# Weed management practices in natural ecosystems: a critical overview

C. F. REINHARDT

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Increasing public pressure against the use of pesticides and other agricultural inputs has placed increased emphasis on the development of ecologically based pest management. One distinct reaction of the Weed Science discipline has been the swing away from herbicide research to increased research on the basic biology and ecology of weeds in hopes of reduced reliance on "technological crutches" such as herbicides and other practices that are potentially harmful to the environment. Biological control is the long-standing alternative to the use of herbicides and interest in the former practice has been boosted by the realization that the use of herbicides may lead to the development of herbicide resistance in weed populations, and that herbicide residues occur in surface and groundwater. Supporters of herbicide use would point out that biological control is generally not effective in crop production systems, and is basically slow-acting. Debates between protagonists for the exclusive use of one or the other weed management practice tend to obscure the benefits that integration of different techniques are likely to have. For natural ecosystems it is proposed that integration of the more subtle practice of biological control with the use of herbicides, which relatively quickly overwhelm a biological system with mortality, is likely to be the most effective weed management tool. Different weed management practices that could be considered in natural ecosystems are discussed in terms of three key performance rating criteria, viz. activity, selectivity and persistence In this concise review, general discussion is focussed on the fundamentals of weed management practices, with the view to promote concept-based approaches that are critical for the development of effective weed management strategies.

Key words: alien invader plants, biocontrol, ecosystems, herbicides, weeds.

*C. F. Reinhardt, Department of Plant Production and Soil Science, University of Pretoria, Pretoria 0002 Republic of South Africa (creinhar@nsnper1.up.ac.za)*

## Introduction

Weeds not only impact negatively on human activities, but also on the environment. Apart from the more or less direct negative effects that weeds have, e.g. crop yield losses, water wastage, health and safety hazards, the potential impacts of diverse control measures need to be considered as well. In broad terms, risks posed to the critical compartments of the environment, *viz*. air, soil and water, are fairly well recognised these days. This is borne out by the acute focus on issues related to "off-target impacts" that is demanded by regulatory authorities of companies which produce pesticides. Of course, herbicide use, or more correctly potential problems associated with herbicide use, is not the only control practice that can threaten environmental integrity. In certain circumstances, soil tillage practices aimed at controlling weeds can be destructive through the promotion of water and wind erosion. A problem that has fairly recently come to light is the decline in the number of weed species in the more intensive crop production systems (Hurle 1998). Ecologists regard this as a negative trend, based on the premise that the more species an ecosystem has, the more stable it is, and *vice versa*. Without question, weed control strategies should reflect sensitivity towards all possible negative impacts that may follow their implementation. The most effective weed management strategies are likely to be those in which different control practices are integrated, and where as much as possible is known about the biology of weed species and their interactions with other organisms in the environment.

Most of the research that has been conducted on weeds and the measures to control them has focussed on agronomic weeds. From the very beginning of farming, man has been involved in a continual struggle against natural diversity in agricultural ecosystems; lately very effectively by means of crop protection agents. In fact, so effectively in its relatively short history has weed science contributed to the management of weeds that in some developed countries the "wheel has turned" to the extent that environmentalists are now clamouring for restrictions to be placed on the volumes of pesticides used. The latest addition to issues taken up by this powerful lobby is the restoration of biodiversity in agro-ecosystems. The debate continues even though it is not clear at this stage whether farmland actually needs biodiversity in order that crop production is done on a sustainable basis (Hurle 1998). Fact is, pressures are mounting for the use of pesticides (including herbicides) to at least be curtailed. Since the 1980s in particular many pesticides have either been banned or their use restricted, often without any toxicological basis but simply on the grounds that it is detectable in potable waters or in food products. Among the alternative weed control practices there are various forms of biological control, e.g. classical biocontrol, mycoherbicides, cover crops, and plant mulches, that are not regarded as hazardous in terms of human, animal and environmental safety. Unfortunately, their apparent benign character is often countered by serious limitations in weed control efficacy.

In natural ecosystems, human influence have contributed to the invasion of natural vegetation by alien invader species. The introduction of plant species, albeit by accident or by design, has contributed most to at least some of them acquiring invasive status in the "host" country. According to Randall (1996), invasive alien biota are responsible for the largest loss of biological diversity on a global scale, next to direct human consumption. The invasion of natural plant communities by alien plants is non-cyclical but rather exponential and permanent (Lotter 1996), and the permanent loss of ecological diversity inevitably leads to reduced stability and resilience within ecosystems. The establishment of more than 200 alien plant species within the KNP in the space of about four decades is at a rate which is unnatural and excessive (Lotter 1996).

The mere introduction of a foreign plant species into an ecosystem does not guarantee that it will attain invader status, in other words, that it will establish and reproduce successfully. The extent to which a species can adapt to its new environment will determine its aggressiveness in relation to endemic species. Genetic diversity within weed populations explains their high capacity to adapt to both environmental factors and diverse control measures (Jordan & Jannink 1997). The genetic basis of adaptation promotes diversity in biological and ecological properties, e.g. germination behaviour, growth form, seed size and dormancy (Cavers 1985; Warwick 1990), and also the development of specific adaptations such as herbicide resistance and resistance to biocontrol agents (Gould 1991). Therefore, in the development of effective weed management strategies, three critical questions need to be addressed:

- what are the environmental factors that determine the establishment and spread of a weed;
- what determines the effectiveness of management practices; and
- what are the potential risks involved with the implementation of different weed management practices?

Although knowledge on the biology and ecology of weeds is fundamentally important for successful weed management strategies, further discussion will not deal with these aspects (point 1 above) but instead will focus on specific practices, and the criteria by which their performances are judged. Practices that are unique to agro-ecosystems are left out, and only those that also pertain to natural ecosystems are discussed.

In assessing the performance of any weed control practice, three key rating criteria need to be considered, *viz*. activity, selectivity and persistence. Optimal performance requires that a sound balance be struck between these criteria. Activity refers to the time it takes for a practice to effectively control weeds. Selectivity is the ability of a practice to discriminate between weeds and desirable species, the idea being that the weeds are killed or their growth inhibited while the plant that needs protection is not appreciably affected. Persistence refers to the time for which a practice remains effective in killing weeds or repressing their growth to non-interference levels.

## Weed management practices

For reasons of space limitations, specific weed management practices (techniques) are glossed over here. The reader is referred to just two of many excellent books that deal exhaustively with the principles and practices of modern weed management (Ashton & Monaco 1991; Zimdahl 1993). Clearly, effective weed management is vital to the protection of desirable vegetation, and other organisms whose existence demands proper vegetation maintenance in both agricultural and natural ecosystems. The question remains "what practices are best for maximum efficacy and minimum off-target impact?". It can best be answered by first considering the three levels or intensities of weed management: prevention, control and eradication.

### *Levels of weed management*

1. Prevention entails that reproductive organs such as seed and vegetative parts that give rise to new plants, are prevented from spreading from infested areas to areas that are not infected. Thus, prevention involves practices aimed at containment and/or exclusion of weeds.
2. Weed control means that the number of unwanted plants are restricted to levels which are not expected to have an appreciable negative effect on desirable plants. This concept is fundamental to modern weed control practices which recognise the need to determine "economic thresholds" in terms of the number of weeds that a crop can tolerate without suffering unacceptable yield losses. From a nature conservation viewpoint, "aesthetic thresholds" or "ecological thresholds" can be set, and weed control measures applied in order to keep alien invader species at those pre-determined levels. This strategy in conservancy areas implies acceptance of the presence of exotic species, hopefully at only very low levels of infestation.

Therefore, in both agricultural and natural ecosystems, adherence to this strategy means that weeds can be tolerated to a certain extent. Economic thresholds in crop production are based on the simple idea that control measures are only worth implementing if the cost does not exceed the monetary value of the yield reduction that will occur in their absence. This strategy requires less chemical and mechanical energy inputs in the form of herbicides and machinery, and therefore, should reduce the risk of adverse impacts on crops and the environment. A drawback of the strategy is that the thresholds are weed/crop- and environment-specific, which complicates decision-making. The high levels of research and management skills that are required restrict implementation to the more affluent parts of the world. In developing and underdeveloped countries the popular strategy remains "control at any price". Here the rationale is to minimise yield reductions by means of intensive weed control measures and to prevent greater weed infestations in following years. This strategy was used all over the world right into the present century. Early on weeds had to be laboriously removed by hand; later on animal-drawn implements were used, followed by tractor-drawn implements and chemicals. The advent of the latter two practices, in particular the use of organic chemicals (herbicides), revolutionised weed control and crop production by replacing to a large extent high human and mechanical energy inputs with relatively low chemical energy inputs.

3. Eradication of weeds is aimed at killing all living plants, and the total destruction of vegetative and reproductive plant organs, including seed in the soil seedbank. Its greatest disadvantage is that implementation is both uneconomical and impractical in extensive crop production systems and in natural ecosystems, therefore, its application is restricted to highly intensive plant production systems such as nurseries and high-value crops on relatively small areas. In spite of the obvious daunting prospect of eradicating an alien invasive species, this ought to be the ideal approach in nature conservation. Realistically, it may turn out to be a case of "aim high in order that at least there is the chance to hit something". To tolerate alien plants, albeit at low levels of infestation, is courting disaster. Tolerance implies that the spread of a species is not effectively curtailed, and given the desired set of environmental conditions coupled with speed of adaptation of the plant, a veritable catastrophe looms.

### *Chemical control*

Herbicides have been heavily relied upon for weed control since their use became popular after World War II. For about three decades thereafter the production and use of herbicides rose to great heights — production of synthetic pesticides in the U.S.A. reached a high of 730 million kg in 1975; in 1991 it had declined to 434 million kg, of which 69 % are herbicides, 19 % are insecticides, and 12 % are fungicides (Pimentel *et al.* 1991). Prior to about 1985, research attention was focussed mainly on herbicide efficacy, with work on the biology and ecology of weeds lagging far behind. During the boom period, herbicides escaped most of the public concern about the impacts of pesticides, notably insecticides, that became evident during the 1960s. But since the 1980s when herbicides were detected together with other pesticides in water sources, public awareness was focussed on perceived risks associated with all synthetic agrochemicals. Nowadays it does not matter whether a compound is benign in terms of humans or animal health, the mere fact that residues can be identified at minimum detectable limits in potable water could, and has, led to the banning of certain products in some countries. A positive spin-off resulted from this in terms of research on the biology and ecology of weeds. Research on these aspects have escalated, and the knowledge are increasingly incorporated into comprehensive Integrated Pest Management (IPM) systems. More on this can be found further on under *Development of weed management strategies*.

Most of the herbicides that are available today show high activity and excellent selectivity. This ideal balance is responsible for the popularity of herbicides in diverse plant production systems. The perfect combination of all three attributes can be elusive though, because for a herbicide to remain effective for the greater part of the growing season of a crop a fair degree of persistence is required. Problems arise when active residues of the herbicide persist beyond the growing season it was applied in, and a sensitive follow-up is planted. In terms of monetary losses, damage to crops caused by herbicide residues that persisted too long in the soil is arguably the biggest problem today. Less obvious, but equally sapping on profits, is the yield losses that occur as a result of inadequate weed control. In natural ecosystems the ideal combination of herbicide attributes should also be high activity and adequate selectivity, but with the difference that as long as possible persistence is important. However, this latter attribute puts the environment at risk. Highly persistent herbicides threaten not only sensitive desirable plant species, but also represent a threat to ground and surface waters that may become contaminated if residues reach them.

Environmental safety considerations demand that the following questions be answered prior to herbicide selection and use:

- Is the herbicide adequately selective in terms of the plants it affect, or are there application techniques available that can make it selective?
- How toxic are the compounds to animals and humans?
- What are the behaviour and fate of herbicides, plus that of their degradation products, in the different compartments of the environment?
  - How long do the biologically active molecules persist in the soil and in water?
  - With what strength are they held (adsorbed) on soil particles?
  - To what extent are they able to leach in soil – what is the potential for groundwater contamination?
  - How sensitive to erosion is the soil in which the residues occur – what risk is there for soil particles to which residues adhere to be washed or blown into surface waters?

Risk assessments must take into account that the risk associated with any chemical (including aspirin and table salt!) is a function of inherent toxicity and time of exposure:

$$\text{Risk} = \text{Toxicity} \times \text{Exposure}$$

It means that a sensitive organism may be exposed to a highly toxic substance for such a brief time that it is not harmed, whereas a compound of relatively low toxicity may be harmful if the organism is exposed to it continually or even periodically for an extended period.

Herbicide development and registration for specific control of alien invasive plant species is outstripped by similar developments in agriculture. Relatively few herbicides are registered for use on alien plants (Vermeulen *et al.* 1998) — a situation that does not reflect the extent and diversity of negative impacts these plants have. Reasons for the perceived lack of progress with chemical control of alien invasive plants in general is attributed to: misconceptions about the cost of control; incorrect selection and application of herbicides; inferior management of control programmes, and an aversion to the use of herbicides for environmental reasons (Kluge & Erasmus 1991). They contend that unrealistic expectations placed on biocontrol agents have also contributed to weakening the incentive to use chemical control.

### *Biological control*

Against the above background biological control has been advocated as an "environmentally friendly" weed management tool. Biological control of weeds has been defined as "the planned use of living organisms to reduce the vigour, reproductive capacity, or effects of weeds" (Quimby *et al.* 1990) — the idea being to reduce competitive intensities to where they do not overwhelm plant communities (Quimby & Birdsall 1995, quoting Vogt 1989). In most crop production systems, however, the shortcomings of classical biological control by means of natural enemies of a weed is well known. Factors that obstruct classical biocontrol of weeds in agro-ecosystems include: the absolute host specificity of the biocontrol agent, the variety of weed species in a particular plant community, and the regular disturbance of the environment (Aldrich 1984). In contrast, biological control that employs natural enemies has been spectacularly successful in natural or relatively undisturbed areas (including established plantations) where the spectrum of weeds is usually smaller than in crop production systems.

The definition for biological control that was given above does not provide for weed-suppressing effects exerted by live plants, dead plant material, or for allelopathic (chemical) interactions between plants. In broad context, all practices that directly or indirectly utilise plants or their residues (both vegetative and chemical) for weed management can be classified as biological control. The closest, existing affiliation of weed biocontrol with allelopathy has been the development of mycoherbicides from native fungi. It is a form of augmentative biocontrol, involving the manipulation of fungal plant pathogens that are already present (Quimby & Birdsall 1995). Countries where variable success with mycoherbicides have been reported are: Canada, People's Republic of China, South Africa, Union of Soviet Socialist Republics, and the United States of America. The same authors suggested that the term "mycoherbicide" be reserved for fungal-produced chemicals or phytotoxins used for weed management; and that the term "bioherbicide" should be reserved for biologically produced chemicals used for weed management.

The perfect selectivity of biocontrol agents that renders their use impractical in most agro-ecosystems, is a great asset in natural ecosystems. Crops are usually grown in monoculture, and also in multiple cropping systems, but rarely are more than two crops grown together at a particular site. Therefore, weeds dominate in terms of species composition in plant communities of agro-ecosystems. In contrast, in nature, relatively few alien invaders occur at a particular site, hence indigenous plant types that dominate in terms of numbers are likely to take the place of an alien upon its demise.

The greatest shortcoming of the biocontrol strategy is that it usually takes a long time to work, in other words, activity is relatively low. Also, the target species can never be eradicated. Both these issues is not really a problem where the alien plant already completely infests an area, since any degree of control would constitute an improvement of the situation. However, where containment of a species is required biocontrol implemented on its own is a poor choice, since it will allow the infestation to radiate outwards, thus worsening the situation. In terms of its performance rating, therefore, it can be argued that activity is rather poor, selectivity is near-perfect, and persistence is good, provided the control agents need not be re-introduced from time to time.

*Vegetation management*

In natural ecosystems the obvious alternative to the above two strategies is to manage natural vegetation in such a way that alien invaders can not take hold. It simply means that bare areas or sparse vegetation are excellent niches for alien plants. Poor veld management, notably over-grazing, is the main reason why alien plants adapt so rapidly and effectively in natural vegetation. Fires can be used to suppress the growth of existing alien plants or to maintain a dense grass cover that could prevent their germination and establishment. Of course, once an area has been mismanaged to such an extent that grass is denuded, fire is no longer an option. Some areas for natural reasons such as brackish soils can not support much of a grass cover in any case, thus rendering them susceptible to invasion by alien species, provided of course that they are adapted to said conditions.

*Mechanical control*

This technique requires much more manual labour inputs than any of the foregoing measures. High labour costs and not enough people to perform tasks within acceptable time-frames are probably the greatest drawbacks. This type of control is very specific, and "activity" is also high in terms of the time it takes for a tree or shrub to felled, but "persistence" is poor if the plant is not killed and is able to regrow. For example, the cutting down of *Opuntia* spp. will be ineffective in terms of control because they can regrow from cladodes that are left behind. In this particular case, the plants will need to concentrated in heaps and burned. Most alien invaders are able to recover from mechanical control, and in fact, denser infestations are likely to result because a single cut stem or trunk can develop into multiple-stemmed plants from below the cutting surface. Further with regard to "persistence" of this control measure, regular follow-up treatments will be required. Apart from regrowth of cut plants, seeds will germinate after removal of dense cover that prevented sunlight from reaching the soil surface. In addition, the demise of "mother plants" would mean that chemical inhibitors which might have been exuded by them, and which suppressed the growth of seedlings or the germination of seed, within the tree/shrub drip-area, are thereby removed. The success of this control measure relies heavily on the ability of the team doing the work not only to do regular, but also timely, follow-up treatments. The level of management required in this case is often woefully underestimated, and sometimes not even recognised when lack of management ends in inevitable failure.

## Development of weed management strategies

The protocol for development of effective weed management strategies (programmes) should involve the following steps in the order they are presented in:

- Identify the weed, and determine its distribution. Mapping of alien infestation is a good way of assessing the extent of the problem, and also assists in judgements on the success of on-going control measures.
- Examine the pros and cons of candidate weed management practices. The criteria that require close scrutiny were dealt with above.
- Select those techniques that meet most of the requirements. It is unlikely that a single measure will be ideal. Synergism in terms of effectiveness is what should be aimed for. Reliance on a single management practice reflects an ill-conceived plan, since failure of that measure for some or other reason, is likely to cost any project both time and money. In addition, human skills that are developed in only one direction, will cost a project dearly if suddenly the focus shifts to techniques that require different aptitudes. Integration of control measures in such a way that they complement one another is the obvious way forward. Examples of strategies based on integration of weed control practices are those proposed by Lotter & Hoffmann (1998) and Hoffmann *et al.* (1998) for the control of *Opuntia stricta* in the Kruger National Park.
- After implementation of management practices, regular assessments of performance are needed, in order that timely adjustments may be made where necessary. External reviewers should be appointed for this task.

Overriding all other decisions is the management level practised (Ashton & Monaco 1991). Critical questions are: is there enough time, equipment and attention available to execute the planned programme? Needless to say, the management team should possess adequate skills, and must ensure that appropriate levels of skill exist or are developed within the project teams.

Any weed management strategy must also consider the laws pertaining to weeds and their control. In South Africa, the relevant act is the Conservation of Agricultural Resources Act, 1983 (Act 43 of 1983). According to new, draft regulations of this act many of the weeds that occur in conservation areas must be eradicated, and not simply be controlled. Weeds belonging to this class, i.e. Category 1 of the legislation currently being drafted, include: *Opuntia stricta* (Australian pest pear), *Lantana camara* (lantana), *Cardiospermum grandiflorum* (balloon vine), *Datura* spp. (thorn apples), *Xanthium* spp. (cockleburs), a host of aquatic weeds, and many others that have already procured problem status in many of our national parks and other conservancy areas. The act has far-reaching implications as regards the selection of weed management strategies. For instance, the species classified as Category 1 types can strictly speaking not be controlled but must be eradicated using all reliable control measures. This illustrates perfectly why an integrated approach in weed management should always be considered, and followed as far as is possible for maximum success. For example, biocontrol when implemented alone will not meet the expectations associated with eradication, because by its very nature, biological control will not lead to the eradication of a weed. To be fair in this regard, in the Kruger National Park for example, no other control measure applied on its own is likely to be successful either.

Unfortunately, as with all legislation, enforcement to the full extent of the law is often difficult. But it is important that management programmes must be developed within the framework of existing legislation. Finally, it should be kept in mind that the best designed plan, incorporating the most effective combination of control measures, will not fully succeed if the commitment in terms of a balanced combination of knowledge acquisition, skills, labour, money and time is not optimal.


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