TECHNICAL ASPECTS OF WEED MANAGEMENT IN AUSTRALIAN RANGELANDS

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Summary Techniques for prevention, individual plant treatment (low densities) and whole area treatment (medium to high densities) are reviewed. In the last 10–15 years, significant advances have been made with preventative, chemical, mechanical, biological and fire techniques. Individual plant techniques are generally effective but broad scale techniques are limited by partial and variable efficacy and high cost. Further successes will be achieved so technique-based research must continue but must be linked to establishing integrated management within a total land management framework. The strategy for exotic species will also include eradication techniques (where higher costs are justifiable) and classical biological control. Greater attention is required to creative use of herbicides, adaptive management, modelling and delivery of complex control technology.

INTRODUCTION

Techniques for rangeland weed management generally differ according to the weed density. This paper will consider those for individual plant treatment where the density is usually low, and those implemented on an area basis where the density is usually medium to high. Low densities usually occur where the species is at an early stage of invasion, or at a late stage of a management or restoration program. In addition, techniques for preventative control will be addressed.

Techniques are reviewed for their current effectiveness, recent advances and future research needs. Finally, suggestions for the future improvement and implementation of techniques are presented. I have placed an emphasis on information from Australian weeds conferences since 1981.

Where an exotic species is invading and the area is limited, effectiveness of the control technique is critical and the importance of cost is reduced. However for large areas of low density populations and for high density areas, cost-effectiveness is critical.

PREVENTATIVE WEED CONTROL

The cheapest form of weed control is prevention. This concept is gaining wider recognition and will be assisted by its inclusion as the leading goal in the National Weeds Strategy. Prevention applies at all levels of scale from the whole of Australia down to the paddock. It means preventing new weeds entering Australia and preventing weeds from moving between States, catchments, local government areas, properties and paddocks. This involves many agencies as well as individual land managers. The techniques involve care in moving fodder, animals and machinery from infested to clean areas, early detection and eradication, enforced control and quarantine. Early intervention applies to native as well as introduced species. Control of isolated infestations to prevent spread to the remainder of a region or catchment is strategic control. This has gained increasing adoption in Queensland with support from a State government program.

The technique of not allowing contaminated fodder, animals and machinery into clean areas is simple enough and is partially implemented at the property, region and State level for some high profile weeds such as parthenium weed (*Parthenium hysterophorus* L.) and Noogoora burr (*Xanthium occidentale* Bertol.). On the one hand, increased use of this technique requires greater education and awareness, but on the other hand, it must be supported by regulation. The development of effective regulation is a challenge.

INDIVIDUAL PLANT CONTROL

Only chemical and physical control techniques are used for control of individual plants. If biological control techniques have been developed for dense populations elsewhere then they will have a role. However, a high level of control should be the target for low densities, and this will not be provided by many biological techniques.

CHEMICAL CONTROL

Cut stump Cut stump is a combined physical/chemical control method that normally gives 95–100% control. An effective herbicide recommendation is available for many weed species and should be progressively developed for remaining species.

The efficacy of the cut stump method is not affected by season or moisture status (Vitelli unpublished data, Jeffrey unpublished data) and uses only a small quantity of herbicide per plant. The major cost is labour. A modified brush-cutter is a recent development which reduces labour costs in a range of situations – where plants are hard to reach, for larger stem diameters and for higher plant densities. The brush-cutter is fitted with application equipment for immediately applying herbicide to the cut stump (Dallison 1992).

Basal bark The basal bark method involves spraying the basal portion of the stem with a herbicide plus a bark penetrating carrier, usually diesel. Efficacy is usually >90% control but is sensitive to spray coverage and stem diameter (the length of treated stem must be increased with stem diameter). It is insensitive to season but is most effective in good growing conditions (Vitelli unpublished data). Effective herbicide recommendations are available for all significant species and need to be progressively developed for other species. Herbicide, diesel and labour all need to be considered in research to reduce costs. Diesel alone is as effective as diesel plus herbicide in good growing conditions but the limits of its effectiveness need to be better defined for widespread adoption. Attempts have been made to reduce the quantity of diesel required by using diesel/water emulsions. These are as effective as using 100% diesel carrier in some situations, but as with using diesel without herbicide, the increased risk of reduced effectiveness has limited the adoption. A practical means of reducing costs is to use waste diesel from cleaning fuel storages. Other carriers, such as isopropyl alcohol are being evaluated (Diatloff personal communication).

Tree injection Tree injection is usually carried out with angled axe cuts into the bark at waist height followed by application of a measured dose of herbicide with the other hand. The method is widely used for control of native tree species (such as poplar box, *Eucalyptus populnea*) because of accessibility of the stem whereas it is not suitable for very multi-stemmed and thorny plant forms. Effective herbicide recommendations are available for most species for which the method is suitable. Effectiveness has been improved with special axe designs and modern applicator guns but there is probably little scope for further improvement.

Ground-based foliar application Foliar herbicides are usually applied by ground equipment for scattered to medium densities and by aerial application for large scale dense infestations. Use of this method is restricted to shrubs and small trees which can be reached by ground based equipment, but for herbaceous species is the major method of chemical control.

High volume application has been used almost exclusively in rangeland areas. Chemical control recommendations have been developed for most rangeland species. A particular effort has been necessary over the last ten years since the demise of 2,4,5-T and the introduction of new active ingredients or new products based on herbicide mixtures. Despite the new products, foliar chemical control for some woody weeds is less than acceptable. Furthermore, the level of control, particularly for woody species is inconsistent (for example, Fossett *et al.* 1996). The factors affecting the efficacy of foliar herbicides are discussed later.

Spray volume is a significant factor in herbicide activity on woody plants. For hand held high volume spraying, the operator must make a judgment on wetness leading to substantial variation in the volume applied (McMillan 1987). This is almost certainly a factor in the variability of results from ground spraying.

Soil-application Soil-applied herbicides for woody species are now used in a variety of ways – pellets, gridballs, liquid spots and soil injection. Hexazinone and tebuthiuron are specifically for soil application although other herbicides may have some effect through the soil following foliar application. Hexazinone and tebuthiuron are effective on a wide range of species. An advantage of this method is that dry formulations can be carried in a vehicle and used whenever a weed is detected during farm operations, no water or diesel carrier is required and application time is moderately fast. The disadvantages are lack of selectivity, dependence on an erratic rainfall and not knowing if plants are treated.

The efficacy of soil applied herbicides is dependent on soil type and rainfall. Improvements in the reliability of these herbicides requires further study of their activity in Australian conditions.

A novel method of delivery has been trialled in the US, involving an electronic control system which measures canopy diameter and delivers an appropriate dose of hexazinone (Wiedemann *et al.* 1992). It worked for trees with a canopy of 0.8–4.6 m diameter.

MECHANICAL CONTROL

In addition to cutting plants and applying a herbicide (cut stump method), or using a bulldozer, there is a new physical control method, a tractor mounted grubber (Thompson and Jeffrey 1992). A blade is forced under individual woody weeds with the forward movement of the tractor lifting the plant out of the soil. The cost for prickly acacia (*Acacia nilotica* Benth.) is 19–22 cents per tree, only slightly more than the cost of basal barking. However, the operator is riding and not walking, is not exposed to a diesel/herbicide mixture and can see what is treated. This device clearly illustrates the potential for innovation to further the cause of weed control. The tree pinching equipment used in harvesting pine trees, fitted with a herbicide applicator for applying herbicide to the cut stump, may be another means of control.

WHOLE AREA CONTROL

Chemical control

Aerial foliar application Aerial application is the primary option for applying herbicides to large areas of dense weed infestations. Aerially applied 2,4,5-T was effective for many woody species, so as with ground-based applications, methods based on new products have had to be developed to replace 2,4,5-T. This process is not complete as research has not been done on all species (e.g. mesquite, *Prosopis* spp.) and on others the herbicide efficacy is too low or variable.

Some of the factors affecting efficacy are discussed in the next section. However one that is more specific to aerial application is application technology. High volume application cannot be used so volume, carrier, droplet size and adjuvant become very important. The technology of aerial application was reviewed at the 1981 Australian Weeds Conference (Yates 1981) and with extensive research in progress in the US (Wilson 1991), a good understanding of the principles and technology should be available. However, despite this, it is still necessary to evaluate variables such volume and nozzle type (or droplet size). Vitelli (1993) found that the highest spray volume of 400 L ha^{-1} gave the best control of rubber vine (*Cryptostegia grandiflora* Roxb. R.Br.) with triclopyr/picloram. However, Whisenet (personal communication) found that spray volume (22–88 L ha^{-1}) and droplet size (325–650 microns) did not affect the control of mesquite with clopyralid. There clearly remains a significant challenge to close the gap between the general technology of application and the most effective application method for specific herbicide/weed combinations.

An objective with aerial application must be to reduce spray volume to reduce costs. There is a range of nozzle possibilities, including the experimental air-assist nozzles (McWhorter and Hanks 1992). Low volumes open up the possibility of directly applying oil-based formulations and expensive adjuvants. There is considerable aerial application research in the US, and although it is focused on the application of seed, fertilizer and pesticides for crops, should be monitored for its applicability to Australian situations.

Other herbicide applications Other herbicide application methods such as aerial application of soil-applied herbicides and boom-spraying of seedlings have specific roles. The use of diuron in bore drains is a recent innovation to control adjacent woody weeds (principally prickly acacia). It has usually produced complete control and adoption is estimated at greater than 80% (Jeffrey, personal communication). The carpeted roller of Crane *et al.* (1989) may have a role in specific situations.

Efficacy of herbicides There are two challenges in herbicide research:

1. to improve cost effectiveness i.e., improve efficacy and/or reduce costs, and
2. to improve the reliability of methods.

A multitude of factors affect the efficacy of foliar applications – air temperature, relative humidity, moisture status of the plants, rainfall, leaf age, plant age, spray volume, droplet size, adjuvants, formulation, water quality and herbicide mixtures. Spray application factors have been discussed above. Very high temperatures, low relative humidity, low soil moisture and plants hardened by extreme environmental variation all reduce herbicide activity. Operators are advised not to apply herbicides at air temperatures above 35°C but the effect of air temperatures with current herbicides and formulations has not been studied. The effect of moisture status has received minimal attention. In current research, Vitelli (1990) has found that metsulfuron activity is less affected by moisture status than that of 2,4-D. Much of the information on environmental and plant factors has however, been developed for crop situations in Europe, UK and USA where the conditions are very different from those of the Australian rangelands, as illustrated by a review at the First International Weed Control Congress (Kudsk and Kristensen 1992).

There are two reasons why these environmental and plant factors should be studied:

1. to quantify the impact of the factors so we can accurately define when herbicide activity will be optimal, and
2. to develop means of reducing the adverse impact of these factors.

Adjuvants and formulations are a possible means of overcoming the impact of other factors by improving absorption, translocation or activity. For example, lipophilic herbicides are less affected by low humidity than water-soluble herbicides and adjuvants can overcome the adverse effects of low humidity (Kudsk and Kristensen 1992).

Apart from any benefits under adverse conditions, adjuvants can substantially increase herbicide efficacy. A surfactant with an appropriate hydrophilic-lipophilic balance (HLB) and adequate concentration gave up to a 10-fold increase in herbicide efficacy (Green 1992). Silicone surfactants are a recent development, producing a marked increase in droplet spread (Vitelli 1987). Their use has been limited by high cost and care is needed. Buick and Field (1992) found that two of three silicone surfactants increased triclopyr uptake and for amine, but not ester formulations. There are other adjuvants such as paraffinic oils; their potential for increasing herbicide efficacy has been recently demonstrated (Fossett *et al.* 1996).

Chemical control could be advanced by the availability of some herbicide formulations that are available in the US, such as picloram K salt, oil-based imazapyr and dicamba ester (the latter two may assist the cost-effectiveness of basal bark techniques). The same argument applies to herbicide mixtures such as triclopyr/picloram which could have been made available sooner. These situations are based on company decisions, and although there would be a community benefit from their availability it is difficult for government to get involved in registration and marketing.

The efficacy of soil applied herbicides may be increased in rangelands by a new formulation currently being tested (Jeffrey personal communication).

Research on herbicide uptake and translocation to improve efficacy can range down to the molecular level. Bayer (personal communication, University of California) believes that the cell wall/plasmalemma interface is probably the limiting factor, not the cuticle, and that in future there will be 'designer' herbicides based on receptor sites for transporting. While this research is not specifically addressing rangeland weeds, it could lead to significant improvements and should continue; a quantum breakthrough is required.

Mechanical control

Blade ploughing Blade ploughing involves pulling a horizontal blade through the soil at depths greater than 15 cm. It has given at least 90% control of woody weeds in western New South Wales (NSW) provided lifters are used (Harland 1992), and greater than 90% control of rubber vine in north Queensland (Vitelli unpublished data). Depth of operation is important particularly for resprouting species for which the minimum depth is 20 cm (Harland 1992). In north Queensland, July to September is the best time; earlier, during the wet season rubber vine survival is higher, and in October–November, the soil is too hard. The disadvantages of blade ploughing are killing of perennial pastures and high cost. Hence excluding grazing pressure is important for re-establishment of pastures. Costs will vary with soil texture, soil moisture, depth of operation, type of equipment and weed density. Further research is necessary on the factors affecting control, cost of operation and the role for blade ploughing within integrated weed management.

The long term effects of blade ploughing must also be understood. Sixteen years after treatment in Texas, the ground cover of honey mesquite (*Prosopis glandulosa* Torrey) was 23% compared with 59% in the untreated. Many minor species were completely controlled, but huisache (*Acacia smallii*) had increased from 10% cover in the untreated to 72% (Ruthven *et al.* 1993). The area had changed to dominance by another species and species diversity had been lost.

Pulling Pulling using a heavy chain and/or cable is a well established method of controlling woody vegetation. Single pulling is effective for large tree species such as brigalow (*Acacia harpophylla* Benth.) (Johnson 1968) whereas double pulling (in opposite directions) is necessary for shrubs to small trees such as prickly acacia (Jeffrey and Bode 1992). The level of control from pulling is much higher for trees and large shrubs than for small plants (Harland 1992, Jeffrey and Bode 1992). Jeffrey and Bode found that kill of prickly acacia larger than 75 mm stem diameter was 80%, but fell to 55% and 14% for plants with a stem diameter of 31–75 and 0–30 mm respectively. Regrowth is lowest if pulling is done in the wet season (Harland 1992, Johnson 1968). However pulling is best done in dry conditions for prickly acacia because the main root is snapped rather than the entire root system being removed (Jeffrey 1995).

In all vegetation types there is a need to follow up with other control methods such as fire, herbicides, raking or ploughing to maximize the benefit. Harland has noted that for western NSW, chaining has been successful only where it was followed by cultivation and work is still in progress to develop follow-up treatments for non-cultivation areas. The costs for pulling are \$A15–25 ha^{-1} in western NSW (Harland 1992) and \$A20–40 ha^{-1} for double pulling prickly acacia (Jeffrey 1995). Although in the case of prickly acacia, the value of the land is approximately \$A21 ha^{-1}, double pulling is viable where the cost is partly recovered by the feeding value particularly in drought.

Although pulling is well established for timber clearing it is still being developed for some woody weeds. It was for many years considered unsuitable for prickly acacia so the above research shows the importance of questioning such assumptions.

Stickraking A stickrake, i.e. a very wide blade with fingers along the base, has been fitted with a cutter bar and successfully used for control of prickly acacia (Jeffrey 1995). The plants are cut off just below the soil surface. The technique is expensive but suitable for special purpose areas.

Fire

The use of fire in northern rangelands has been recently reviewed by Grice (1996) and includes a consideration of fire elsewhere in Australia. The reduction or cessation of fire has led to an increase in native woody vegetation in both Australia and the US. The same consequences apply to exotic woody weeds, enabling them to increase more rapidly. The decrease in fires is attributable to graziers preserving pasture growth for livestock, and the removal of pasture as a fuel source by grazing and competition from the woody vegetation (Grice 1996).

The possible use of fire varies from annually in the wet dry tropics to opportunistically in the semi-arid regions. The effect of fire varies substantially across species and is generally well documented. For example, Robertson and Walker (1981) reported a 62–94% reduction in two wattle species but only a 20–52% reduction in false sandalwood in southern Queensland. Subsequent re-establishment was by seedlings for the wattles (*Acacia deanei* and *Cassia nemophila* J.R.T. Vogel) and resprouting by false sandalwood (*Eremophila mitchellii* Benth.). In contrast, the susceptibility of mesquite to fire was only recently established and the effect of fire on prickly acacia is not well understood (but from observations appears to be minimal) (Jeffrey personal communication).

Plant mortality from a fire depends on fire intensity (Grice 1996) and fire intensity depends on environmental factors, fuel moisture content, fuel load, fuel height and slope. These factors have been incorporated in a model in the US which predicts factors such as energy released (Wilson 1991). With data on the energy (or intensity) necessary for mortality of each species, a model could be used to predict the outcome of a burn and so increase the reliability of an effective burn.

There is a substantial cost to using fire as stock must be excluded before and after a burn. The use of fire is economically viable (Burgess 1987) but additional data for the wide range of vegetation communities is necessary.

There are many variables in using fire and a decision support system is the means to address these. Shrubkill is a program available for north-western NSW and south-western Queensland and is suitable for adaptation to other areas (Ludwig 1990).

Biological management

Classical biological control Classical biocontrol involves the introduction of agents (insects and pathogens) from the area of origin of introduced weeds. This form of biocontrol is very successful on cacti as indicated by the well known control of prickly pear and more recently the control of Harrisia cactus (*Eriocereus martinii* [Labouret] Riccob.) with a mealy bug (*Hypogeococcus festerianus*) (McFadyen and Tomley 1981), both in regions bordering the rangelands. Some herbaceous weeds are being partially controlled e.g. Noogoora burr by a rust and stem-boring insect (*Epiblema strenuata*), and parthenium weed by three insect species.

A woody vine, rubber vine, is at a stage where biological control appears to be successful. A rust (*Maravalia cryptostegia*) and moth (*Euclasta whalleyi*, with a leaf-feeding caterpillar stage) have recently spread widely and caused a high level of defoliation, although the two agents will need other methods integrated with them to maximize the benefit.

Other key woody weeds, such as prickly acacia, Parkinsonia (*Parkinsonia aculeata* L.) and mesquite, are the subject of current research programs. One seed feeding insect is widely established on prickly acacia with no obvious short term impact. Apart from this, all three weeds are at various stages of research from exploration to early establishment of new insect introductions.

The chances of success with biological control are influenced by the number of host specific agents that exist, type of agent, accessibility of the countries of origin and how closely the weed and native species are related. The life form of the target may be a factor with the chance of success on woody weeds being open to challenge. However, in South Africa, an *Acacia* spp. has been controlled with a galling wasp and another *Acacia* spp. with a rust (McFadyen personal communication). Also relevant is the damage done to desirable tree species, for example the effect of Dutch elm disease.

The successes quoted above are with weeds growing in the more humid areas adjacent to the rangelands, or the agent has been more successful in the humid areas (e.g. Noogoora burr rust). The extremes of variation in temperature and moisture conditions in the semi-arid and arid areas may make biological control more difficult but with the target woody weeds at least a host is always present.

After all these considerations it is widely agreed that it is not possible to predict success with biological control, so it must therefore be pursued for all key species with the above criteria simply influencing order of priority. For rangeland areas, biological control is the only option for dense populations of some species.

Inundative and augmentive biological control A broad range of other biological control possibilities exists in which the agents have to be regularly produced and distributed. These may be introduced or native agents applied to introduced or native weeds. In NSW, a native scale insect (*Austrotachardia* spp.) killed large areas of *Cassinia* spp. in 1988–92 (Campbell and Wykes 1992). Human transmission of the insects resulted in a 70% kill of *Cassinia* on one property and has resulted in establishment of the insect on about 300 properties. Campbell and Wykes (1992) proposed that a better understanding of native insects and their predators and parasitoids, could lead to effective control of some native weeds.

In Hawaii, a wilt organism was found on C*assia suratensis*, a woody weed. Spore suspensions applied to man-made wounds on the trunk gives control (Wilson 1991). In the US and Canada, three mycoherbicides are now available and in Australia, development of a mycoherbicide for *Xanthium* spp. is in progress (Auld *et al*. 1990). To further advance the use of pathogens in this way, research is under way studying the mechanism of action rather than only the organism, looking for chemicals to mix with pathogens to weaken plant defences, and invert emulsion formulations to overcome the need for a dew period (Wilson 1991). Although these examples are the equivalent of tree injection and foliar herbicide applications, they offer some advantages, being chemical free (possibly an important future issue in some areas for beef production) or possibly being more effective.

Biotechnology, including genetic engineering, has advanced rapidly in recent years and must have potential for future advances in both classical and inundative biocontrol.

Grazing The use of grazing animals for weed control has been recently reviewed (Popay and Field 1996). Cattle, sheep and goats all have a role in weed control although the animals may also be the cause of some weed problems. Introducing different classes of stock and integrating grazing with other control methods all require consideration. It appears from the review that very little is known about the use of grazing for weed control in rangelands, but there is information not included.

Goats are especially effective in browsing on woody plants. Goats can open up shrub-infested rangelands in NSW provided the areas are dominated by species acceptable to goats (Condon 1986, Muir 1992). A heavy stocking rate of goats in western Queensland (3–4 ha^{-1}) caused the death of 68% of prickly acacia and 62% of gidyea (*Acacia cambagei* R.T. Bak.) regrowth for trees within browseable range (Cobon 1996). In the US, continuous grazing with 0.83 to 1.25 goats ha^{-1} resulted in an 85% reduction in cover of mixed brush species after five years (Merrill and Taylor 1976). Despite the effectiveness of goats, there use is not being adopted. The grazier involved in the work of Cobon believes they are too hard on the country (Fysh 1996) and there is a cost in higher standard fencing. Any additional research needs to define the role of goats in a whole property context.

Plant competition Maintaining an herbaceous plant population is important in suppressing weed impact. Perennial grasses reduce native woody weed seedling establishment (Harrington 1991), brigalow sucker regrowth (Johnson 1968) and minimize parthenium weed populations. However Brown and McIvor (1993) found no effect of perennial grasses on prickly acacia and rubber vine survival in pot and small plot experiments. The competitive relationship between herbaceous plant populations and weedy species must surely vary substantially with the composition and density of herbaceous populations, the type of weed species (woody or herbaceous) and seasonal conditions. The survival of weed seedlings is often low if there is no rainfall for several months following emergence (Campbell unpublished data) so any factor which places added stress on seedlings should reduce survival and be a useful component of management.

Integrated control

The objective with individual plant treatment is a high level of control with one technique and this is usually achievable. However single-treatment use of area based techniques usually gives inadequate long term control so the integration or repeat use of techniques is required. Pulling, burning, herbicides, sheep grazing and pasture competition were successfully integrated to convert brigalow and gidyea areas into productive pastures although in the long term there are still problems with regrowth. These areas are not rangelands and are more productive areas; the challenge to achieve cost effective methods for rangelands is greater.

In western NSW, fire followed by chemical defoliation is being investigated (Noble *et al.* 1991). Research is addressing application techniques and also the possible integration of pulling and blade ploughing. Vitelli (personal communication) has evaluated the integration of sequential use of different herbicides, slashing, blade ploughing and burning for rubber vine management and has developed recommendations for different situations. These have been adopted in more highly productive areas but costs are too high for large scale adoption in low productivity areas. The work of Jeffrey and Bode (1992) with pulling of prickly acacia has been extended to controlling regrowth with herbicides or a stick rake fitted with a cutter bar (Fysh 1996). The results are being implemented by Fysh, the property owner, and to date a small number of other graziers. Research has just been commenced through the Tropical Weeds Research Centre on the integration of mechanical methods, herbicides and burning for mesquite management.

Many authors here (for example, Noble and Harrington 1992) and in the US have stressed the need to integrate control methods (and also to integrate woody weed management into whole property planning). This is occurring as described but not to the extent that would be expected from the words that have been written about it. Another important feature is that no principles have been established; the integration of methods is based on general plant growth and population principles plus the intuition of researchers and/or the graziers they are working with.

FUTURE

Implementing control practices must be done with a focus on establishing a system, whether for production or nature conservation, in which weed impact is minimized, as proposed by Grice and Brown (1996). Simply asking what is the best way to kill a weed is inadequate. However, to develop a whole property, catchment or regional plan requires effective integrated weed management practices, and in turn integrated practices require effective single-treatment components. Thus, if we are to advance land management, research to develop or improve integrated and single-treatment techniques must continue, provided the priorities and objectives are addressing the holistic approach. In the last few years there has been a surprising array of advances – diuron for bore drain weed control, grubber technique, new herbicide products, pulling of prickly acacia, brush-cutter with applicator for cut stump treatment, refinement of fire management for rubber vine and mesquite control, and development of the fire/chemical defoliation technique for testing on shrub control. In addition, effective biocontrol agents for rubber vine have come to fruition. The delivery of equivalent advances will continue with adequate research.

Chemical control is particularly complex. Whilst further refinement of current technology will lead to significant improvements, it will not produce highly effective low cost solutions for all situations. In pursuing the refinement of chemical control techniques, a point could be reached where the benefits do not return the cost of the research. The challenge is to focus on the most critical variables and to apply creative thinking to develop herbicide techniques outside the bounds of current uses.

In developing future weed management techniques, two approaches are required:

1. research where cost of the technique is not a limitation, and
2. research aimed at improving the cost effectiveness of single or integrated techniques. If we always place a cost filter on new techniques before they are evaluated then advances will certainly be limited. Cost-based refinements can be developed later and cost relativities do change over time.

In seeking to develop cost-effective techniques for the rangelands, it is important to draw a distinction between native and exotic species. The strategy for native species should be vegetation management, involving long term economical management for production, whilst also retaining significant areas for biodiversity. The strategy for exotic species, whilst based on vegetation management principles, will also include eradication from some areas and prevention of spread; in these cases, higher cost options are justifiable. Classical biological control is an option only for exotic species and given the enormous challenge of achieving cost-effective techniques for the rangelands, must continue to receive a high priority.

‘Adaptive management’ is a means to address the development of cost effective practices and a holistic approach at the same time. It is learning by doing, using the experience of the land manager and giving land manager ownership whilst trying improved approaches. It is being used by Noble (personal communication) and needs to be an important component of future research.

Guidance in the development and integration of techniques in the future will come from modelling their long term consequences. This approach is demonstrated by Mooy *et al.* (1992). The need in this case is for ecological data to support the modelling.

As cost is a major limitation in rangelands and treatments may only be applied once in say five years, it is critical to apply techniques correctly to ensure maximum efficacy. Also there is a range of specific requirements for many of the techniques. It is difficult for land holders to ensure that they do everything correctly. This needs addressing with decision support systems. A start has been made with Shrubkill but systems are needed for other land use situations. In their absence, good best practice documentation is essential.

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REFERENCES

Auld, B.A., McRae, C.F. and Morin, L. (1990). Research on mycoherbicides for control of *Xanthium* spp. Proceedings of the Ninth Australian Weeds Conference, p. 527.

Brown, J.R. and McIvor, J.G. (1993). Ecology of woody weed invasions in the tropical woodlands of north-eastern Australia: implications for management. Proceedings of the 10th Australian and 14th Asian-Pacific Weed Conference 1, 471-4.

Buick, R.D. and Field, R.J. (1992). The mechanism of organosilicone surfactant-induced uptake of amine and ester formulations of triclopyr. Proceedings of the First International Weed Congress 2, 103-5.

Burgess, D.M.N. (1987). Prescribed burning for profitable shrub management in the semi-arid rangelands of NSW. Proceedings of the Eighth Australian Weeds Conference, pp. 55-8.

Campbell, M.H. and Wykes, P.J. (1992). Possible biocontrol of native weeds by native insects. Proceedings of the First International Weed Control Congress, 2, 106-8.

Obon, D. (1996). Use of goats for woody weed control. Working Papers, Fourth Queensland Weeds Symposium, pp. 69-74.

Condon, R.W. (1986). Financial and other benefits from goats on scrub (brush)-infested semi-arid rangelands in western New South Wales. Rangelands: a Resource Under Siege, Australian Academy of Science, pp. 235-6.

Crane, R.A., Scifres, C.J., Koerth, B.H. and Flinn, R.C. (1989). Control of honey mesquite, huisache, and blackbrush acacia with herbicides applied by carpeted roller. Management of South Texas Mixed Brush with Herbicides, pp. 9-22.

Dalliston, K. (1992). Combination of chemical and mechanical: a new concept of woody weed control. Working Papers, Second Queensland Weeds Symposium, pp. 29-30.

Fossett, G., Vitelli, J. and Jeffrey, P. (1996). Aerial application of herbicides for the control of prickly acacia (*Acacia nilotica*). Working Papers of the Fourth Queensland Weeds Symposium. (In press).

Fysh, F. (1996) Experience with prickly acacia on a property north of Longreach. Working Papers, Fourth Queensland Weeds Symposium, pp. 23-4.

Green, J.M. (1992). Increasing efficiency with adjuvants and herbicide mixtures. Proceedings of the First International Weed Control Congress. 1, 187-92.

Grice, A.C. (1996). A review of fire in northern pastoral lands. Working Papers, Fire Workshop, Townsville. (In press).

Grice, A.C. and J.R. Brown (1996). An overview of the current status of weed management in Australian rangelands. Proceedings of the Eleventh Australian Weeds Conference, Melbourne, Australia, pp. 195-204.

Harland, R. (1992). Mechanical woody weed control techniques. Woody Weed Management Strategy, Proceedings of a National Workshop, Cobar, pp. 54-58.

Harrington, G.N. (1991). Effects of soil moisture on shrub seedling survival in a semi-arid grassland. *Ecology* 72, 1138-49.

Jeffrey, P.L. (1995). ‘Prickly acacia. Exotic Woody Weeds and Their Control in North-West Queensland’, ed. N. Marsh, pp. 3-9. (Queensland Department of Lands).

Jeffrey, P.L. and Bode, R. (1992). Chain pulling prickly acacia. Working Papers, Second Queensland Weeds Symposium, pp. 36-9.

Johnson, R.W. (1968). Brigalow clearing must be planned. Brigalow Development. Queensland Department of Primary Industries, pp. 14-27.

Kudsk, P. and Kristensen, J.L. (1992). Effect of environmental factors on herbicide performance. Proceedings of the First International Weed Control Congress 1, 173-86.

Ludwig, J.A. (1990). Shrubkill: a decision support system for management burns in Australian savannas. *Journal of Biogeography* 17, 547-50.

McFadyen, R.E. and Tomley, A.J. (1981). The successful control of Harrisia cactus (*Eriocereus martinii*) in Queensland. Proceedings of the Sixth Australian Weeds Conference 1, 139-43.

McMillan, M.G. (1987). Operator variability in the application of herbicides to woody weeds. Proceedings of the Eighth Australian Weeds Conference. pp. 73-6.

McWhorter, C.G. and Hanks, J.E. (1992). Spray equipment for applying herbicides in ultra-low volume. Proceedings of the First International Weed Control Congress 1, 165-7.

Merrill, L.B. and Taylor, C.A. (1976). Take note of the versatile goat. *Rangeman’s Journal* 3, 74-6.

Mooy, L.M., Scanlan, J.C., Bolton, M.P. and Dorney, W.J. (1992). Management guidelines derived from ecological studies of prickly acacia (*Acacia nilotica*). Proceedings of the First International Weeds Congress 2, 347-9.

Muir, S. (1992). Benefits and limitations of using goats to manage woody weeds. Woody Weed Management Strategy, Proceedings of a National Workshop, Cobar, pp. 54-8.

Noble, J.C. and Hodgkinson, K.C. (1992). The woody weed problem in Australian rangelands: assessment, ecology and prospects for management. Woody Weed Management Strategy, Proceedings of a National Workshop, Cobar, pp. 8-14.

Noble, J.C., MacLeod, J.A., Ludwig, J.A. and Grice, A.C. (1991). Integrated shrub control strategies in Australian semi-arid woodlands. Proceedings of the Fourth International Rangeland Congress 2, 846-9.

Popay, I. and Field, R. (1996). Grazing animals as weed control agents. *Weed Technology* 10, 217-31.

Robertson, J.A. and Walker, J. (1981). Effect of fire on three shrub species in a previously disturbed *Eucalptus populnea* woodland. Proceedings of the Sixth Australian Weeds Conference 1, 175-8.

Ruthven, D.C., Fulbright, T.E., Beasom, S.L. and Hellgren, E.C. (1993). Long-term effects of root plowing on vegetation in the eastern south Texas plains. *Journal of Range Management* 46, 351-4.

Thompson, G. and Jeffrey, P.L. (1992). Trial of a tractor grubber attachment as a method of control of prickly acacia (*Acacia nilotica*). Working Papers, Second Queensland Weeds Symposium, pp. 32-5.
Vitelli, J.S. (1987). Effect of a new organosilicone surfactant on droplet spread. Proceedings of the Eighth Australian Weeds Conference, pp. 77-9.
Vitelli, J.S. (1990). Effect of soil moisture on the efficacy of 2,4-D and metsulfuron-methyl on rubber vine – preliminary investigations. Proceedings of the Ninth Australian Weeds Conference, pp. 407-10.
Vitelli, J.S. (1993). Effect of aerial water volume on triclopyr/picloram applied to rubber vine (*Cryptostegia grandiflora*). Proceedings of the 10th Australian and 14th Asian-Pacific Weed Conference 2, 150.
Wiedemann, H.I., Bowman, D.N. and McCollum, W.A. (1992). Tree-sensing boom for rangeland. *Transactions of the American Society of Agricultural Engineers* 35, 429-34.
Wilson, B.J. (1991). Development and integration of control methods for exotic weeds impacting on production and conservation in northern Australia. Winston Churchill Memorial Trust of Australia Report, pp.1-39.
Yates, W.E. (1981). Techniques available for aerial application. Proceedings of the Sixth Australian Weeds Conference, pp. 179-202.