Control and management of invasive alien woody plants in the tropics

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Summary

This report draws together recent research and practice on combatting the growing problem caused by alien trees and shrubs. It has most applicability to the tropics and sub-tropics, and concentrates on "environmental" weeds in protected areas, rather than those affecting agriculture or intensive forestry. The main points from the report can be summarised thus:

Ecology. An understanding of the biology of the alien and the ecology of the invasion process should be fundamental. Ecological data can be costly to obtain, so an assessment has to be made of what level of information is necessary for the most appropriate management response.

Management. Managers of natural areas should recognise that generally a key requirement is to maintain ecosystems in as close to their 'original state' as possible, but that perhaps all ecosystems apparently undisturbed by human activities can be vulnerable to invasion. Managers should be cautious about introducing exotic plants into protected areas and should try to ensure that potentially invasive plants are detected as early as possible.

Assessing effects. Many invasive species affect, to a varying degree, the structure and function of invaded ecosystems. However it is difficult to determine accurately their impacts. Furthermore, even if demonstrated, these impacts cannot easily be classified as neutral, positive or negative because the cultural, political, social and employment background of the observer will to a large extent determine the conclusions reached.

Control. The initial step in developing an effective management programme should be the mapping of the current and potential range of the species, its density and size class distribution. Biological control is at present impractical for tackling many invasions in the tropics, but there is a wide variety of physical/chemical methods for control available, and the labour-intensive nature of this work should be less of a deterrent than in rich countries. Removing dense infestations of woody plants can take over 30 man-days per hectare.

1 Introduction

A large number of woody plant species have been introduced to various tropical regions, but only a fraction (around 1%) of them have spread into new habitats and even fewer have become serious pests. Here we consider how land managers can detect invasive woody plant species, assess their threat to native vegetation, and manage and control them if this is necessary. Of particular importance is the gathering of information on the invasive plant and the ecosystems it invades prior to decision making.

In many parts of the world introduced woody plants have become invasive and have necessitated some form of management. The resources needed to control invasive plants can be very large, for example in 1991 the Australian Federal Government provided AS$2 million to mechanically and chemically control *Mimosa pigra* to halt its spread and protect a nearby World Heritage site from invasion (Miller *et al*. 1992).

Emphasis is placed on the management of alien species in protected areas rather than man-made habitats. Protected area is a term used to include all areas of natural or semi-natural vegetation in which the conservation of the natural community is a major objective, and it therefore includes areas designated as national parks, nature reserves, wildlife conservation zones and so on. The management of land outside a protected area can often be crucial to the conservation objectives within it, and to broader conservation goals within a country. Land outside protected areas, and forestry plantations and amenity areas in particular, often act as the main seed source for a number of invasive woody plants. Therefore, control of alien plants outside protected areas can be very important.

2 Addressing the underlying causes of invasions

2.1 Knowledge requirements

An understanding of the biology of the alien and the ecology of the invasion process should be fundamental to all attempts at managing alien plants, but can be difficult and costly to obtain. Therefore, an assessment has to be made of what level of information is desirable and is feasible to obtain. The primary objectives here are to gather necessary information on the following:

- The taxonomic identity of the alien plant. In some cases specimens will need to be collected for identification by experts. Molecular biology techniques hold potential for distinguishing species or provenance from close relatives where this cannot readily be done by morphological criteria.

- The ecological history of the invader. This entails an assessment of the potential time-lag between the species introduction and spread, the intensity, extent, rate of change and impact of the invasion as well as the environmental factors (e.g. disturbance) affecting the invasion.

- The type of control that is likely to be most effective, or effective at least cost. The level of information needed depends primarily on the extent of the invasion, and the identification of underlying causes or predisposing factors that facilitate the invasion.

- Details of the actual control method. The level of information needed depends mostly on the type of control. If the invasion is small, and containable with the use of manual control only, rather limited information is needed - how does the species respond to physical damage and herbicides? Much more detailed information is needed for biological control and, usually, for habitat manipulation.

2.2 Maintain the natural ecosystem processes

A key requirement is to maintain the ecosystem in as close to the 'original state', the most recent state before the impact of modern man, in which the native plant and animal communities evolved, as possible. The key processes are discussed below, though managers have little control over some of them.

Canopy disturbance regime. Many invasive species are dispersed more rapidly into disturbed areas and many are also competitively favoured in conditions of higher levels of available resources, especially light. Therefore, disturbance of the existing vegetation canopy, whether it is of trees, shrubs or herbs, is a key feature of many invasions. Disturbance caused by tree cutting or livestock grazing can clearly increase the rate of invasion by alien plants and can be limited by man.

Fire. Fire suppression policies carried out in many Mediterranean and warm temperate countries change the natural functioning of the ecosystem and so can lead to the invasion of fire sensitive species, as in the case of *Pittosporum undulatum* in Australia (Narayan 1993). The interaction between fire and invasive woody plants has been extensively reviewed by Bond & van Wilgen (1995).

Nutrient budgets. Many invasive species are competitively favoured in conditions of higher levels of available mineral nutrients than normally experienced by the native vegetation. In the Everglades, Florida, agricultural soil, derived from crushed limestone, was removed to exclude *Schinus terebinthifolius* (Doren & Whiteaker 1990).

Hydrological regime. Drainage, and consequent lowering of the water table below soil surface level, has been a major factor in the invasion of alien woody species in southern Florida. It could be predicted that where shortage of water is a limiting factor for plant growth, an increase in the availability of water is likely to favour invasive species more than native species.

Herbivores. Introduced pigs and goats create the disturbance essential for the establishment of many alien plant species on several islands (Stone & Loope 1987), or can preferentially eat native plants, giving the alien a competitive advantage. In such cases it will often make more sense to remove the animal (if this is feasible and politically acceptable), rather than try to directly control the alien plant species.

Seed dispersers. Alien vertebrates, including birds and mammals, can be important dispersers of alien woody plants, (Cuddihy & Stone (1990) have reported a number of cases for Hawaii). Investigation of the main means of dispersal of the alien plant species should be carried out to determine if this provides the best opportunity to control the invasion.

3 The detection and extent of the species

3.1 Detection

The early detection of alien plants is crucial. This may be achieved by paying attention to the following:

- Establish a list of plant species known to be invasive in regions with similar climatic and ecological characteristics.
- Determine which of these species are present in the protected area and surrounding region. Set up and regularly update a list of newly introduced ornamental plants. A database of recorded locations of introduced species should be initiated and distribution maps for fieldworkers produced.
- The vegetative and reproductive potential of the alien species should be assessed. The mode of dispersal of propagules (i.e. fruit, seed, vegetative material) needs to be identified and in the case of animal dispersal the identification of the animal(s) is required.
- Monitor potential natural regeneration. The frequency of monitoring should be determined by the biology of the weed(s) or potential weed(s), particularly the time taken to reach reproductive maturity, and should be more frequent in habitats in which the weed is more likely to establish or grow more rapidly. For wind-dispersed species only the 'seed shadow' needs to be investigated whereas for vertebrate-dispersed species the area to be monitored will depend on the behaviour and range of the disperser. Species dispersed by water may disperse over very long distances during heavy flooding and this should be taken into consideration during monitoring operations.

- Roads and tracks often act as corridors for the spread of invasive plants into natural areas and need to be looked at in detail. Propagules may be transported by animals, humans (e.g. shoes), vehicles (e.g. tyres), soil and dumping of horticultural refuse and the extent of these activities needs to be monitored.

- Very large disturbance events occur at irregular intervals (often centuries) and may affect large areas. Conditions caused by such events are ideal for the spread of most introduced species and special care should be shown to monitor the recovery of vegetation and possible spread of invasive plants.

- Staff of protected areas should be made aware of the threat from alien plants and should be instructed to look out for weeds that may be likely to invade, both within and outside protected areas, based on evidence from similar habitats elsewhere. Staff should be issued with invasive woody plant distribution maps and identification guides.

3.2 Determining the extent and density

The initial step in developing an effective management programme should be the mapping of the current and potential range of the species, its density and size class distribution. However, care must be taken not to use so much time or resources in this step that the population is allowed to expand significantly before control measures are initiated. The level of detail required is determined by the purpose of the assessment. A survey to assess the extent of alien plant invasions in a large number of areas (perhaps as part of a programme to compare the conservation status of these different areas) would need less detailed information than one to plan an actual manual control operation.

The survey method depends on the extent of the invasion, the terrain in which it occurs and the resources available. Regular surveys should be undertaken to provide information on the rate of weed expansion and the effectiveness of any control measures. Survey methods include:

Remote sensing. At the largest scale satellite images could be useful, especially where an alien woody plant has heavily invaded large areas of a treeless vegetation. However, the use of LANDSAT data to map the distribution of *Melaleuca quinquenervia* in south Florida was unsuccessful (Bodle *et al*. 1994). On rangelands remote sensing techniques, including computer based image analysis, are effective in assessing infestations of noxious plants as long as the right phenological stage of the targeted species is investigated (Everitt *et al.* 1995).

Aerial photographs have been used and are generally more useful, allowing much greater resolution and a longer historical record. In the case of species which can regenerate under forest canopy, such as *Miconia calvescens* in Tahiti, aerial photographs will only detect canopy individuals and fail to reveal the true extent of the invasion (Meyer 1996). To monitor the spread of *Melaleuca quinquenervia* into non-forested ecosystems of Florida, the use of infrared photography at a scale of 1:12,000 was suggested to detect individual trees. A survey at a scale of 1:40,000 was carried out but only allowed the detection of mature, monotypic stands larger than one hectare (Bodel *et al*. 1994). The rate of spread can be estimated from aerial photographs for a number of different years (e.g. *Mimosa pigra* in northern Australia, Lonsdale 1993). Aerial photographs must be verified with ground surveys. In some specific cases an invader may be detected in natural vegetation using aerial photographs or in mountainous areas from vantage points. Although the phenological status of plant is critical, some species with contrasting foliage, such the pale-leafed *Aleurites moluccana*, can be readily recognized in forest stands at any time of the year either from aerial photographs or from vantage points in mountainous areas (Kepler 1990, p. 71).

In North America *Tamarix chinensis* has been readily detected and it distribution mapped in late November, when its foliage turned a yellow-orange to orange-brown colour prior to leaf drop, using airborne video data in conjunction with global positioning system and geographic information system technologies (Everitt *et al.* 1996).

Ground survey. The various techniques of ground survey are not dealt with fully here, but should include areal stratification if the area is composed of relatively distinct sub-areas, defined by degree of invasion or forest type, for example. Plots (permanent or temporary) are usually the best means to record the information, transects being useful if the intention is to sample along a gradient of some vegetational or environmental factor. Nested sub-plots are useful for sampling successively smaller individuals in smaller areas. The level of data collection should be dictated by the objectives and available resources, but ranges from:

- Assessments of the frequency of alien plants as seen from roads throughout a region (as with Henderson & Musil 1984). Regular monitoring near points of introduction of alien species (e.g. forestry plantations, amenity planting, botanic gardens) is desirable.

- Simple estimations of coverage of alien and native species in each sampling unit or plot.

- The permanent marking, measuring and identification of all individuals of all species, native and alien, within each sampling unit or plot (refer to Alder & Synott (1992) for techniques of permanent sample plots).

Historical survey. Much useful information can be gained from research of local records and unpublished material. For management the greatest value of historical records is where they provide evidence that the spread of a species is dependent on occasional events, such as major hurricanes or changes in livestock grazing pressure. In this case the present rate of invasion (in the absence of such occasional events) may provide little indication of the potential rate. A number of highly invasive species are known to have spread only after major environmental disturbances (see case histories for details).

Local knowledge and public awareness. People who live in the area may have much information, some of it from their predecessors, on the spread of alien plants and other information to do with their use and effects. Locals may also be able to monitor future changes.

It can be very difficult to interest the public in the problem of weeds. In Hawaii for example, where the publicity about invasive plants is probably higher than anywhere else in the world, new tourist developments in or near natural vegetation still landscape their gardens almost exclusively with exotic plants (Yee & Gagné 1992).

In order to prevent the spread of the highly invasive tree *Miconia calvescens* to the remaining islands Society Islands a colour leaflet outlining the problem and providing instructions to local inhabitants on what to do if they came across the species (Meyer undated). It is not known how effective the dissemination of such material is.

4 Assessing the effects of alien woody plants

All introduced species, but particularly invasive species, have some form of impact on the environment of the introduced region. Many species affect the landscape for instance as a result of their distinct morphology or striking floral or fruit displays. Many invasive species affect, to a varying degree, the structure and function of invaded ecosystems. However it is difficult to determine accurately their impact(s). Furthermore, even if demonstrated, these impacts cannot easily be classified as neutral, positive or negative because the cultural, political, social and employment background of the observer will to a large extent determine the conclusions reached. Natural regeneration can be given as a simple example. To foresters the regeneration of a desirable species (e.g. introduced timber trees) is judged positive but that of a forest weed (e.g. *Chromolaena odorata*, *Clidemia hirta*) as negative whereas to a manager of a 'natural' ecosystem the regeneration of any exotic species will be seen as negative. In this report we assume that an introduced species has a negative impact if it alters ecosystem structure and function.

Accurately determining the effects of an alien woody plant is difficult or impossible without long term research. This is due mainly to the length of the life cycle of woody plants and to the medium and long term disturbance cycles usually affecting the invaded ecosystems. Here we can only make a few general points about how someone could go about assessing the effects of an invasive plant.

4.1 Negative effects

The negative effects of an invasive species are closely correlated with the maximum density that the species can attain and its persistence at any one site, so the most heavily invaded areas should be investigated first. The principal questions are:

- How dependent is the alien on disturbance for its recruitment? How persistent is the species in the community under the prevailing long-term disturbance regime?

- What is the negative impact of the species? Does the species grow so densely or produce allelopathic compounds that native vegetation is very sparse beneath? In cases of early invasion, seed production or dispersal may be insufficient to lead to dense regeneration of the alien, but with more established populations the seed rain or soil seed bank can be so large that seed availability ceases to be a limiting factor.

- In areas with a high species richness and endemism, does the invader significantly affect the regeneration of rare and endangered plant species? Similarly what is the impact of the invader on animals with significant conservation value? Does the invader favour introduced animals to the detriment of native ones?

- Does the invader alter nutrient and hydrological cycles, light regime and fire susceptibility?

- Species may seriously affect human activities. A number of species create physical barriers to humans (e.g. *Clidemia hirta*) or may create a health problem (e.g. *Lantana camara*, *Melaleuca quiquenervia*). Some invasive species are poisonous to domestic animals (e.g. *Lantana camara*) while others become weeds of agricultural, forestry or pasture land (e.g. *Mimosa pigra*).

4.2 Positive effects

Beneficial effects can be great and have in the past sometimes been overlooked by protected areas managers, scientists and conservationists. The role of the weed in the local economy and the public perception of its value must considered. Possible beneficial effects of alien woody plants include:

- Timber; alien trees can produce good quality timber, (e.g. *Pittosporum undulatum* in Jamaica).

- Wood for use as firewood or charcoal; invasive woody plants can often be a highly productive source, often with a high coppicing ability.

- Coloniser of steep or bare slopes; the highly invasive *Pueraria lobata* and *Pueraria thunbergiana* stabilise steep slopes in, respectively, south eastern U.S.A. and Puerto Rico (Markin & Gardner 1993; Telford & Childers 1947).

- As a source of nectar and pollen for bees and insects.

- As a source of fruit for animals and people; for example, in Fiji *Psidium guajava* (guava), a noxious weed of pasture, is very popular for making jellies and jams (Mune & Parham 1967).

- Aesthetic values; the public may prefer the pretty flowers or tallness of an alien tree to the more subtle appearance of a native tree, and do not share to such a degree concerns about the ancestry of the plant or how "natural" is its presence.

- Traditional medicine often uses invasive species although it is unclear whether these 'new drugs' have any practical purpose.

- Biodiversity value; on Philip Island (south Pacific Ocean) *Olea europea* L. subsp. *africana*, and associated leaf litter, is probably responsible for the survival of an endemic species cricket (Rentz 1993). On this rabbit infested island the introduced plant, which also protect the island's only naturally occurring clone of *Hibiscus insularis*, needs to be preserved until native shrubs flourish once again and provide the protection the cricket needs.

4.3 Selecting which alien to control

Generally, tropical plant communities susceptible to invasive woody plants tend to be invaded by more than one species at a time. Furthermore, in a given region, different species will spread in different plant communities. Resources rarely permit more than a few species to be controlled, so prioritising which species to control in which habitat is necessary. Not only must the cost and benefit of removing each species be considered, but the effect that each species may have on other alien weeds, and the consequences of its removal, should also be assessed. It is very difficult to predict the invasiveness of alien species and even more difficult to accurately predict the relative effects each may have, but some assessment is necessary. Some of the factors that should be considered are:

- Invasiveness and potential impact of the species.
- Current extent and density of the invading population.
- Habitat types invaded and their recent disturbance history.
- Effect that the species or its removal has on the invasion of other weeds.
- Ease of control and the threat of re-invasion from outside the area.
- Species characteristics including dispersal agent and potential dispersal distance, presence or absence of seed bank (if present need to know size, duration of seed viability) and vegetative propagation (suckering, coppicing, layering) ability.

For important species for which there is much information, a Cost-Benefit type analysis can be done. With less information or more species, a simpler approach would be to:

- Score for each species each factor that could affect the cost and benefit of control (such as potential impact on the ecosystem if the species were allowed to spread, relative extent, resistance to herbicides).

- Weight each factor based on more or less subjective assessments of how important it is and whether it is 'good' (plus) or 'bad' (minus).

- Combine the scores to derive a ranking of control priority.

Since 1982 in the Hawaii Volcanoes National Park there has been a growing emphasis on controlling easily eradicable species (Tunison & Zimmer 1992). In 1988 forty-one alien plant species were being controlled, mostly species present in low numbers but judged to be potentially widespread and troublesome. This emphasis on the control of alien species with still only limited ranges is supported by uncertainties about which species will eventually become a problem. However, another 29 species were so widespread that manual control was no longer attempted against them, except in Special Ecological Areas (see below). Work was initiated on the biological control of three of these more widespread species (Tunison 1992). In Réunion in the Indian Ocean a ranking system based on five criteria has been established (Macdonald *et al*. 1991). Thirty three species were ranked for each of the following criteria:

A. Current extent of invasions of primary habitats
B. Difficulty with which a species can be controlled
C. Potential extent of invasion
D. Potential rate of spread
E. Ecological-impact ranking

There is much subjectivity involved in ranking the species, particularly with criterion E, but the broad expertise and detailed knowledge of ecological characteristics of both species and habitats by managers should ensure that such a ranking system is fairly reliable.

5 Managing populations of invasive woody plants

Having decided which species to control, the next decision is where in the species' range to begin control and how much to remove in each area. Allowance must be made in the costing of control for follow-up control operations if it is thought that they may be needed.

5.1 Where to control

As with the choice of which species to control, the decision about which areas to control needs to be taken after a consideration of the costs and benefits of controlling different areas. There has been a tendency in the past to concentrate research and effort on the methods of eradicating individual plants, without giving enough attention to where the priority of control should be. Much past effort has been directed towards clearing weeds where the invasion is most pronounced, where the greatest impact on native vegetation has already taken place. This tendency has often been reinforced by a reliance on volunteer labour, which means that effort has to be expended in areas that are accessible, safe and where the clearest results can be obtained. This is an overconcentration on tactics rather than strategy. A strategic approach needs to consider the importance of "nascent foci" (Moody & Mack 1988). Moody & Mack modelled the invasion process and clearly showed that, to slow the overall area invaded, in just about all conceivable circumstances, it was more effective to eradicate small founding populations ("nascent foci") first.

5.1.1 Scattered populations of the species

Although clearing isolated populations is the best strategy to control an invasion, the costs per plant can be high. The areas are often remote and sometimes steep, and plants are often difficult to find. However, it is usually much less expensive to clear these areas than more heavily invaded areas, so the policy has a favourable cost:benefit ratio. Areas with a low abundance of the invading species could be sub-optimal for it, and so not vulnerable to heavy invasion and therefore major change, they could act as corridors for the invasion of more vulnerable areas.

5.1.2 Clearing limited areas

With more advanced invasions where the prospect of eradication from the whole of the invaded range is slight the objective could be to keep the weed out of limited areas; control of outlying satellite populations may still take place, unless a decision has been made to rely solely on biological control in the long term. But this decision should be a last resort, as not only are the areas outside likely to become very heavily invaded, but also the seed input may increase so much that the policy of exclusion of the alien becomes unsustainable.

These limited areas should therefore be as large as possible and the presence of buffer zones of reasonably intact and uninvaded vegetation around them will increase their viability.

One type of area is the Special Ecological Area (SEA) that has been developed in the Hawaii Volcanoes National Park (Tunison & Stone 1992). These areas now cover 5,266 hectares of the park (7.5% of the total), ranging in area from 17 to 3,380 hectares. The main reasons for the development of the concept of SEAs were:

- The impossibility of managing widespread alien species.
- The need to protect the most intact, representative and diverse areas, and valuable research and interpretive sites.
- The relatively small alien plant populations within the area and so the relative ease of control.
- The need to integrate feral animal control. Sometimes smaller areas are fenced to keep damaging animals out.
- When the incremental control of weeds is effective. When control of a species is assured the area can be expanded or more areas established.
- Biological control cannot be guaranteed to be successful against all weeds.

Workload requirements inside SEAs in the Hawaii Volcanoes National Park have dropped by 73% as the weed density has decreased, uprooting replaced stump cutting treatments and workers became more efficient at finding the plants (Tunison & Stone 1992). In several other places in Hawaii control is focusing on steep gullies as they are relatively uninvaded, largely because pigs cannot get access to them (Tanimoto & Char 1992).

The use of "Intensive Control Areas" (ICA) is a similar idea, used in the control programme against *Cinchona succirubra* on Santa Cruz Island in the Galapagos Islands. Control was concentrated in a 1,000 hectare ICA, which was gradually expanded westwards into the prevailing wind from where most of the *C. succirubra* seeds came from (Macdonald *et al*. 1988).

5.1.3 Clearing heavily invaded areas

Clearing heavily invaded areas should normally be a lower priority because the costs of clearance and follow up management can be great with little overall impact on the rate of spread. Once the outlying populations are eradicated of course the benefit of starting to eradicate the heavily invaded areas rises. There are two circumstances in which clearing dense populations of the alien could be as high a priority as clearing scattered populations:

- If the value of the alien (its timber for example) is greater than the cost of harvesting it. This may be the case with *Pittosporum undulatum* in Jamaica.

- If the soil seed bank of dense infestations of the alien plant were to start to rise and/or the soil seed bank of native species were to start to fall after say 20 years, so that after this the chances of re-establishing native vegetation is much reduced, it might make more sense to remove 20 year old populations than younger more scattered ones.

5.2 How much to remove

In sexually reproducing species, removing seed producing individuals is obviously necessary to stop an invasion. In the case of dioecious species the removal of male individuals is not necessary. The relationship between the number of seeds dispersed by birds and size of tree is often not a simple one, larger trees sometimes attracting a disproportionately large number of birds (potential dispersers) than smaller trees (Denslow 1987). With wind-dispersed trees dispersal distance can be much greater if an individual emerges above the canopy, but dispersal distance is usually more restricted than for bird disseminated species. In case the invasive species spreads by vegetative means only, special attention must be paid to the removal of all individuals in riverine habitats as propagules may be spread to distant sites during floods.

Where the alien is scattered and the individuals are generally of a small size (and so the soil seed bank, if present, is likely to be small) it will probably be best policy to remove all reproductive or near reproductive individuals at least.

Removal of an alien tree from heavily invaded forests leads to a greater opening up of the canopy than its removal from lightly invaded areas, increasing the chance of establishment of other alien weeds. This risk is often added to by the usually greater proximity of alien seed sources to areas already heavily invaded, most weed propagules usually coming from the same source (such as a botanic garden) or from the same direction. In regions where the invading woody plants form monotypic stands on a previously shrub-/tree-free landscapes, their removal will result in large bare areas where non-native grasses and forbs often become dominant. However, removing all individuals of the alien from a heavily invaded area does have advantages:

- It will stop, at least temporarily, the species extending its range by seed produced in that area.

- It is relatively straightforward, easy to organise, and more economic than selective treatment of scattered alien plant individuals.

- Follow up management can be concentrated in relatively small, well-defined areas.

But it also has disadvantages:

- Dense recruitment of the same species may be triggered, as with *Pittosporum undulatum* in Jamaica.

- The invasion of other weed species may be promoted. These can be more difficult to control than the original alien (as with *Acacia longifolia* replacing *Hakea sericea* in South Africa (Pieterse & Cairns 1986)) or less desirable (for example, a persistent scrambling herb replacing an alien tree).

- The sudden opening of the canopy can lead to soil erosion, the risk of fire and forest clearance for agricultural crops.

Ways of reducing the probability that the cleared areas will remain dominated by alien plants include:

- Reduce the population of the alien gradually. The rate at which the alien can be removed depends on the amount of disturbance necessary for the establishment of juveniles of the species and other alien plant species (in comparison with native species).

- Girdle trees instead of cutting. In Hawaii the girdling of *Myrica faya* trees lead to the dense regeneration of a native tree fern, *Cibotium glaucum*, whilst cutting and removing all *M. faya* trees lead to the sporadic recruitment of *M. faya* and the native tree *Metrosideros polymorpha* but dense growth of mostly alien herbaceous and woody species (Aplet *et al*. unpublished).

- Use biological control. However, biological control that kills a large proportion of the population suddenly (rather than slowly or, more slowly still, by preventing seed production) leaves the area open to the same sorts of dangers. The danger of serious damage from fire could actually be higher because of all the dead material left standing.

- Replant the areas with native plants (preferably) or "non-invasive, non-persistent" alien plants. This could be expensive, and has been tried very infrequently and nowhere, to our knowledge, with success. There does seem to be potential though for the development of this technique. Similar techniques are used by foresters who aim to replant an area with timber trees as soon after harvest as possible. Direct seeding of native pioneer grass and/or shrub species is an alternative option.

6 Manual methods of killing woody plants

6.1 Physical methods

Uprooting. The uprooting of seedlings is commonly used as it is so quick. Detached root fragments of some species can resprout (e.g. *Cinchona succirubra*), whereas some cannot (e.g. *Pittosporum undulatum*). Uprooted seedlings of some species survive if left in contact with the soil, but some do not. As with all methods of control, it is very important to carry out simple tests to see how each species in a particular area or habitat responds to control techniques. Sometimes control programmes have uprooted larger plants with picks or winches. In the Galapagos Islands picks were used to uproot *Cinchona succirubra* but this was abandoned in preference to herbicides once the techniques had been developed (Macdonald *et al*. 1988).

Cutting. In Zambia, arboricides were used to kill several woody species and the treatment of stumps was almost always more effective than the treatment of girdled trees (Pierce 1980). In the U.S.A., repeated cutting (at least once a year) of the invasive *Lonicera maackii*, without the application of herbicides, killed plants in the forest but not where they were growing in gaps (Luken & Mattimiro 1991).

Girdling. Wiant and Walker (1961) reported variable success after 2 to 3 years with complete girdles 25 mm wide and 45 mm deep, even when no callousing occurred. They suggested that girdling alone may not suffice for the diffuse-porous species if a rapid death is required. In the southern Cape forests *Olea capensis* and *Canthium obovatum* were killed as effectively by ring-barking as by the application of 3% 2,4,5-T in diesoline, the most effective herbicide tried (Geldenhuys 1982).

Bark stripping. Stripping all the bark off trees, either the basal portion or below cutting height, is effective in killing *Maesopsis eminii* in Tanzania (N. Geddes pers. comm. 1993) and *Pittosporum undulatum* in Jamaica.

Mechanical. Sometimes alien trees have been removed mechanically. For example, in Australia two bulldozers dragging a chain from two different directions have been used to destroy monotypic woodland stands of *Prosopis juliflora* (Meadly 1962). Up to 40 ha can be cleared a day (Rentz 1993) but sucker regrowth needs to be controlled by herbicide. This method may be effective in some regions but it can not be recommended more widely, because of the risk of re-invasion of alien plants, as well as other environmental damage, particularly soil erosion.

6.2 Chemical methods

6.2.1 Herbicides. We have not attempted a review of possible herbicides as many are available and the turnover of products is high. The following sources of information are useful, though none deal specifically with tropical trees:

Anon. 1987. Australian weed control handbook, 8th edn. Inkata Press, Melbourne.

Anon. 1989. Herbicide handbook of the Weed Science Society of America, 6th edn. Weed Science Society of America.

Cronk, Q.C.B. & Fuller, J.L. 1995. Invasive plants: the threat to natural ecosystems worldwide. Chapman & Hall, London.

Grossbard, E. & Atkinson, D. (Eds). 1984. The herbicide Glyphosate. Butterworths, London.

Labrasa et. al. 1984 Weed management for developing countries. FAO publication.

Vermeulen, J.B. & Grobler, H. 1987. A guide to the use of herbicides. Dept. of Agriculture and Water Supply, Rep. of South Africa, 10th Edition.

Willoughby, I. & Dewar, J. 1995. The use of herbicides in the forest, 4th edn. Field Book 8. HMSO, London.

If many species are being controlled in the same area it is quite likely that the optimum herbicide for each species will not be the same, so to avoid great complexity, a smaller number of herbicides may be desirable, accepting slightly lower mortality rates.

6.2.2 Method of application. The following methods of applying herbicides have been used, some with limited effectiveness.

Application to cut stumps. This is often the most effective method of killing woody plants. In the Hawaii Volcanoes National Park, in 13 out of 15 species, application of herbicide to cut stumps has been the most effective method of applying herbicide and also minimises waste and damage to native plants.

Foliar application. Translocatable herbicides can be readily absorbed by foliage (though sometimes a surfactant, a chemical that increases the amount of herbicide absorbed, needs to be added if the leaves are thick and waxy). This method is only practical on smaller plants or on sprouts from cut stumps in heavily invaded areas.

Injection. This can be carried out with a specially designed tool such as a Hypohatchet, which is usually effective though the tool is quite expensive.

Drilled holes. Drilling 8-15 mm diameter holes through the bark and cambium of the trunk at 4-6 cm apart about the trunk, below the lowest living branch and 20-50 cm above ground level and filling with undiluted glyphosate was effective at killing many species in Australia. It is essential that holes are placed vertically below any main branches, otherwise they may not be killed. For large trees more than 40 cm DBH up to 20 holes are needed. They should be immediately filled with a suitable herbicide using a Velpar gun (Gillespie 1991). Both injection and drilling methods have the advantage of minimal leakage of herbicide into the environment but are time-consuming.

Branch filling. Some branches are cut and the herbicide applied through a tube attached to the stump of the branch. This was not very effective against *Cinchona succirubra* with a DBH > 10 cm in the Galapagos Islands (Macdonald *et al*. 1988).

Frill girdling. It is faster than drilling but it was not as effective in one study in Australia (Gillespie 1991). Girdling with the herbicide Tordon (2,4-D and picloram) was more effective at killing *Pittosporum undulatum* than cutting and the application of Tordon to the cut stump.

Bark painting. This was effective against small (DBH < 10 cm) *C. succirubra* trees (Macdonald *et al*. 1988), though presumably bark thickness and characteristics strongly influence the effectiveness of this method.

6.2.3 Dosage. This will depend on many factors, but more need not necessarily mean better. Concentrated doses of herbicide, when applied to frilled girdles at the start of the growing season, can kill the developing cambium cells, blocking the translocation of the poison and therefore reducing its effectiveness (Geldenhuys 1982).

6.3 Cost effectiveness of manual control

Manual control can be expensive and is rarely able to achieve complete eradication of a species. This method is effective when the population size of the invader is small and the population has limited or no means of vegetative propagation. The costs of removing a species are highly variable. Some examples below give an idea of the resources needed.

- In the U.S.A. in the early 1980s the cost of removing *Pueraria lobata* was US$563 ha^{-1} whereas the removal of exotic mangrove at Kaloko-Honokohau National Historic Park in Hawaii cost US$123,500 ha^{-1} (Hester 1991).

- Control of *Psidium cattlenianum*, which was at the density of 500 plants ha^{-1} in Kipahulu Valley, Haleakala National Park, Hawaii, took 7.5 man days ha^{-1} if the area was accessible and level. Control started at the highest altitude of invasion as it may not have been practical to control denser infestations lower down and people carry seeds upslope (Anderson *et al*. 1992).

- In the Hawaii Volcanoes National Park as a whole, control of widespread species, as well as localised species, was estimated to require about 20 full time workers for initial control stages (Tunison & Misaki 1992). Control efforts have been highly effective on 26 of the 41 less widespread species. Nine of these have apparently been eradicated from the park and seven others have been reduced to seedling stages (Tunison & Zimmer 1992). Control of *Psidium guajava*, which was at the density of 3000 plants ha^{-1} in the Hawaii Volcanoes National Park, required 30 man days ha^{-1} (Anderson *et al*. 1992).

- On Santa Cruz Island in the Galapagos Islands control against *Cinchona succirubra* started in 1971 and has needed 6 men employed for 6 months of each year (Macdonald *et al*. 1988). Control has been concentrated in a 1000 hectare Intensive Control Area and has managed to prevent the *C. succirubra* population increasing within it, but seed input from plants outside is increasing.

- Control of alien plants in the Cape of Good Hope Nature Reserve, South Africa, was initiated in 1943 and has continued ever since. In recent years, 14 men have been employed full time with 32 men working on following up weeding, costing US$100,000 a year (excluding transport and equipment depreciation) (Macdonald *et al*. 1988).

The effectiveness of some methods of manually killing plants depends on seasonality, and this obviously becomes increasingly important away from the equator. Translocatable herbicides such as glyphosate may be completely ineffective during dormant times of the year.

6.4 Environment and worker impact of manual control

Herbicides can harm non-target plants and the wider environment. For example, after the injection of Tordon (2,4-D and picloram) into the rhizome of a herb, *Hedychium gardneranum*, in Puerto Rico, all native plants of three common species were either killed or showed signs of damage within a one metre radius (Santos *et al*. 1992). Herbicides differ in the extent to which they harm plants, are immobilised and persist in soil. It is particularly important not to damage the ability of native vegetation to re-colonise a site after the removal of all alien woody plants using herbicides. Glyphosate-based herbicides such as Roundup are often claimed to be relatively non-persistent and benign on the environment.

In the tropics safety equipment is often difficult to obtain, is uncomfortable to wear in tropical heat (Negreros-Castillo & Hall 1994) and it can be very difficult to insist that people wear full protective overalls, so the low danger to humans of glyphosate-based herbicides is another major factor in their favour.

The impact on recruitment of other species of weeds is mentioned above.

7 Biological control

The biological control literature is extensive, but the most practical and useful publication is the handbook by Harley and Forno (1992).

7.1 Forms of biological control

Biological control can be of three main types:

- Importation (classical), introduction of a biological control agent from the species' native range. This has been the most successful method to date.
- Augmentation, involving direct manipulation of established populations of natural enemies through mass production or colonisation.
- Conservation, involving habitat manipulation to encourage populations of natural enemies or environmental factors (fire, flood) which kill the invader or seriously reduce its competitive ability.

Biological control is targets the reproductive stage of a plant's life-cycle rather than its vegetative stages. This is generally thought to be more promising (S. Neser pers. comm. 1993).

For forest vegetation management the use of mycoherbicides appears to have much potential (cf. Markin & Gardner 1993). The use of specific rust fungi is being investigated by bodies such as the International Mycological Institute, Egham, U.K. Fungal pathogens are no widely considered for biological control in conjunction with insect agents or where the use of insects has been unsuccessful (Barreto *et al*. 1995, Evans *et al*. 1995).

There are two other methods of biological control, though neither are usually classified as such.

Use of other plant species. There is potential in some situations for the use of native or "non-invasive" plant species to suppress the alien plant. Experiments using native and alien trees to suppress gorse (*Ulex europaeus*) are underway on Maui and Hawaii islands in the Hawaii chain. Native *Acacia koa* appears to be effective within five years. In the long term these methods may be more effective than herbicides, which provide quick suppression but are not a permanent solution (Tulang 1992).

Use of livestock. Goats are used to control *Psidium guajava* and *Schinus terebinthifolius* on a ranch in Hawaii. Cattle can be used to control some species by high stocking rates. The Voison or short-duration grazing system is useful; grazing, hoof action and dung can break up the vegetation sufficiently to allow desirable species to establish, although in many cases this disturbance would facilitate the invasion of alien plants (Bredhoff 1992).

Biological control is a very complex undertaking in which numerous factors need to be taken into account so we can only outline the main features here.

7.2 Effectiveness

The success rate of biological control has been about 50% according to two studies. Julien (1992) reported a 47% success rate (partial or complete control) worldwide. In Hawaii biological control with insect has been used against 21 plant species and in 8 cases control was very good, partially successful in 3 cases and failed in 10 cases (insects either failed to become established or had no significant effect) (Markin *et al*. 1992).

Predictions can be made about the likely effectiveness of biological control by consideration of the weed's abundance in its native range. If it is common or weedy in its native range there is little prospect of classical biological control being effective in a new range (Scott & Panetta 1993). Taxonomic isolation from crop plant is an important criteria for selecting weeds for biological control programmes.

For weeds as a whole, many established insects fail to build up sufficient populations to harm their hosts due to interference from local predators and pathogens. Therefore, assessments of the diversity and abundance of native ants and other predatory insects may give an initial indication of the chances of success (D. Gardner pers. comm. 1994).

Biological control may not be as effective against scattered plants in forest because of insect survival and dispersal difficulties. Most successful programmes have been against rangeland or farmland weeds (Markin and Gardner 1993).

In the past most successful programmes have been against perennial plants. In tropical areas this may not be a serious limitation as many annuals grow throughout the year and so may be equally susceptible to control? (C. Riches pers. comm. 1992).

Markin & Yoshioka (1992) devised a method for comparing the chances of a successful biological control programme against different weeds. Each of 20 factors is scored on a scale 0 to 5, a factor that could hinder or deter a programme scores 0 and one that simplifies or contributes significantly to its success is given the weighting 5.

There is little point in eliminating a weed (by biological control) if another weed takes its place; for example, a successful biological control programme eventually eliminated *Lantana camara* from large areas in Hawaii, only to have some of it invaded by *Schinus terebinthifolius* (Andres 1977).

7.3 Cost and time span

Biological control is not cheap as proper screening is essential. Andres (1977) estimated the total cost of a biological control programme to range from US$1-2 million. Harris (1979) estimated that between 19 to 24 scientist years would be needed per weed, costing between US$1.2-1.5 million and would require the establishment of 2.3 agents.

A facility in which insects can be quarantined whilst their biology and feeding preferences are studied must be available. There were only 11 in the U.S.A. and the simplest cost about US$200,000 to build in 1977, with operating costs of over US$100,000 a year (Andres 1977).

Harris (1979) gave the following average periods of time needed for the development of an agent. Constructing or gaining access to a quarantine facility takes about 2 years; evaluating 10 or more insect species can take 3-5 years; the establishment of say 5 insect species then needs a rearing facility to propagate the insects, taking 2-3 years. Thus a programme may take 7-10 years altogether.

The time period over which biological control agents take to have an effect (if at all) varies greatly. In Hawaii (with a good climate) success occurred in about 3-10 years, but it took up to 60 years for *Lantana camara* (Andres 1977).

7.4 Environmental impact

Although biological control has been considered a more ecologically acceptable method for the control of invasive organisms than chemical methods, this view has recently been questioned (Simberloff & Stiling 1996a, 1996b) as the biological control of a number of animals has resulted in disasters including the extinction of a number of endemic taxa. The use of biological control agents to control weeds can be considered much safer although earlier programmes have caused problems. In the 1960s an insect introduced to West Africa to control *Lantana camara* attacked sorghum, but after this the introduction of systematic screening has meant that there have been no major incidents reported since then. Adult insects have been known to start eating native plants once the alien has been eliminated, though in no case to date has appreciable damage been caused to the native species (Andres 1977). But the element of risk is still present, and it would be wrong to assume that the impact of biological control on the native system can ever be fully predicted. Risks can only be reduced using control agents with high host specificity. Therefore, the legislative position in many countries, properly restricts the scope of this control method.

7.5 Conflicts of interest

If remaining blocks of natural habitat are small, the chance that biological control could be carried out without conflicts with other land uses in the intervening areas declines. Biological control programmes against plants have sometimes been restricted to anti-reproductive agents because the plant had economic value in other locations (S. Neser pers. comm. 1993).

In poorer countries the use of biological control rather than manual control favours scientists and technicians, many from richer countries, instead of local people who would be employed to carry out manual eradication. Therefore, careful political and socio-economic analysis of this option is required and it is crucial that the decision is taken at an appropriate local level.

8 Conclusions

These conclusions apply chiefly to natural and semi-natural areas, however a broader view is necessary as some species, weedy in man-made habitats, will ultimately reach protected areas.

Policy on the transportation of alien plants between and around countries is outside the scope of this section (see Anon. 1993 for discussion) but there are steps that protected areas managers can take to minimise new inputs of alien plants. Some of the ways in which this could be achieved are listed:

- The costs and benefits of new alien plant species introductions for whatever purpose should be carefully appraised. The deliberate introduction of alien woody plants for forestry purposes is discussed in greater detail in the next sections of this report.

- Populations of a weed outside a park or protected area need to be controlled. Otherwise continued re-invasion of the controlled areas is most likely resulting in further control measures. Landowners outside these protected areas need to be made aware of the problem and some form of assistance may be necessary to help them eradicate the invader from their land.

- Promote environmental education and initiate awareness programmes relating to biological invasions. Special attention must be paid to the problem of transferring human value judgment to plants. The current tendency in the British media to link the control of introduced/alien/exotic species to racist attitudes (e.g. Moore 1992, Evans 1995 and see Binggeli 1994 for critique of some of these views) is a good example of the some of difficulties to be overcomed by educational programmes.

- Regulate or reduce the introduction of new alien plant species into gardens in or near protected areas.

- Regulate tourism and the movement of vehicles into and within protected areas. Humans and vehicles can be important carriers of alien propagules.

- Regulate the movement of plant materials and soil into the protected areas. Both can carry seeds, especially those of herbaceous weeds.

- Control all developments that may facilitate the spread of weeds, such as new roads or tourism development projects.

Every invasive event is unique and is affected by the species distinctive set of attributes, and the specific local environmental factors and biological communities. Thus it is important to investigate these specific factors in detail in order to devise a strategy to successfully tackle an invasion. If the knowledge about the invasion and the species is extensive this should allow some flexibility in the management response but this requires long term commitments of resources and management time. Management must set specific targets for areas or species to control and collect and maintain full records. It is only with a better basis of information from past control programmes that future ones can be planned more effectively and at a lower cost.

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