004).

There is currently a poor understanding of the impact on biodiversity of large-scale use of machinery for the control of dense weed infestations. Mechanical methods, though effective at controlling weeds, may severely damage vegetation, disturb soil, and provide prime conditions for reinvasion by the same weeds or invasion by other species. Conversely, the soil disturbance provides an ideal seed bed for a range of pasture and forb species. Damage to vegetation can be minimised by selecting machinery that is appropriate for the situation based on the scale of the weed infestation, access and native vegetation present. Front-mounted blade ploughs are designed to fit machinery ranging from backhoes to D8 dozers. A backhoe fitted with a front mounted blade plough could operate in species-rich rangelands and selectively remove isolated to medium-density weed infestations with minimal damage to desirable vegetation.

Slashing is an effective technique for controlling annuals and some perennials. The method prevents seed production, reduces carbohydrate reserves, and encourages perennial grasses (DiTomaso 2000). The effectiveness of slashing often depends on the height of the cut, timing of application and species involved. Cutting at ground level will kill 100% of bellyache bush (*Jatropha gossypifolia* L.) irrespective of season, but mortality is reduced to 40% when plants are cut in winter at 10 cm above ground level (Bebawi and Campbell 2002*c*). Spotted knapweed (*Centaurea maculosa* Lam.), on the other hand, can be effectively controlled (85% mortality) when slashed in autumn when the plants are flowering (Rinella *et al*. 2001). Even repeated slashing will not control St Barnaby's thistle (*Centaurea solstitialis* L.), which has profuse basal branching (DiTomaso 2000). Combining slashing and herbicide application can increase the level of control of some species (Henson *et al*. 1996, 2003).

Biodiversity management influences mechanical control of weeds by restricting some options (for example chaining). However, some deleterious effects to biodiversity will be experienced irrespective of the mechanical control option selected. Nevertheless, mechanical control can be effective, including in areas important for conservation where other options are limited. For example, honey mesquite (*Prosopis glandulosa* Torr.) that had been mechanically treated using a blade plough increased its canopy cover from 0 to 21.9% (mean of 1.1% per year) over a 20-year period. In contrast the canopy of an untreated dense mesquite infestation increased from 14.6 to 58.7% over the same period (mean of 2.2% per year) (Ansley *et al*. 2001).

Though mechanical treatments can be effective, like all other control methods, follow-up action is essential for long-term weed management. Resources must be allocated for follow-up work (e.g. treat regrowth) before beginning a mechanical control program if the initial control work is not to be wasted. Treating a smaller dense area will provide information on its costs and benefits. This will give a more accurate indication of how much area can be realistically cleared at a time and will aid in planning future control activities. Rehabilitation of vegetation following mechanical treatment will help reduce the re-establishment of weeds.

An important issue influencing weed management options in rangelands is the fact that mechanical methods are constrained by tree clearing legislation and gazetted Acts of the state or territory in which mechanical control is being carried out. The purpose of each of the state Acts is to regulate the clearing of native vegetation, preserve 'endangered' or 'of concern' regional ecosystems, maintain vegetation cover and biodiversity, avoid land degradation, reduce salinity and soil erosion, and maintain water quality in catchments. These constraints can influence biodiversity management and the mechanical options used. For example, in Queensland, restrictions apply to the mechanical control of weeds in riparian habitats. Buffers of 200 m each side of rivers, 100 m each side of creeks, 50 m each side of gullies and 50 m, where possible, around wetlands, lakes or springs are imposed. Permits are required to use mechanical control elsewhere in a riparian habitat. In South Australia, if damage to native vegetation is anticipated a vegetation clearance approval is required irrespective of land tenure or land type. The control of riparian woody weeds is more difficult and costly if mechanical control is to be excluded from riparian areas, particularly when a weed has formed dense thickets and is the dominant species.

Fire

Fires are important in maintaining plant diversity by creating space and recycling nutrients bound up in above ground tissue (Stafford Smith and Morton 1990). Plant species persist through fire in different ways: by resprouting from unburnt tissue, establishing from a seed bank or by dispersal from unburnt patches (Griffin 1984). Many native plants have mechanisms to deal with fire, giving land managers a degree of flexibility in maintaining biodiversity while managing weeds. Plants in riparian areas and the associated stream biota however, are sensitive to fires, regardless of fire intensity (Andersen *et al*. 2005). In general, fire frequencies of one every 3–5 years will maintain biodiversity in rangelands (Dyer *et al*. 2001). Less frequent fires allow many weed species to grow sufficiently large to be tolerant of fire, while too frequent fires with low fuel loads will have little effect on weed populations (Dyer *et al*. 2001). No fire regime will control weeds without some elements of the biodiversity increasing while others decrease. Anecdotal evidence indicates that, in many areas of Australian rangelands, an increase in exotic woody weeds has been associated with reduced fire frequency and/or intensity. Major weed germination events occur during relatively infrequent, above average wet years and a lack of fire allows the resultant weed seedlings to survive (Freckleton 2004). This has been associated with a corresponding decline in biodiversity (Freckleton 2004).

The number of woody weeds killed by burning depends on the species present, the age of the plant and the density of the infestation (Grice and Slatter 1997). However, the response of a particular species may vary considerably depending on the fire regime adopted. For example, many woody weeds will regrow from original stems or from the stump following a sublethal fire. Fire intensity itself is dependent on environmental factors such as air temperature, wind, relative humidity, fuel composition and quantity. From a series of winter burning trials conducted in north Texas, Ansley *et al.* (1998) concluded that varying fuel type, moisture content and quantity, air temperature and relative humidity affected above ground kill (top-kill) of honey mesquite. Mesquite top-kill increased with increasing amounts of fine fuel, decreasing fuel moisture content, increasing air temperature and decreasing relative humidity. However a series of burning trials (hot and cool burns) conducted on mesquite during winter and summer over a five-year period resulted in <5% total mortality of mesquite (Ansley and Jacoby 1998). The above ground biomass of kangaroo grass (*Themeda triandra* Forsk.), a species often managed by regular burning in wetter temperate and tropical zones (burnt in the late dry season), was significantly reduced after burning, compared with unburnt control plots 2.5 years after burning (Bennett *et al*. 2003).

Prescribed fires could be used in years when there is sufficient fuel to carry the fire and produce the desired control level. In drier rangelands, fire may be possible only following several years of above-average rainfall. In grazed areas, the link between total grazing pressure and fuel load is important. Feral herbivores can deplete available fuel and in pastoral situations it may be necessary to exclude stock before and after a burn. When heavy grazing follows fire, post-fire plant composition may be altered to the detriment of palatable species (Suijdendorp 1981). Soft spinifex (*Triodia pungens* R. Br.) was found to disappear from the Pilbara region after fire and heavy grazing (Craig 1999). Teague *et al*. (1997) also found that under continuous grazing, most rangelands in Texas could not support a burning program to control mesquite, as fuel was insufficient or too patchy to effectively control this species. Nevertheless, the direct costs of fire are lower than those of alternative control techniques such as chemical application or mechanical clearing.

Woody weeds are most easily killed by fire when they are young. High mortality of seedlings of most species is achievable if burnt (fuel loads greater than 2500 kg/ha) during the first 2 years after germination or when less than 30 cm high. In contrast, a large proportion (90%) of even small chinee apple (*Ziziphus mauritana* L.) plants will survive fire (Grice 1997). Mortality of mature woody weeds varies with species. For example, mortality of mature chinee apple (Grice 1997), rubber vine (Grice 1997) and mesquite (*Prosopis pallida*) (Campbell and Setter 2002) was 0, 45 and 93%, respectively.

When undertaking a burning program to control woody weeds, one will need to consider the potential damage to desirable vegetation. The timing of a prescribed burn is critical in this regard. Burns will be more effective if they are undertaken after seed dispersal and senescence of desirable grasses and before seeding of the target weeds. In pastoral rangelands, the interaction between fire and livestock grazing is important for the management of biodiversity. Rest from grazing during the first post-fire wet season is likely to benefit many native plant species. It will assist the establishment of vegetation cover and provide opportunities for grasses to set seed (Letnic 2004). If healthy stands of perennial grasses are allowed to establish, they will compete for moisture with woody weed seedlings, reducing the likelihood of weed establishment during the first or second season after fire.

A single fire will not control woody weeds. Repeated fires or the integration of fire with other control options such as mechanical, chemical or biological control are generally required. In some cases, fire may be used as an initial control technique which will also improve access for future weed control and surveillance. For example, a hot fire will kill a large percentage of rubber vine plants after which secondary techniques such as slashing, chemicals or a second fire can be used to control survivors. Rubber vine mortality increased from 32% after a first late season (November) fire to 86% after a second fire (Bebawi and Campbell 2002*a*). Similarly, an initial fire killed 76% of bellyache bush plants while a second fire a year later extended the kill to 92% (Bebawi and Campbell 2002*b*). Alternatively, fire can be used as a secondary treatment to control seedlings where mature plants have been treated by mechanical or chemical means.

On a very small scale, weeds can also be targeted individually via direct heat through the use of flame burners rather than by using broad-scale fires. The technique allows individual plants to be burnt without consuming grass as a fuel or damaging native plants. The equipment consists of a nozzle gas-phase burner with propane as the fuel pressurised to ~200 kPa. The effect of flaming depends on several factors including temperature, exposure time and energy input. Temperatures up to 800°C were recorded on bellyache bush, parkinsonia and rubber vine plants with exposure times of over 60 s (Vitelli and Madigan 2004). A 10 s treatment was sufficient to achieve 90% mortality of bellyache bush and 80% mortality of parkinsonia (Vitelli and Madigan 2004).

Some of the introduced African grasses such as gamba grass (*Andropogon gayanus* Knuth.) and mission grass (*Pennisetum polystachion* (L.) Schult.) are altering the structure, composition and habitat of native plant communities. Rangelands invaded by these grasses have fuel loads three to five times greater than those dominated by native grasses. The higher fuel loads are supporting fire intensities three to eight times greater than those recorded in rangelands dominated by native grasses (Rossiter *et al*. 2004; Douglas *et al*. 2004). These changes are likely to have serious negative long-term consequences for the biodiversity of some rangeland areas, favouring species that are tolerant of hot fires.

Grazing management

In pastoral rangelands, weed management must be closely linked with total grazing management, involving both livestock and feral herbivores (such as rabbits, camels, horses and donkeys). Rangelands degraded by grazing are likely to be more susceptible to invasion by at least some weed species compared with unstocked or well managed pastoral rangelands. A study in the Victoria River District of the Northern Territory demonstrated that annual grasses and forbs established within 5 years inside enclosures on predominately bare red calcareous loam soils. Maintaining a light to moderate grazing level (when compared with heavy grazing) increased the proportions of perennial grasses and prevented the establishment of calotrope [*Calotropis procera* (Aiton) Aiton f.] (Bastin *et al*. 2003). In contrast, the complete exclusion of grazing animals for 20 years on scalded claypans did not enable recolonisation of perennial grasses unless the surface was modified (Silcock and Beale 1986). Gardiner (1986*a*, 1986*b*) showed that complete exclusion of native and feral herbivores was necessary to substantially increase desired perennial plant species. The provision of additional livestock watering points in dry Australian rangelands is resulting in a decrease in plant species richness and an increase in weed species with increasing proximity to the watering points (James *et al*. 1999; Landsberg *et al*. 2003). Increasing the number of watering points in arid rangelands is likely to lead to certain native species being reduced to very small populations that are scattered across the landscape.

A competitive, healthy well managed ground layer is recognised as an essential component for long-term weed control in rangelands. Control of native and feral herbivores can substantially reduce total grazing pressure and soil disturbance, resulting in a less favourable environment for unpalatable invasive species. Sound total grazing management can be used to encourage desirable species and reduce weed establishment, growth and spread. This will vary greatly from one rangeland type to another and will also depend upon the management history of the rangelands and the weeds present. For example, bellyache bush growth rates and time to reproductive maturity have been significantly reduced and delayed by competition from herbaceous species (F. F. Bebawi, pers. comm.). Bellyache bush takes about 4 months to reach reproductive maturity when growing on bare soil, but up to 2 years in the presence of a healthy ground layer. In contrast, honey mesquite (*Prosopis glandulosa* var. *glandulosa*) invasion in grasslands is minimally influenced by grass competition, and an effective fire regime is crucial for its control (Brown and Archer 1999).

Grazing by livestock, including cattle, sheep, goats and camels, has also been used to control weeds, although this practice may exacerbate some weed problems. A heavy stocking rate of goats (3–4/ha) in western Queensland caused the death of 68% of prickly acacia trees within browseable range (Cobon 1996). Camels have been introduced to several northern Australian properties to control prickly acacia and parkinsonia. The camels browse the weeds, reducing both above ground biomass and seed production (J. R. McKenzie, pers. comm.). No conclusive results are at hand to date. Further studies are also needed to quantify if stocking goats and camels to control unpalatable woody weeds will increase the risk of pasture and soil degradation from overgrazing and lead to off-target damage to native species from browsing. Cattle properties in the USA are incorporating sheep in their enterprises to economically control leafy spurge (*Euphorbia esula* L.) (Bangsund *et al*. 2001).

Land management in conservation and recreational areas also requires input of resources to control weeds and other species. Where resources are insufficient pest species are likely to reinfest. Independent of land tenure, resources are required for on-going weed management. Conservation reserves are vulnerable to weed invasion due to heavy visitation loads by people from outside the immediate area, potentially introducing weeds.

Chemical control

Herbicides are a primary method of weed control in most rangeland situations. Generally, herbicides operate by disrupting plant growth. Before an agricultural or veterinary chemical product can be sold, supplied, distributed or used in Australia, it must go through a rigorous assessment process operated by the Australian Pesticide Veterinary and Medical Authority (APVMA) to ensure that it meets high standards of safety and effectiveness. Herbicides are labelled to indicate which weeds are susceptible to the herbicide, the appropriate application method and any withholding period, if applicable, for crops or other products that could come into contact with the herbicide. Labels also describe situations in which the herbicides may be applied. 'Rangeland' is not a situation that appears on any herbicide label, though several situations where herbicides can be used are located within rangelands. The following are examples of how such situations are described (Australian Pesticide and Veterinary Medicines Authority 2002).

- Agricultural non-crop areas – includes land associated with farmland but not used for regular cultivation and/or grazing.

- Aquatic areas – includes irrigation channels, streams, lakes, dams, and drainage ditches.
- Bushland/native forests – includes natural forest areas used for recreational/scenic purposes, and national parks.
- Commercial forests – includes plantations grown specifically for timber production.
- Fallow land.
- Native pastures.
- Non-crop areas – includes areas of land not being used or intended to be used for cropping or grazing. These include areas around farm buildings, along fences and roadsides, rights-of-way, storage areas and wastelands.
- Ornamentals.
- Pastures – forage grown specifically for the purpose of being grazed by, or fed to, livestock. Pastures include lucerne, medics, clovers and grasses, whether for grazing or seed crops.

There are no chemical recommendations for over half of the 92 taxa listed as threats to rangeland biodiversity (Table 1) (Martin *et al.* 2006, this issue). For four species (*Calotropis procera*, *Tamarix aphylla* (L.) Karst, *Thunbergia grandiflora* Roxb, and *Thunbergia laurifolia* Lindl.), the herbicide registrations have expired or have not been renewed on label updates. For a further three weeds [*Asphodelus fistulosus* L., *Datura ferox* L., and *Hyptis suaveolens* (L.) Poit] herbicide registrations are not applicable to rangelands situations. In Australia it is illegal to use a product for a purpose for which it is not registered unless an off-label permit has been obtained.

Herbicides commonly used to control rangeland weeds include 2,4-D (2,4-dichlorophenoxyacetic acid), dicamba, glyphosate, metsulfuron, picloram, tebuthiuron and triclopyr. An effective herbicide and an economically optimum dose must be determined for each weed species. In rangelands, herbicides are applied by several methods including ground or hand-held applications for low to medium densities and by helicopter or fixed-wing aircraft for large dense infestations where access to other control options is limited. The cost of herbicides often influences a land manager's decision as to which active ingredient to select when controlling a weed species, particularly when several herbicides are registered for that weed. The cheapest herbicide mix may not always be the most cost-effective herbicide to apply in the long-term.

The decision of which herbicide to select should also consider environmental and ecological factors. Herbicide application methodology can be adapted to minimise off-target damage. For example basal bark application, cut stump, stem injection, and side winder (drill and fill) are all methods that enable spray operators to target individual plants. Bridal creeper [*Asparagus asparagoides* (L.) Druce] has been the target of an eradication program in Kings Park, Western Australia since 1991 (Meney *et al.* 2002). By utilising the herbicide metsulfuron (a broadleaf herbicide) as a foliar spray a 100% reduction in the above ground biomass of bridal creeper was achieved with minimal off-target damage, in a control program that focused on preserving biodiversity richness. Other application methods such as soil applied herbicides and foliar application may be less selective techniques for use in biodiversity conservation. Spot spraying individual weed plants can reduce damage to off-target species but the cost of application may be greater and it is generally not feasible to treat extensive rangelands in this way.

Weeds vary greatly in their susceptibility to different herbicides. Herbicide performance is affected by methods of application, concentrations and the addition of surfactants, and is reduced by inadequate herbicide spray coverage, moisture-stressed plants, fruiting plants, high ambient temperatures ($>35^\circ C$), and plants infested with biological control agents (for example, leaf feeders or rust). Season can also influence herbicide activity. The herbicides glyphosate, fluroxypyr, dichlorprop and metsulfuron applied to lantana (*Lantana camara* L.) (Helidon White biotype) in south-eastern Queensland were most effective between December and April (Swarbrick *et al.* 1995). Though the use of herbicides is often criticised, chemicals often provide the most cost-effective means of managing small weed infestations.

Herbicides seldom provide long-term control of weeds when used alone, and often, combining herbicides with other control methods improves weed control. The application of broadleaf herbicides plus the sowing of grass seeds controlled 66–93% of the treated Russian knapweed [*Acroptilon repens* (L.) DC.], compared with only 7% weed control when the herbicides were used in isolation (Benz *et al.* 1999). However, herbicide control of weeds can last for several years. In a study of control of honey mesquite (*Prosopis glandulosa* Torr.) the herbicide treatment effect was 20 years for a root applied herbicide and 10 years for an aerially applied herbicide (Ansley *et al.* 2004). It generally takes non-target species longer to recover from application of a root-applied herbicide than from aerially applied herbicides.

Within any population of weeds there are potentially a few individual plants genetically able to resist the action of herbicides that have a certain mode of action. If even a few plants survive, they may set seed that can subsequently germinate to produce plants containing the herbicide-resistant gene. Repeated use of the same herbicide or other herbicides with the same mode of action can result in the development of a resistant population of weeds and consequent herbicide failure (Powles *et al.* 1997). An example of this is the development of herbicide-resistant annual ryegrass (*Lolium rigidum* Gaudin), a weed widespread across areas of intensive crop production in southern Australia. Annual ryegrass shows resistance to herbicides of most modes of action including Group A (lipid biosynthesis inhibitors, e.g. haloxyfop), Group B (branched

Table 1. Australian rangeland weeds that pose a threat to biodiversity that are without a chemical registration (adapted from Martin *et al*. 2006)

Family	Tribe	Species	Life cycle
Acanthaceae	Barlerieae	*Barleria prionitis* L.	Shrub-perennial
	Brillantaisieae	*Brillantaisia lamium* Benth.	Herb-perennial
	Thunbergieae	*Thunbergia grandiflora* Roxb.	Vine-perennial
		Thunbergia laurifolia Lindl.	Vine-perennial
Agavaceae	Agaveae	*Agave americana* L.	Shrub-perennial
		Agave sisalana Perrine ex Engelm	Shrub-perennial
		Agave vivipara L.	Shrub-perennial
Amaranthaceae	Gomphreneae	*Gomphrena celosioides* Mart.	Herb-annual or perennial
Anacardiaceae	Rhoeae	*Schinus molle* L.	Woody-perennial
Apocynaceae	Plumerieae	*Cascabela thevetia* H. Lippold	Woody-perennial
Asclepiadaceae	Calotropidinae - subtribe	*Calotropis procera* (Aiton) W.T. Aiton	Woody-perennial
		Calotropis gigantea (L.) W.T. Aiton	Woody-perennial
Asteraceae	Aeschynomeninae - subtribe	*Aeschynomene brasiliana* DC.	Herb-perennial
		Aeschynomene paniculata Willd. ex Vogel	Herb-perennial
	Centaureeae	*Centaurea maculosa* Lam.	Herb-biennial or perennial
		Centaurea nigra L.	Herb-perennial
	Cichorieae	*Hieracium caespitosum* Dahlst	Herb-perennial
	Crupineae	*Crupina vulgaris* Pers. ex Cass.	Herb-annual
	Scolyminae	*Scolymus maculatus* L.	Herb-annual
	Xanthieae	*Xanthium occidentale* Bertol.	Herb-annual
Cactaceae	Paniceae	*Pennisetum setaceum* (Forssk.) Chiov.	Graminoid-perennial
Convolvulaceae	Cuscuteae	*Cuscuta planiflora* Ten.	Vine-annual or perennial
	Ipomoeeae	*Ipomoea indica* (Burm. f.) Merr.	Vine-annual or perennial
Crassulaceae	Umbiliceae	*Bryophyllum daigremontianum* A.Berger × *Bryophyllum delagoense* (Eckl. & Zeyh) Schinz	Forb-perennial
Euphorbiaceae	Jatropheae	*Jatropha curcas* L.	Woody-perennial
Fabaceae	—	*Proboscidea louisianica* (P. Mill.) Thellung	Herb-annual
	Cassieae	*Senna occidentalis* (L.) Link	Herb-annual or perennial
		Senna tora (L.) Roxb.	Herb-perennial
	Stylosanthinae - subtribe	*Stylosanthes scabra var. seca* Vog.	Shrub-perennial
Meliaceae	Azadirachteae	*Azadirachta indica* A. Juss.	Woody-perennial
Mimosaceae	Acacieae	*Acacia catechu* (L. f.) Willd.	Woody-perennial
		Acacia curassavica (Britton & Killip) Stehle	Woody-perennial
		Acacia karroo Hayne	Woody-perennial
Oleaceae	Ligustreae	*Ligustrum sinense* Lour.	Woody-perennial
Papaveraceae	Argemoneae	*Argemone mexicana* L.	Herb-annual
Pedaliaceae	Eupatorieae	*Praxelis clematidea* (Griseb.) R.M. King & H. Rob.	Herb-annual or biennial
Poaceae	Andropogoneae	*Andropogon gayanus* Kunth	Graminoid-perennial
		Hyparrhenia rufa (Nees) Stapf	Graminoid-annual or perennial
		Themeda quadrivalvis (L.) Kuntze	Graminoid-annual
	Paniceae	*Echinochloa polystachya* (H.B. & Kunth) Roberty	Graminoid-perennial
		Pennisetum polystachion (L.) J.A. Schultes	Graminoid-perennial
	Sporoboleae	*Sporobolus fertilis* (Steud.) Clayton	Graminoid-perennial
		Sporobolus jacquemontii Kunth	Graminoid-perennial
		Sporobolus natalensis (Steud.) T. Durand & Schinz.	Graminoid-perennial
		Sporobolus pyramidalis P. Beauv.	Graminoid-perennial
		Sporobolus africanus (Poir.) Robyns & Tournay	Graminoid-perennial
	Stipeae	*Achnatherum caudatum* (Trin.) S.L.W. Jacobs & J. Everett	Graminoid-perennial
Sapindaceae	Koelreuterieae	*Koelreuteria elegans* ssp. *formosana* (Seem.) A.C. Sm.	Woody-perennial
Solanaceae	Datureae	*Datura ferox* L.	Herb-annual
Tamaricaceae	Tamariceae	*Tamarix aphylla* (L.) H. Karst	Woody-perennial
		Tamarix ramosissima Leded.	Woody-perennial
Tiliaceae	Grewieae	*Grewia asiatica* L.	Woody-perennial
Verbenaceae	—	*Gmelina elliptica* J.E. Sm.	Shrub-perennial
	Pereskieae	*Pereskia aculeata* P. Mill.	Woody-perennial
Zygophyllaceae	Peganeae	*Peganum harmala* L.	Shrub-perennial

chain amino acid biosynthesis inhibitors, e.g. metsulfuron) and Group M (inhibitors of aromatic amino acid biosynthesis, e.g. glyphosate) herbicides (Powles *et al*. 1998; Pratley *et al*. 1999). To date, no herbicide-resistant weeds are known to occur in Australian rangelands. However, there are concerns over the repeated use of metsulfuron, a Group B herbicide, used to control parthenium (*Parthenium hysterophorus* L.) in pasture. To minimise the risk of developing herbicide-resistant parthenium plants, metsulfuron should be rotated with 2,4-D (Group I herbicide). Since 1997, all herbicide labels in Australia have displayed a letter denoting the mode of action of the active ingredient. This labelling is part of a strategy to manage herbicide-resistant weeds. Rotating between different herbicide groups is one of the keys to preventing or delaying resistance.

Biological control

Classical biocontrol involves the introduction of agents (insects or microorganisms) from the area of origin of the introduced weed. When little is known about a weed and its natural enemies, the research required to implement classical biological control using insects has taken up to 13 years (Andres 1977). Successful biological control results in the abundance of the weed being reduced to a level where it no longer constitutes a problem or causes economic loss (Harley and Forno 1992). The agents can have this impact directly, or can stress the plant, making it more vulnerable to other forms of control such as fire. The agents may maintain this situation indefinitely with little or no further expense or input of labour. Biological control is particularly suited to control of perennial weeds in rangelands, while annual weeds often require the rearing of massive numbers of insects for multiple releases on a seasonal or annual basis. Most biological control programs commence when conventional forms of weed control are too costly. At this point, the weed is normally widespread, has formed dense infestations and is impacting on biodiversity. A more detailed discussion of biological control of Australian rangeland weeds is provided by Julien (2006).

Integrated weed management

It is unlikely that any rangeland weed problem can be solved with a one-off treatment of a single technique. Rather, weed management in rangelands requires a strategic approach that most effectively integrates available techniques. Integrated Weed Management (IWM) combines chemical, mechanical, biological, and fire control options (DiTomaso 2000). Unfortunately, integrated weed management programs to date are available for <10% of the Australian rangelands weeds listed by Martin *et al*. (2006, this issue). At best, only single control options are available for the majority of these weeds (Martin *et al*. 2006, this issue), highlighting the need for research on approaches to the management of weeds of Australian rangelands. Strategic weed management refers to the application of weed control techniques at times and places that make them most effective and efficient (Grice *et al*. 2000). This highlights the importance of tackling weed problems not simply at the level of the individual infestation but also at scales ranging from the management unit (grazing property, conservation reserve, Aboriginal community, etc.), to catchment, landscape and region. The advantages of such a strategic approach are reflected in the national strategies that have been developed for the 20 Weeds of National Significance (Weeds Australia 2004*a*) and some other species.

Development of an IWM strategy at whatever scale and location requires sound understanding of the biology of targeted weed species, including factors such as the size of the soil seed-bank, seed longevity, requirements for germination and establishment, age at first reproduction and plant life span (Campbell and Grice 2000). A strategy must also consider the size, density, and accessibility of the weed population. These factors will strongly influence the economics, feasibility, timing and frequency of control. Due to economic and climatic constraints many control options can only be applied once every 5–10 years in rangelands. Therefore, it is critical that techniques are appropriate and used correctly at the most effective time to ensure maximum control. Buckley *et al*. (2004) modelled a 3-year IWM strategy for *Mimosa pigra* L. control in the Northern Territory. The application of herbicide in year 1, a combination of mechanical control and fire in year 2, and the reapplication of herbicides in year 3 was an effective strategy for controlling *Mimosa pigra*. The addition of biological control agents and competitive vegetation would further improve the overall control strategy (Buckley *et al*. 2004). Similar approaches could be used for controlling rangeland weeds.

Finally, it is important to consider factors relating to the nature of the invaded environment including the nature of non-target vegetation. Virtually any control technique will have potential off-target damage. Broad-scale mechanical treatment of weeds may also damage native species, herbicides are generally not so specific in their actions that non-target species are not affected, and any fire regime that is imposed for weed management is likely to favour some native species over others, and thereby influence community composition. A particular challenge is to develop and apply weed management methods that are suitable for rangelands use but minimise any negative consequences to the natural ecosystems. Clearly, it is important that application of a particular weed management regime has more desirable net consequences for biodiversity compared with the effects of the targeted weed.

In Australia, relatively little effort has been directed at evaluating weed management strategies in terms of their effectiveness against the targeted weed and the side effects of that control option on non-target components of the ecosystem (Grice 2004, 2006). Approaches to weed management have been judged on their efficacy in achieving weed management goals with minor referencing to the consequences of different control options for biodiversity. The main means whereby decisions relating to weed management take environmental consequences into account are via legislation relating to vegetation management and the use of herbicides. In some jurisdictions, the use of fire is also governed under vegetation management legislation.

Future restoration of rangelands degraded by invasive plants must be based on ecological principles and concepts that provide for predictable outcomes. A general objective for ecologically based weed management is to develop and maintain a healthy plant community that is largely resistant to invasion. The challenge is to follow ecological principles on which management can be based (Sheley and Krueger-Mangold 2003). Land management activities, irrespective of land use, require prioritisation to preserve the biodiversity values that are threatened by weeds. Pest herbivores assist the introduction and spread of weeds and add to total grazing pressure, reducing competition for weeds. Weeds can be introduced by animals and people, and by natural means such as wind and water. Management of these incursions is a priority for land managers to achieve sustainable production and biodiversity outcomes.

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