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An ecosystem approach for planning sustainable management of environmental weeds in South Africa

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Abstract

Environmental weeds are an escalating problem worldwide. Integrated control is unable to keep up with the demands for management strategies for existing and new, potentially invasive plant species. The primary goal of the ecosystem approach used here is sustainable conservation management of natural systems. Only ecologically and/or economically viable habitats are given priority for environmental weed management. We recommend that habitats be ranked according to criteria that encompass the habitat's status, protection and management. Highest priority areas are treated first according to available resources to balance urgent environmental needs with management budgets. Practical guidelines in drawing up control programmes and management plans are provided. © 1998 Elsevier Science B.V.

Keywords: Environmental weeds; Management; Priority areas; Surveys; Integrated control; Rehabilitation

1. Introduction

Undesirable, exotic plant species that invade vegetation and landscapes are called environmental weeds (Groves, 1991). Cosmopolitan trade has had far-reaching consequences on exotic organisms and environmental weeds have become a major problem throughout the world (Soulé, 1990). Early colonists in South Africa considered indigenous species to be of little value and according to Stirton (1983) many exotics were introduced for food and fodder (*Opuntia ficus-indica*), aesthetic reasons (*Lantana camara*), afforestation (*Acacia mearnsii*), some being introduced accidentally (*Stipa trichotoma*). Although many exotic plants remain benign, 858 taxa (Arnold and de Wet, 1993) comprising 974 species (Wells et al., 1986) have become naturalised over the last 345 years. Of these, 161 species (38 herbaceous, 13 succulent and 110 woody) are currently invading aquatic and terrestrial ecosystems throughout southern Africa (Henderson, 1995).

The ability of land users to contain the spread of environmental weeds in South Africa has been unsatisfactory (Kluge and Erasmus, 1991) and their diversity and distribution are creating problems of such magnitude that in many situations cost-effective control has become impossible. The long-term prognosis is not good. Weed research has resources to investigate only a few of the problem species. This has resulted in serious deficiencies in the control effectiveness; 45 species (about 5%) have specific herbicide registrations (Vermeulen et al., 1996) and only 15 (about 2%) have been certified for biological

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control (Hoffmann, 1991). In an attempt to reverse a worsening situation, Kluge and Erasmus (1991) proposed the 'land unit approach'. The idea was to reduce systematically all environmental weed species in defined tracts of land to a level where they no longer presented a problem. In this manner it was speculated that whole farms could be cleared over a number of years.

This approach was tested on seven farms between 1991 and 1996 in the Umzinto magisterial district (30°05′35″S; 30°10′50″E) on the KwaZulu–Natal coast. This paper documents the planning principles and procedures developed for managing environmental weeds on whole farm systems. The ecosystem approach and 'land-unit approach' were used as the foundation for advancement.

2. Approaching the problem

Kluge and Erasmus (1991) proposed a block approach to delineating 'land-units' (tracts of land earmarked for control), the intention being to deal first with sparse infestations. In practice this approach had many weaknesses. Environmental weeds occurred in mosaics of species and densities, dispersed in a variety of habitats. The division of so called 'land-units' therefore needed to shift away from a block system to a more ecological approach.

A logical step from the block system was a habitat approach focusing on the ecosystem as a unit. Conserving and sustaining landscapes as complete ecosystems was the primary goal of the ecosystem approach (Rowe, 1992). The ecosystem approach was therefore adapted for environmental weed management. Areas given priority for weed management are habitat-orientated, namely sites requiring specific management practices, e.g., forest (fire intolerant) as opposed to grassland (fire dependent). Sharp contrasts in the character of vegetation delineate the ecotone and should be interpreted as the boundary of management units rather than abstract lines drawn on a map. Larger habitats are subdivided using topographical or cadastral features as boundaries.

Most land owners affected by environmental weeds cannot physically and/or financially treat all infested habitats in one year. Furthermore, predicting follow-up control strategies for disturbed areas that have diverse residual weed–seed banks is difficult. Natural areas worth conserving but requiring management need to be put in order of priority (Fox, 1991). These areas are called 'priority areas' rather than 'land units'. Areas falling outside priority areas are not ecologically or economically important enough to warrant management and should be left alone. These areas are usually sites that are highly disturbed (e.g., roadside vegetation) and consequently, will always be prone to weed invasions. Management programmes should therefore desist from spending time, money and labour on weed control in areas that have a low production potential or low potential return per unit effort invested. Concentrating conservation efforts and management expenses on viable ecosystems and living with environmental weeds in non-priority areas is considered more effective.

3. Planning environmental weed management programmes

The term 'programme' refers to the long term management and rehabilitation of ecosystems and all the operations required to achieve this. The term 'management plan' specifically refers to planned annual management actions in priority areas. Fig. 1 illustrates the elements in designing management programmes.

3.1. Selecting priority areas

The selection of priority areas should focus on optimum habitat management. A global picture of each private property should be viewed rather than only weed infestations. All viable ecosystems need to be determined. A mosaic of habitats will maximise the biological diversity, productivity and stability of ecosystems on the property (Burton et al., 1992). Habitats that are well managed with a minimum of disturbance are naturally resilient and self-maintaining. Factors such as areal extent, species diversity, palatability (grazing value), sustainable resources (e.g., timber, venison), threatened or rare species, can be used to help determine priority areas. Only once baseline information of key habitats has been collected can the conservation goals and priorities be set for the longer term management and rehabilitation of these ecosystems.

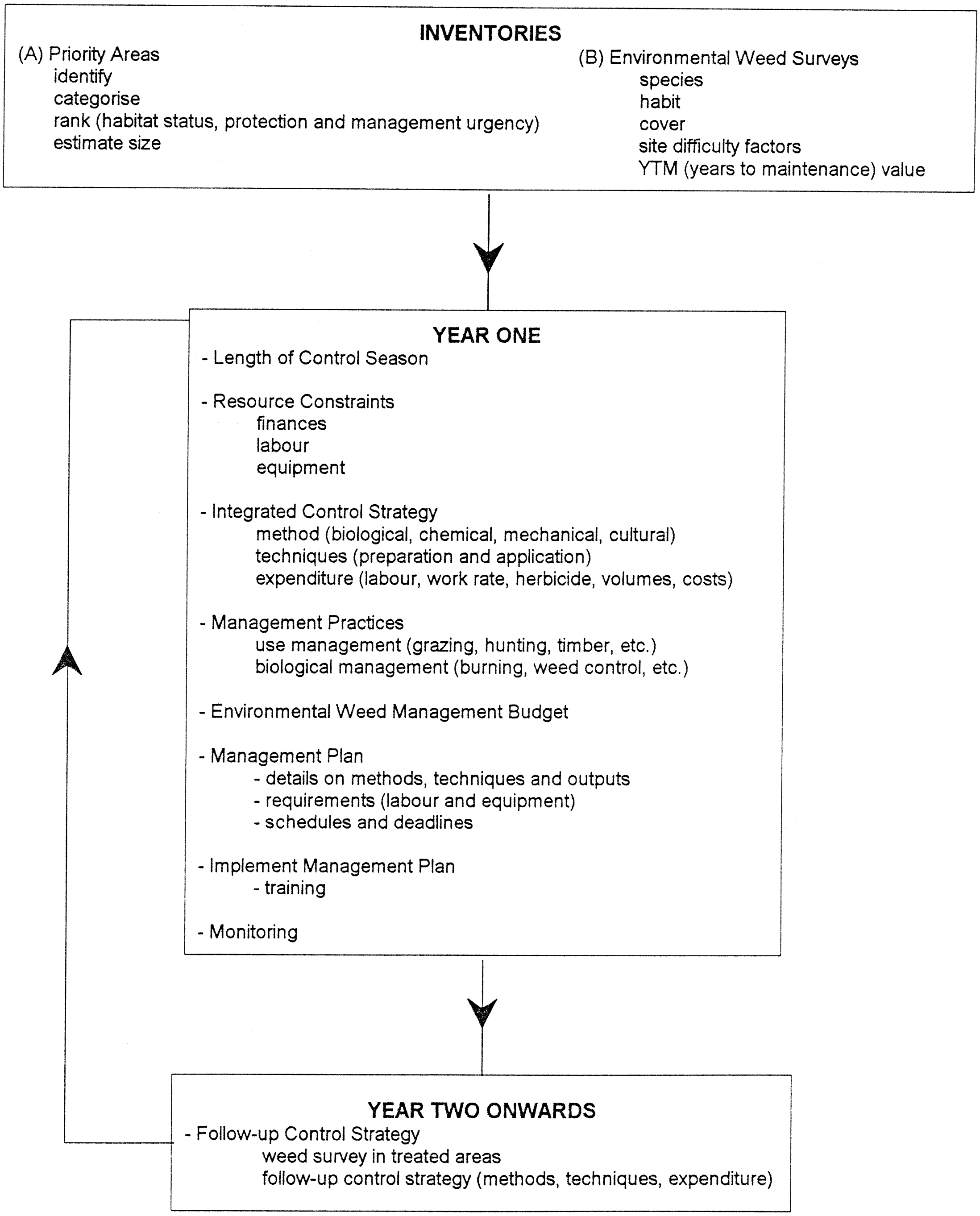

Fig. 1. Simplified flow diagram showing the elements used in planning environmental weed management programmes.

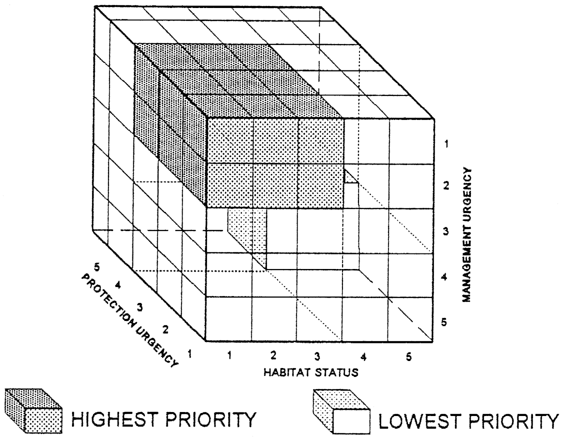

Fig. 2. Cube for ranking ecosystem priority according to habitat status, protection and management urgencies.

3.2. Ranking priority areas

An inventory of priority areas must be drawn up before any other work is undertaken (Fig. 1). Habitats with the highest rankings are treated first (Fig. 2). Priority areas can be identified from aerial photographs and verified by ground-truth surveys if land changes have occurred. Usually only a fraction of the priority areas can be treated in a season. Priority areas are ranked according to ecological criteria to promote conformity and consistency in the ranking process, and to ensure systematic treatment of priority areas over the long term. Habitats are ranked in importance to balance environmental needs with generally small weed management budgets. Each priority area is ranked according to habitat status, protection urgency and management urgency (Table 1, modified from Buttrick, 1992).

Habitat status is an assessment of quantitative and qualitative factors such as abundance, value (ecological and economic) and condition. Protection urgency involves raising the status of affected sites if threats to habitat survival are apparent. This means that potential threats have to be identified. A threat should be seen as actions or forces that result in habitat destruction that cannot be rectified through corrective management practices. Examples of threats to ecosystems are direct habitat conversion (e.g., conversion to cropland, land development) and large scale disturbances (e.g., edge effect disturbance from road construction). Ecosystem threats to sites with a habitat status of between one and three (Table 1) should be resolved wherever possible, by looking at alternative sites where development or other activities would be more appropriate. If threats to these habitats cannot be resolved and the ecosystem is to be modified, these areas should be excluded from the

Table 1
Habitat ranking for environmental weed management, after the work of Buttrick, 1992

Category	1	2	3	4	5
Habitat Status (H)	Habitats not well represented on the property (rare). Variations can include protection of rare species or breeding sites of rare animals	Habitats serving a vital function, especially wetlands, sponges, marshes and springs, i.e., water sources. Habitats with commercial value (e.g., grazing, hunting) should also be included	Habitats prone to degradation, viz. rivers, streams and aquatic habitats. These are differentiated from wetlands in that they are conduits (transport) and not sources (production) of water	Habitats common and viable. Factors such as size (area), shape, condition and spatial distribution are important constraints for habitat viability	Habitats common but degraded, e.g., disturbed and invaded by environmental weeds
Protection Urgency (P)	Habitat immediately threatened	Habitat expected to be threatened within five years	Habitat likely to be threatened after five years	Habitat unlikely to be threatened in the foreseeable future	Habitat protected
Management Urgency (M)	Management action required immediately to save a population or habitat	Management action required within five years to prevent loss	Management action required within five years to maintain quality	Management action may be needed after five years to maintain quality	Management action not necessary

control programme. Natural disturbances, succession, exotic pests, imbalances in animal populations and inappropriate management practices can result in habitat loss (Buttrick, 1992), but they are not seen as threats because ecosystems can be repaired through corrective management practices. Management urgencies refer both to biological management practices (e.g., prescribed burning, exotic removal, mowing) and use management practices (e.g., grazing, timber, hunting).

Disturbance and succession are both natural processes that can result in gradual vegetation transformation and increased risk of weed invasions (Clark, 1992; Lauenroth and Coffin, 1992; Numata, 1992; Ramakrishnan and Vitousek, 1989; Solbrig et al., 1992; Sprugel, 1991). For example, tropical grasslands are fire climax communities that are modified to secondary forest or savanna if fires are prevented from occurring (Weisser and Marques, 1979). Although land use practices will vary, e.g., grasslands managed to conserve natural pastures or used as agricultural rangelands, sustaining the resource is crucial to both.

Commercial timber plantations are often not perceived as cropland because of the prolonged rotation (10 to 40 years) and are semi-natural habitats that need to be ranked on silvicultural principles. Criteria for determining priorities are timber species, age class of stand, rotation period and weed density. Young stands with dense infestations should be given highest ranking and old stands with sparse infestations lowest ranking.

3.3. Environmental weed survey

Weed species, habit (herbaceous, reeds, shrubs (1–5 m) or trees (> 5 m)), age class (seedlings (< 1 m), saplings (1–5 m), trees (> 5 m)) and percentage estimated cover per species is recorded in each priority area. Natural variation in density and spread can make population estimates of patchy weed distributions difficult. Patchy dynamics should, however, be visualised as having homogeneous cover. A single representative value of percentage weed cover is then given per species age class per priority area to simplify matters. Five major densities have been classified, namely maintenance (0–5%), sparse (6–25%), medium (26–50%), dense (51–75%) and very dense (76–100%).

An element of difficulty must be allocated in priority areas where site factors are likely to influence the work rate of operations (Table 2). Originally three factors for correcting the labour requirements were used, namely not difficult (×1), difficult (×1.5) or very difficult (×1.75). This proved too crude and caused overestimates in grassland and underestimates in sclerophyllous vegetation. Two alternative approaches are suggested.

Firstly, an objective approach is to factorise variables (X) that impede progress, viz. slope (X_1), terrain (X_2), vegetation (X_3) and access time (X_4). Slopes are divided into four gradients, viz. 0–15°($X_1 = 1$), 16–25° ($X_1 = 1.2$), 26–35° ($X_1 = 1.5$) and 36–45°($X_1 = 2$). The nature of the terrain (e.g., rockiness) is divided into three categories, viz. not difficult ($X_2 = 1$), moderately difficult ($X_2 = 1.2$) and very difficult ($X_2 = 1.5$). Vegetation is classified according to its potential to impede operations, viz. short/open ($X_3 = 1$), variable from open to closed ($X_3 = 1.4$) and thicket ($X_3 = 2$). Access time is the percentage labour-day time taken up in reaching and leaving areas due to distance factors, viz. round trip up to 10% ($X_4 = 1$), 11–25% ($X_4 = 1.3$) and more than 25% ($X_4 = 1.5$). A work study was not conducted to validate these values under field conditions and therefore the synergistic effect of these variables is unknown. It is likely that interactions will require changes from locality to locality. A multiple regression equation with $X_{1\ldots4}$ as independent variables uses Y to correct the work rate (Table 2) for field conditions (when $Y > 1$).

$$Y = a + \sum_{n=1}^{4} (b_n X_n)$$

where: X_1 = slope; X_2 = rockiness; X_3 = vegetation; X_4 = time.

$$Y = -2.363 + 1.028X_1 + 0.646X_2 + 1.090X_3 + 0.663X_4\left(r^2 = 0.947, df = 140, p < 0.001\right)$$

Example: slope = 18° (X_1 = 1.2); terrain = moderately difficult (X_2 = 1.2); vegetation = moderately difficult ($X_3 = 1.4$); access time = 20% ($X_4 = 1.3$); $\therefore Y = 2.03$ multiplied by work rate (Table 2), e.g., 30 becomes 61 labour-days.

Secondly, a subjective approach is to rate the priority area as to its potential for increasing work rate and make adjustments using Table 2. If site factors are likely to increase the work rate, e.g., 10%, the action selected in Table 2 must then be increased by the same amount.

In each priority area it is necessary to estimate the number of years of treatment or 'years to maintenance' (YTM) before exotic species will be reduced to a level where they can be managed with minimal resources (Fig. 1 and Fig. 3). The estimate should be based on an initial treatment in the first year and, depending on weed density and complexity, a number of subsequent annual follow-up operations. For example, a sparse infestation (20% cover) can be controlled with one initial foliar spray and two annual follow-up spot-sprays, i.e., YTM = three years. Other infestations, e.g., leguminous tree species like *A. mearnsii*, have seed banks that persist for many years after clear felling and therefore the period under treatment will be much longer.

3.4. Management practices

Management practices can be used to kill or suppress environmental weeds. Fire will control most weed seedlings in grassland and savanna (Goodall and Erasmus, 1996). The use of goats to suppress weeds, e.g., *Rubus cuneifolius* (Byford-Jones, 1988; Von Krosigk, 1988; Vere and Holst, 1979), is a cultural practice used in forestry that could generate income through the sale of livestock. Incentive strategies could be used to increase land productivity on weed-degraded sites and fallow lands with depleted soil fertility, e.g., fallow cropping with species like *Chromolaena odorata* (Slaats, 1995) and the use of woody tree weeds for fuel-wood (e.g., *Acacia dealbata*) or lumber (e.g., *Acacia melanoxylon*).

Table 2
Average work rates for normal conditions expressed as labour-days per hectare for control actions in five infestation densities on study farms in KwaZulu–Natal

Habit	Action	Labour-days per hectare				
		Maintenance 0–5%	Sparse 6–25%	Moderate 26–50%	Dense 51–75%	Very dense 76–100%
Trees[b]	fell only	3	4	6	9	12
	fell and stack in situ	10	18	27	45	60
	fell and remove logs	14	25	37	60	80
	burn brush	1	1	1	2	2
	herbicide stumps[a]	0.25	0.5	1	2	2
	herbicide basal-stem[a]	2	3	5	8	10
	herbicide stem-injection[a]	2	3	5	8	10
	herbicide coppice[a]	0.25	0.5	1	2	3
	strip-bark (ringbark)	5	9	14	23	31
Saplings	slash only	5	9	14	22	30
	fell and stack in situ	7	14	20	39	55
	burn brush	1	1	1	2	2
	herbicide stumps[a]	0.5	1	2	4	5
	herbicide basal-stem[a]	3	5	7	10	12
	herbicide coppice[a]	0.25	0.5	1	2	3
Shrubs/	slash only	7	14	24	28	33
Thickets	uprooting	11	22	37	43	52
	burn brush	0.5	0.5	0.5	0.5	0.5
	herbicide coppice[a]	0.5	1	2	3	4
	herbicide stumps[a]	1	3	4	5	5
Herbaceous	uproot	6	12	18	30	40
	herbicide foliage[a]	0.25	1	2	3	4
Seedlings	handpull	1	5	n/a	n/a	n/a
	herbicide foliage[a]	0.25	0.25	0.25	0.5	0.5

[a] Types of herbicide application (treatments).
[b] Campbell, 1993.

(a) Example Priority Area (PA) Data Sheet (TM = 10)

PA	Ranking (HPM)	PA (ha)	YTM	Follow-ups
1	H1P2M1	15	7	6
2	H1P2M2	4	7	6
3	H2P2M2	8	5	4
4	H2P2M3	3	4	3
5	H2P3M3	9	4	3
6	H3P3M2	12	5	4
7	H3P3M4	1	3	2
8	H4P3M3	1	3	2
9	H4P4M5	10	3	2
10	H5P4M5	8	7	6
Total		71		

$$IPA = \sum_{n=1}^{10} \frac{PA_n}{((TM-1)-YTM_n)}$$

$$IPA = \frac{15}{((10-1)-7)} + \frac{4}{((10-1)-7)} + \frac{8}{((10-1)-5)} + \frac{3}{((10-1)-4)} + \frac{9}{((10-1)-4)} + \frac{12}{((10-1)-5)} + \frac{1}{((10-1)-3)} + \frac{1}{((10-1)-3)} + \frac{10}{((10-1)-3)} + \frac{8}{((10-1)-7)} = 23ha$$

(b) Scale and Phases of Programme

IPA (nearest whole priority area) = 23 ha

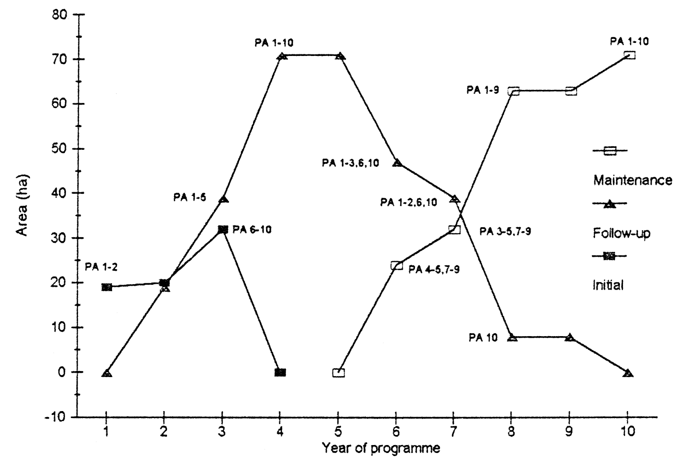

Fig. 3. Scaling the control phases of a programme for sustainable management of environmental weeds. (a) An example of a priority areas data sheet with 10 ranked habitats of variable size and YTM values. IPA = 23 ha to the nearest whole priority area using the scaling formula, where TM = 10 years. (b) Graph illustrating the allocation of area to control phase in each year of the management programme for the example data sheet (PA = priority area number).

3.5. Integrated control

Integrated control is a pest population management system that utilizes all suitable techniques either to reduce pest populations and maintain them at levels below those causing economic injury, or to manipulate the populations so that they are prevented from causing such injury. Integrated control achieves this ideal by harmonizing techniques in an organised way, by making the techniques compatible, and by blending them into a multifaceted, flexible system. In other words, it is a holistic approach aimed at minimizing pest impact while simultaneously maintaining the integrity of the ecosystem (Smith and Reynolds, 1966; van den Bosch et al., 1971).

The term ‘integrated control’ is more often associated with insect pest management in crops. Insecticides overall are far more toxic than herbicides and their effects are frequently felt across trophic levels. Herbicides used in environmental weed management (e.g., glyphosate, imazapyr, picloram, triclopyr) generally only effect plant metabolism. These herbicides have high LD_{50} (Lethal Dosage that will kill 50% of the test group of animals) oral and dermal ratings (2000–8000 mg ai kg^{-1} body mass) and do not adversely affect ecosystems and wildlife if applied correctly.

Weed management in the past had the tendency to promote integrated control as methods complementing biological control. However, according to the definition, integrated control uses the best available methods to suppress weeds without adversely affecting the environment. The danger of promoting some methods above others, e.g., not considering chemical control, is that the holistic principles of integrated control are negatively affected, restricting control options and strategies. Although biological control is the popular choice, most environmental weeds can only be controlled using herbicides and/or mechanical control. Biological control as the leading method in the integrated control of environmental weeds is limited to *Hypericum perforatum*, *Sesbania punicea*, cactus weeds (*Opuntia* species) and several aquatic weed species (Hoffmann, 1991).

In South Africa integrated control uses biological, chemical, mechanical and cultural control as methods to combat heterogeneous weed populations. Weed research organisations are likely to be the only sources of expertise when it comes to integrated control strategies for diverse environmental weeds.

3.5.1. Phases of control

Whole-farm studies have shown that three distinct phases of control need to be completed before effective rehabilitation is achieved, i.e., initial, follow-up and maintenance control phases. Initial control consists of all actions aimed at removing the original infestation. The period of initial control is usually one year. From the second season copious numbers of environmental weed seedlings will emerge in treated areas. Therefore a follow-up control phase, commencing the second year, aimed at preventing reinfestation and continuing for several years is required. One follow-up per annum per priority area is usually sufficient and must continue until population numbers decline to a level where they can be controlled with minimum input. The maintenance control phase is reached when priority areas require low annual or biennial commitment to prevent reinfestation (less than 5% cover), or can be maintained using management practices like fire and livestock. Control programmes should strive to reach maintenance control and not eradication, which is unrealistic. Manual weed control is only feasible in weed populations of low density. Tables 2 and 3 present labour-day values and volumes for herbicide application techniques used in the most important control operations.

3.6. Scaling environmental weed management

There is reluctance to control environmental weeds on low potential land because control costs can exceed the land’s value. Drought, political instability and low profits have compounded the problem by forcing adoption of short-term options like overstocking and cutbacks in weed control. However, such action can have disastrous consequences in the long term by causing land degradation, loss in carrying capacity and escalating the costs of future weed control in neglected areas. In the light of economic limitations environmental weed management must be viewed as a long-term commitment.

Management plans need to be reviewed and updated annually because it is (a) often impractical to treat all the areas in the same year and (b) impossible to predict accurately weed successional responses. Planning errors must be expected and are likely to be greatest in estimating weed density, allocating site-specific work rates, costing operations and predicting follow-up control requirements. If management plans are not updated annually, these errors will become compounded over time and seriously affect control reliability. The scope of what can be treated in a given financial year, inter alia time, labour and

Table 3
Average carrier volumes for different herbicide application techniques in five infestation densities on study farms in KwaZulu–Natal

Site	Carrier	Active ingredient (g ai l^{-1}/kg^{-1})	Volumes applied (l ha^{-1})				
			Maintenance 0–5%	Sparse 6–25%	Moderate 26–50%	Dense 51–75%	Very Dense 76–100%
Foliage	water	glyphosate (360 g l^{-1})	10	30	90	150	200
		triclopyr (480 g l^{-1})	20	60	180	300	400
		clopyralid (100 g l^{-1})	20	50	150	250	300
		metsulfuron methyl (600 g l^{-1})	20	60	180	300	400
Cut stump	water	imazapyr (100 g l^{-1})	8	25	100	120	150
		picloram (240 g l^{-1})	8	25	100	120	150
Total stump	diesel	triclopyr (480 g l^{-1})	15	40	120	140	170
		picloram/triclopyr (120/240 g l^{-1})	15	40	120	140	170
Basal-stem	diesel	triclopyr (480 g l^{-1})	35	90	140	150	170
		fluroxypyr (200 g l^{-1})	35	90	140	150	170
		picloram/triclopyr (120/240 g l^{-1})	35	90	140	150	170
Frill	water	picloram (240 g l^{-1})	0.5	2	4	6	8
		MSMA (720 g l^{-1})	0.5	2	4	6	8
Soil	water	tebuthiuron (752 g kg^{-1})	0.5	3	6	12	18

money, should be the chief criteria for estimating the annual scale of the management plan. The following formula can be used to determine the area to be initially treated per annum if the goal is reaching maintenance control in a specified time:

$$\mathrm{IPA} = \sum_{n=1}^{0} \frac{\mathrm{PA}_n}{((\mathrm{TM}-1)-\mathrm{YTM}_n)}$$

where: n = priority area number; 0 = total number of priority areas; IPA = area of initial control (ha per annum); PA = area of priority area (ha); TM = programme's target goal to reach maintenance control (years); YTM = years to maintenance control in each priority area.

Depending on TM, the area requiring follow-up treatment will accumulate for several years before control efforts become less demanding, but this relationship is area dependent (Fig. 3). Bearing in mind that demands increase exponentially in the first five to ten years of the control programme, management plans should start on a small scale to cope with the requirements. The golden rule is not to start new areas unless a commitment of time, labour and finances is allocated to follow-up control operations. It is vital to the survival of weed management programmes that control operations represent an acceptable financial burden to the rest of land management. Annual updating will ensure that all priority areas are systematically treated over the long term.

3.7. Modelling

Regression models are important for predicting purposes and in giving managers an idea of expected progress and trends. Simple linear regressions were used for predicting work rate requirements for the different weed densities in Table 2. However, rehabilitation rates differ from site to site and predictions become more difficult when more than one factor affects the rate of recovery. Stepwise multiple regression techniques use all-subsets correlation to find the minimal model that satisfactorily explains the dependent variable. For example, variables that could influence a grassland rehabilitation model are years of control, weed cover, herbicide applications, burns, labour-day input and annual rainfall (Table 4). A correlation matrix was used to identify high correlation between year and burns ($r = 0.988$). It was decided to use number of burns as a predictor variable. Stepwise regression suggests independent variables that significantly affect the rate of grass recovery are sprays (X_3) and burns (X_4). It is interesting that the independent variables weed cover, labour and rainfall had no significant effect and were excluded from the model. Multiple regression should

Table 4
An example of simple vs. stepwise multiple regression analysis for predicting the rate of rehabilitation in grassland ecosystems

Independent variables (X)						Dependent variable
Year (X_1)	% Weedcover (X_2)	Sprays (X_3)	Burns (X_4)	Labour-days (X_5)	% Deviation of mean rainfall (X_6)	% Rehabilitated cover (Y)
0	100	0	0	0	−10	0
1	10	0	1	35	5	5
2	70	1	1	39	0	25
3	20	1	2	41	15	70
4	25	1	2	41	−30	60
5	5	1	3	43	−10	55
6	5	1	3	43	10	80
7	5	1	4	45	0	91
8	0	1	4	45	−5	97
9	0	1	5	47	5	93
10	0	1	5	47	15	95

Simple Regression: Model using one independent (e.g., X_2) variable: $Y = a + bX_2$; $a = 78.70$; $b = -0.81 \pm 0.25$; $r^2 = 49.9\%$; residual $df = 9$; $p = 0.009$; Model: $Y = 78.7 - 0.811 X_2$.
Multiple regression: Year (X_1) and Burns (X_4) are autocorrelated ($r = 0.998$), ∴ Burns is the best option; X_2, X_5 and X_6 did not significantly improve the model, ∴ minimal model uses X_3 and X_4.
Model using two independent ($X_3 .. X_4$) variables: $Y = a + \sum_{n=1}^{2} (b_n X_n)$; $a = -4.93$; $b_1 = 31.10 \pm 12.10$; $b_2 = 14.85 \pm -2.93$; $r^2 = 89.4\%$; residual $df = 8$; $p = < 0.001$;
Model: $Y = -4.93 + 31.10 X_3 + 14.85 X_4$.

therefore be used instead of simple linear regression models in complex relationships to improve prediction.

4. Ecosystem rehabilitation

Ecosystems disturbed by clearing operations will be susceptible to re-invasion. Therefore, landowners must realise that once time, effort and money are spent on environmental weed control, commitment to rehabilitating and managing these areas correctly is essential. The most common practices of ‘rehabilitation’ are restoration, reclamation and rehabilitation (United States National Research Council, 1974). Restoration implies returning a degraded site back to its original state. Reclamation implies sites are habitable to organisms originally present or to others that approximate the original inhabitants. It is a term frequently used in the reclamation of surface mined ecosystems and salt-affected soils for agriculture, but is often confused with the term ‘rehabilitation’ (Wali, 1992a). Rehabilitation means that the site is made useful again by (a) creating productive or purposeful plant cover, and (b) stopping further degradation, e.g., by stabilizing the soil surface in bare, exposed areas. Rehabilitation is a more flexible concept than restoration or reclamation which requires abiding by the rigid criteria of repeating the original state.

Rehabilitation is best carried out soon after initial control operations have been completed in a given priority area. Where infestations are sparse, many natural growth forms remain and succession quickly fills the gaps left by the alien species. In dense infestations however, the soil surface is exposed making it prone to soil erosion and re-invasion. Wali (1992a) provides a useful checklist of ecosystem properties that need to be evaluated before determining rehabilitation strategy and end use. The success of rehabilitation projects rests on experimentation carried out in situ as the establishment of effective ground cover is dependant on site limitations. However, the subject has been comprehensively dealt in Wali (1992b,c).

General practises used in ‘rehabilitating’ weed degraded sites are spreading of brushwood and plant debris, sowing grass seed and planting trees. On densely infested slopes stacking plant debris into brushlines helps reduce surface soil runoff. Sowing the seeds of useful grass species like *Eragrostis curvula*, *Chloris gayana*, *Digitaria eriantha* and *Panicum maximum* are examples where species can be used to bind the soil surface, prevent re-invasion through competition and increase land productivity, e.g., grazing value. Tree planting is usually undertaken for stabilizing stream banks and restoring riverine vegetation.

5. Management plans

Management plans should be compiled and updated annually. The management plan is a document that informs the manager on the control of exotic plants in priority areas and must be brief and easy to follow. The management plan therefore needs only document prescriptions (species, habit, method, technique, dose), dates, labour and durations to treat areas. Tabulated information is preferable to descriptive information. Plans should never be binding and information must be easily added, replaced or updated.

Geographic Information Systems (GIS) are a useful tool used in a range of applications in weed management programmes, e.g., interpreting progress, scheduling operations, analysing ecological responses to treatment and map production. GIS provides a means for merging spatial and attribute data into a computerised data base allowing input, storage, retrieval and analysis of geographically referenced data. It is therefore a planning tool that can be used to measure the dynamics of the management programme.

5.1. Financial considerations

Environmental weeds are usually most problematic in non crop situations and as such are given low priority status. Although managers usually have budgets for different farming activities, weed control is generally associated with crop protection. Few farmers have budgets for the control of invasive plants in natural vegetation, e.g., indigenous forest, because these habitats are seldom used and therefore are not seen as economically viable. The control of environmental weeds is expensive and most farmers neglect vegetation that is only of conservation value.

The main components of the environmental weed budget are labour costs, consumables and equipment. Labour costs are included in the budget when seasonal workers are used and generally excluded when permanent staff are used, as environmental weed control forms only a small part of their farm activities. Labour costs include wages, rations and housing calculated per labour-day by dividing the monthly labour costs by the number of working days in the month. Consumables are expendable items, e.g., protective clothing, herbicide, diesel, light tools prone to wear and tear (e.g., machetes) etc., that can be replaced by budget running costs.

Equipment refers to capital items (e.g., tractors, light delivery vehicles, trucks and tractor driven implements) and should be costed out hourly. Costs are calculated on depreciation, interest (if bought on credit), insurance, licence, repairs, maintenance and fuel consumption. Standard tables on machinery costs (e.g. Brett, 1996) are available from agricultural information services.

5.2. Management plan design

The following items need to be determined for the first year of the management plan (Fig. 1):

1. Priority areas (see Sections 3.1 and 3.2).
2. Environmental weed survey (see Section 3.3).
3. Length of the weed management season
   Climate, species, method and application technique are the primary delimiters of the weed control season. Plants should not be treated if they are in a stressed condition. For example, *C. odorata* is a weed of subtropical areas and in high rainfall regions can be controlled throughout the year, but in semi-arid regions the plant is severely stressed in winter. *R. cuneifolius* is a deciduous weed and thus unsuitable for herbicide treatment in winter. Tree species like *Solanum mauritianum*, which is invasive in high rainfall regions of South Africa, can be controlled throughout the year by basal stem applications of herbicide. Labour resources may also influence the length of the control season, i.e., the number of areas that can be treated.

4. Resource constraints
The availability of labour and funds for wages, herbicides and equipment will determine the scale of the operation, i.e., number of areas treated per fiscal year will be determined by control costs and the budget.
5. Integrated control strategies
Information on the control of species found during the 'weeds survey' can be sought in literature (e.g. Campbell, 1993; Erasmus and Clayton, 1992; Goodall and Erasmus, 1996; Hoffmann, 1991) and software information systems. [1] However, weed research organisations should be approached for information on site-specific control strategies, especially for mixed weed communities. Once methods and techniques have been determined, calculate work rates (Table 2, see also Section 3.3), labour costs, herbicide volumes (Table 3), miscellaneous expenses and machinery costs.
6. Management practices
Identify practices that could complement weed control operations (see Section 3.4).
7. Management plan
Produce a management plan for the first year, to be used as a working document.
8. Training
The training of labour in the methods and techniques to be used, including the calibration of equipment for applying herbicide, is essential, ensuring that treatments are applied according to the management plan, safely. Calibrations for environmental weed control cannot be compared with agricultural weed control. Environmental weeds often occur as a mosaic of species requiring more than one application technique to treat an infestation. Therefore, calibrations are crude and the following serve only as a guideline:
(a) Foliar application: a 10×10 m plot must be laid out in an infestation where the weed cover is 100%. Select herbicide and application rate from Table 3 and multiply this value by 10 to calculate the volume in ml to apply to the plot (100 m^2). Prime the spray apparatus to the correct pressure (e.g., 300 kPa) and time the output (ml s). The volume divided by the output is the time it will take to apply the liquid evenly over the plot to get the correct rate of application. Visually appraise degree of leaf wetness, i.e., the distribution of spray droplets or lustre of the leaf surface and use this as the benchmark for similar applications in variable weed densities. Herbicide sprayed to runoff is wasteful as translocation of assimilates takes place in the leaves.
(b) Stump treatments can either be applied as 'cut-stump' applications where herbicides are applied to the cut surface only soon after felling, or 'total-stump' applications where the entire stump is treated.
(c) Basal stem treatments are applied to the lower trunk (0.5 m) of standing trees.
(d) Frills are horizontal notches incised into the bark and cambium around the circumference of trees. Each frill should hold approximately 1 ml of herbicide mixture. The number of frills per tree depends on the stem diameter.
9. Implementation of plan
10. Monitoring
Treatments need to be monitored and records kept on the use of substances and labour for auditing, planning and budgeting purposes. These records can be used to monitor the consistency of applications (rates per hectare), the state of the environmental weed budget and accountability in situations where environmental contamination or damage has occurred. They may also be used to fine tune the database (Tables 2 and 3) to suit the local conditions and improve the accuracy of future planning exercises.
The following items are undertaken from the second year (Fig. 1).
11. Weed surveys
Weed surveys must be carried out in areas treated in the previous year to ascertain the requirements for follow-up control. Data of interest are degree of initial control and current weed density matrix.
12. Follow-up control strategy
Determine the follow-up control strategy and cost. Subtract this from the budget to ascertain

[1] Noxious and Nuisance Plant Management Information System™, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi 39180 6199. WeedOut™, Plant Protection Research Institute, Pietermaritzburg 3200, South Africa.

availability of funds for initial control in new priority areas.
13. Repeat the first year's steps

5.3. Common sense aspects

Only registered products should be used for chemical control. Therefore, the herbicide label is an important document. Some species are resistant to certain active ingredients, e.g., *Lantana camara* is resistant to triclopyr, a widely used herbicide for woody weed control. Some herbicides have a range of registrations, e.g., glyphosate and imazapyr, and concentration is dependent on the species. The higher concentration must always be used if treating a combination of species with the same mixture. Water quality affects the efficacy of foliar application, viz. soil colloids, pH and electrical conductivity (mS m^{-1}). Dense infestations of weed should be left until areas with lower weed densities are treated, according to the habitat ranking procedure (Section 3.2).

5.4. Contingencies

The management programme will only survive hard economic times if it is flexible and can adapt to rapidly changing circumstances. When finances are scarce, the programme should be halted until favourable financial conditions return. Contingencies need to be anticipated so that the programme can be used to free resources to other sectors during crisis periods. However, depending on the period of abstention, weeds may have reclaimed some ground and extra follow-up control operations may be required.

6. Discussion

Environmental weed management in South Africa ranges from farm-scale (1:6000) to catchment-scale (1:50,000) programmes. Farm-scale programmes use a yearly budget covering all farming operations, the weed portion usually extremely limited. At this level the onus is on the individual to provide funds for the programme. On a larger scale such as mountain catchment action, funds from local and international sources are allocated to specific project budgets. For example, a project planning budget (e.g., social, ecological and commercial feasibility studies) and a project implementation budget (e.g., weed control and rehabilitation).

The weed management model described in this paper has been implemented for the sustainable protection of natural vegetation on sugar estates, timber plantations, timeshare resorts, coal mines and in mountain catchment areas, with variable success. The model has been successful in a few cases where land owners have been trained to make decisions and plan future control operations through carrying out the first year's management plan. However, the lack of finances to sustain even small-scale control programmes has proved the biggest obstacle in the success of these programmes. Usually management plans are designed for land owners but application of these plans is often not carried out. This is because land owners often have a preconceived cost of weed control for their properties, usually a gross underestimation. Once proper planning reveals true costs many land owners become unmotivated and indifferent. The reluctance by land owners to run an operation from an 'annual plan of an operations' type document like a management plan continues to jeopardise environmental weed management programmes in South Africa.

7. Conclusion

Eradication is a term that should be used with caution. Disturbances are a feature of most ecosystems and they will therefore always be prone to invasions (Ramakrishnan and Vitousek, 1989). Species compositions of weed infestations will vary according to the disturbance regimes. Until biological control strategies aimed at suppressing vegetative growth and reproduction are available for the major invasive weed species, environmental weeds must be managed sustainably on limited resources using integrated control methods. This will only be possible if proper planning principles are followed. Environmental weed management is a long term commitment to rehabilitation and the prevention of further ecosystem degradation. The ecosystem approach to environmental weed management should therefore be seen as an integral part of vegetation management.

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References

Arnold, T.H., de Wet, B.C., (Eds.), 1993. Plants of southern Africa: names and distribution. Memoirs of the Botanical Survey of South Africa No. 62, National Botanic Institute, Pretoria, 823 pp.

Brett, M.A., 1996. Guide to machinery costs. Division of Agricultural Economics, KwaZulu–Natal Department of Agriculture, Pietermaritzburg, 51 pp.

Burton, P.J., Balisky, A.C., Coward, L.P., Cumming, S.G., Kneeshaw, D.D., 1992. The value of managing for diversity. Forestry Chronicle 68 (2), 225–237.

Buttrick, S.C., 1992. Habitat management: a decision-making process. Rhodora 94 (879), 258–286.

Byford-Jones, C., 1988. Use goats to weed timber lands. Farmers Weekly, October 7, 46.

Campbell, P., 1993. Wattle Control. Plant Protection Research Institute Handbook No. 3. Arrow Print, Pietermaritzburg, 42 pp.

Clark, J.S., 1992. Disturbance, climate change, and forest rehabilitation. In: Wali, M.K. (Ed.), Ecosystem Rehabilitation: Ecosystem Analysis and Synthesis, Vol. 2. SPB Academic Publ., The Hague, The Netherlands: pp. 165–186.

Erasmus, D.J., Clayton, J.N.G., 1992. Towards costing chemical control of *Lantana camara* L. S. Afr. J. Plant Soil 9 (4), 206–210.

Fox, M.D., 1991. Developing control strategies for environmental weeds. Plant Protection Q. 6 (3), 109–110.

Goodall, J.M., Erasmus, D.J., 1996. Review on the status and integrated control of the invasive alien weed, *Chromolaena odorata*, in South Africa. Agric. Ecosyst. Environ. 56 (3), 151–164.

Groves, R.H., 1991. Control of environmental weeds. Plant Protection Q. 6 (3), 95–98.

Henderson, L., 1995. Plant invaders of southern Africa. Plant Protection Research Institute Handbook No. 5, Agricultural Research Council, Pretoria, 5, 1995, p. 177.

Hoffmann, J.R. (Ed.), 1991. Biological control of weeds in South Africa. Agri. Ecosyst. Environ., 37 (1–3) 1–255.

Kluge, R.L., Erasmus, D.J., 1991. An approach towards promoting progress with the control of woody alien invasive plants in Natal. S. Afr. Forestry J. 157, 86–90.

Lauenroth, W.K., Coffin, D.P., 1992. Below ground processes and the recovery of semiarid grasslands from disturbance. In: Wali, M.K. (Ed.), Ecosystem Rehabilitation: Ecosystem Analysis and Synthesis, Vol. 2. SPB Academic Publ., The Hague, The Netherlands, pp. 131–150.

Numata, M., 1992. The degradation of grassland ecosystems and their recovery. In: Wali, M.K. (Ed.), Ecosystem Rehabilitation: Ecosystem Analysis and Synthesis, Vol. 2. SPB Academic Publ., The Hague, The Netherlands, pp. 75–84.

Ramakrishnan, P.S., Vitousek, P., 1989. Ecosystem-level processes and the consequences of biological invasions. In: Biological Invasions: A Global Perspective, Drake, J.A., (Ed.), Scope. Wiley, Chichester, pp. 281–300.

Rowe, J.S., 1992. The ecosystem approach to forestland management. Forestry Chronicle 68 (1), 222–224.

Slaats, J., 1995. *Chromolaena odorata* fallow in food cropping systems: an agronomic assessment in South–West Ivory Coast. PhD Thesis, Wageningen Agricultural University, ISBN 90-5485-442-1, 176 pp.

Smith, R.F., Reynolds, H.T., 1966. Principles, definitions and scope of integrated control. Proc. FAO Symp. Integrated Pest Control, Rome, 1, pp. 11-17.

Solbrig, O.T., Goldstein, G., Medina, E., Sarmiento, G., Silva, J., 1992. Responses of tropical savannas to stress and disturbance: a research approach. In: Wali, M.K. (Ed.), Ecosystem Rehabilitation: Ecosystem Analysis and Synthesis, Vol. 2. SPB Academic Publ., The Hague, The Netherlands, pp. 63–73.

Soulé, M.E., 1990. The onslaught of alien species, and other challenges in the coming decades. Conservation Biol. 4 (3), 233–239.

Sprugel, D.G., 1991. Disturbance, equilibrium, and environmental variability: what is 'natural' vegetation in a changing environment?. Biol. Conservation 58, 1–18.

Stirton, C.H. (Ed.), 1983. Plant invaders: beautiful, but dangerous. Botanical Research Institute, Department of Agricultural Technical Services, Cape Town, 168 pp.

United States National Research Council, 1974. Rehabilitation potential of western coal lands. Ballinger Publ., Cambridge, MA.

van den Bosch, R., Leigh, T.F., Falcon, L.A., Stern, V.M., Gonzales, D., Hagen, K.S., 1971. The developing program of integrated control of cotton pests in California. In: Huffaker, C.B. (Ed.), Biological Control. Plenum, New York, pp. 377–394.

Vere, D.T., Holst, P.J., 1979. Using goats to control blackberries and briars. Agric. Gazette New South Wales 90 (4), 11–13.

Vermeulen, J.B., Dreyer, M., Grobler, H., van Zyl, K., 1996. A guide to the use of herbicides (15th edn.). National Department of Agriculture, Pretoria, Republic of South Africa, 153 pp.

Von Krosigk, F.K., 1988. Goats to control weeds. Forestry News 4, 11.

Wali, M.K., 1992a. Ecology of the rehabilitation process. In: Wali, M.K., (Ed.), Ecosystem Rehabilitation: Policy Issues, Vol. 1. SPB Academic Publ., The Hague, The Netherlands, pp. 3–23.

Wali, M.K. (Ed.), 1992b. Ecosystem Rehabilitation: Policy Issues, Vol. 1. SPB Academic Publ., The Hague, The Netherlands.

Wali, M.K. (Ed.), 1992c. Ecosystem Rehabilitation: Ecosystem Analysis and Synthesis, Vol. 2. SPB Academic Publ., The Hague, The Netherlands.

Weisser, P.J., Marques, F., 1979. Gross vegetation changes in the dune area between Richards Bay and the Mfolozi River, 1937–1974. Bothalia 12 (4), 711–721.

Wells, M.J., Balsinhas, A.A., Joffe, H., Engelbrecht, V.M., Harding, G., Stirton, C.H., 1986. A catalogue of problem plants in southern Africa. Memoirs of the Botanical Survey of South Africa, No. 53, 658 pp.