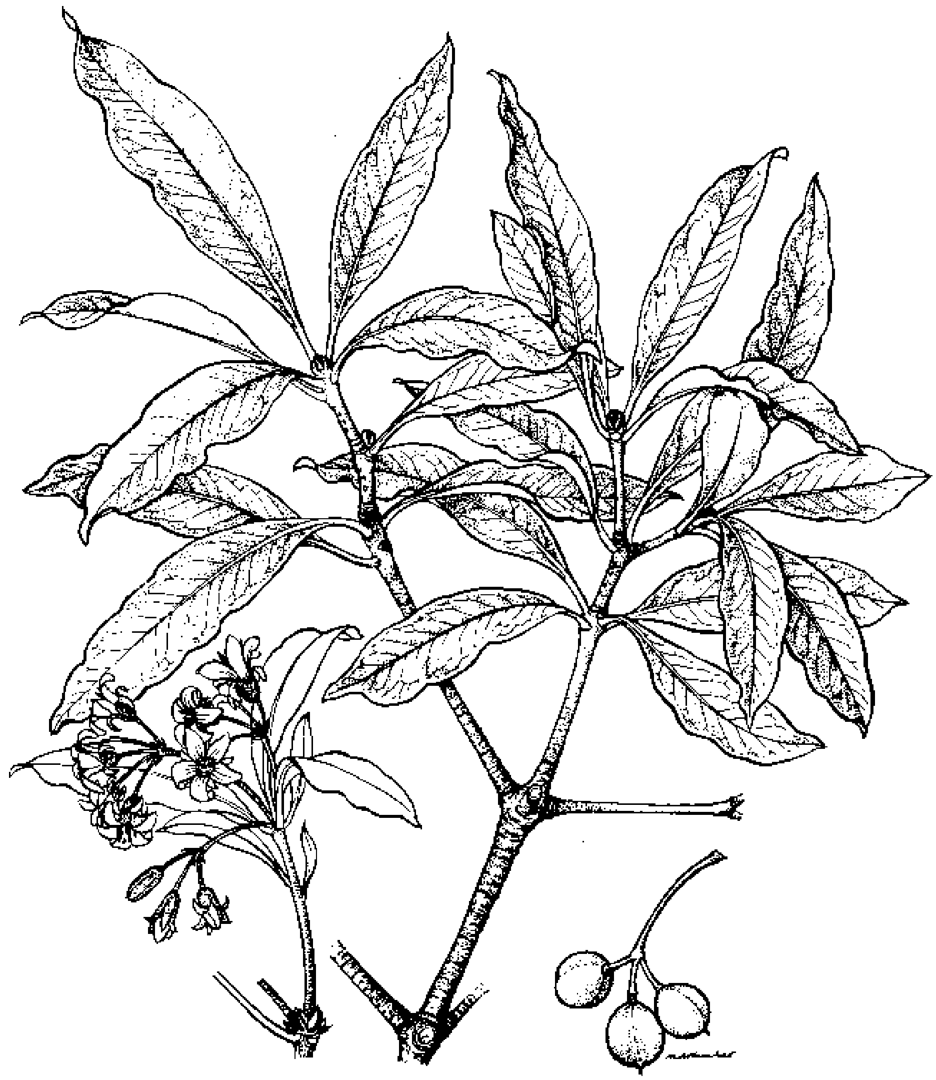
The control of the Australian tree *Pittosporum undulatum* in the Blue Mountains of Jamaica



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The Australian tree *Pittosporum undulatum* Vent. was introduced to the Blue Mountains of Jamaica in 1883. This bird dispersed tree has so far spread throughout at least 1000 ha of primary and 300 ha of secondary montane forest and has accelerated its rate of invasion following Hurricane Gilbert in 1988. We estimate that the potential range of the species in the Blue Mountains could be as high as 40,000 hectares, very seriously threatening the high biodiversity of the range. This report gives our latest information and recommendations on the control of *P. undulatum* in the Blue Mountains. It is in five parts.

1. An assessment of the ways in which the extent and degree of invasion can be more accurately mapped.
2. An investigation of manual methods for the killing of individual plants, the term manual control meaning chemical and/or physical control.
3. An assessment of the potential of non-manual (mainly biological) methods of control.
4. A strategy for the control of *P. undulatum* in the Blue Mountains.
5. Recommendations.

1. Assessing the distribution of *Pittosporum undulatum*

1.1 Present extent and density

We have been able to determine the present distribution and density of *Pittosporum undulatum* within about four kilometres of the Cinchona Botanic Gardens (the place of introduction) fairy accurately and give this information below. Our information on the extent of two separate *P. undulatum* invasions in the Blue Mountains, at Hardwar Gap and Whitfield Hall, is less complete. We have restricted this assessment to the Cinchona invasion, as not enough is known about the other two invasions.

1.1.1 Methods

We have assessed the distribution and density of *P. undulatum* by observation from vantage points (often with binoculars or telescope), extensive exploration of the area, and by calculation of the *P. undulatum* density in sample plots. Also, the frequency of *P. undulatum* was compared with that of native species by calculating the number of plots (out of 144) that each species occurred in as a tree.

The two 1:12,500 scale maps (sheets 105B and 115A) that cover most of the western end of the Blue Mountains were joined together. A 16×16 mm grid on clear acetate (giving “cells” of 4 hectare (planimetrically)) was superimposed over all the land which we either have evidence for or strongly suspect that *P. undulatum* occurs as a tree, the southern boundary coinciding with Cinchona; (boundaries: western 76^0 40’ 30’; eastern 76^0 37’ 40’’, southern 18^0 03’ 58’’, northern 18^0 06’ 14’’). Four hectares was used as we have sufficient information at present to make good estimates of density for areas this size, though managers in future may need information at a finer scale, so the cells can of course readily be a divided into four. The number of *P. undulatum* trees (ie. stems ≥ 3 cm DBH) was estimated within each of these cells and put into four classes:

Class 1 - 1-9 individuals per cell
Class 2 - 10-99
Class 3 - 100-999
Class 4 - 1000-9999

The accessibility of each cell from Cinchona was estimated by calculating the straight line distance between the two. The mean slope angle of this end of the Blue Mountains was estimated, using the Digital Elevation Model of the Blue Mountains and the data on the slope angle in the 144 plots, to be approximately 35^0. This was used to increase the *P. undulatum* density from the planimetric value, by multiplying it by 1.26.

1.1.2 Results

P. undulatum occured in 74 out of 144 plots (51.6 %), and was the seventh most frequent species, remarkable bearing in mind the fact that it has only been in the country 110 years. Of the plots where it was not present as a tree, it is already present as a seedling in 15 of 16 of the plots for which we have seedling data and altogether we estimate that it occurs as a tree or seedling in 123 (85%) of the plots.

Our estimate is that *P. undulatum* occurs in 330 four hectare cells, ie. in a total of 1320 hectares, see Figure 1. Note that the class of a given cell does not necessarily equate with density in that cell, as some cells on the forest boundary are only part forest so may be in a low class even if very heavily invaded. Of the 330, we estimate that 108 are predominantly in secondary forest, some of it old and not necessarily heavily invaded. The positive correlation between past forest disturbance, mostly around Cinchona and the *Cinchona* plantations in the Sir Johns Peak-Bellevue Peak area, and the density of *P. undulatum* is very striking. Concentrations also occur far down the north slopes, in steep landslide-prone areas. However, these calculations should be taken as an approximation only, bearing mind that isolated *P. undulatum* seedlings may occur several hundreds of metres beyond the boundary. And whilst *P. undulatum* seedlings are generally common within the boundary, some areas (of up to several hectares) of mostly undisturbed forest will be free of *P. undulatum* seedlings. It is quite possible that there are isolated trees or clumps of trees well outside the area, on the north slopes, in addition to *P. undulatum* spreading from the Whitfield Hall and the Hardwar Gap *P. undulatum* invasion.

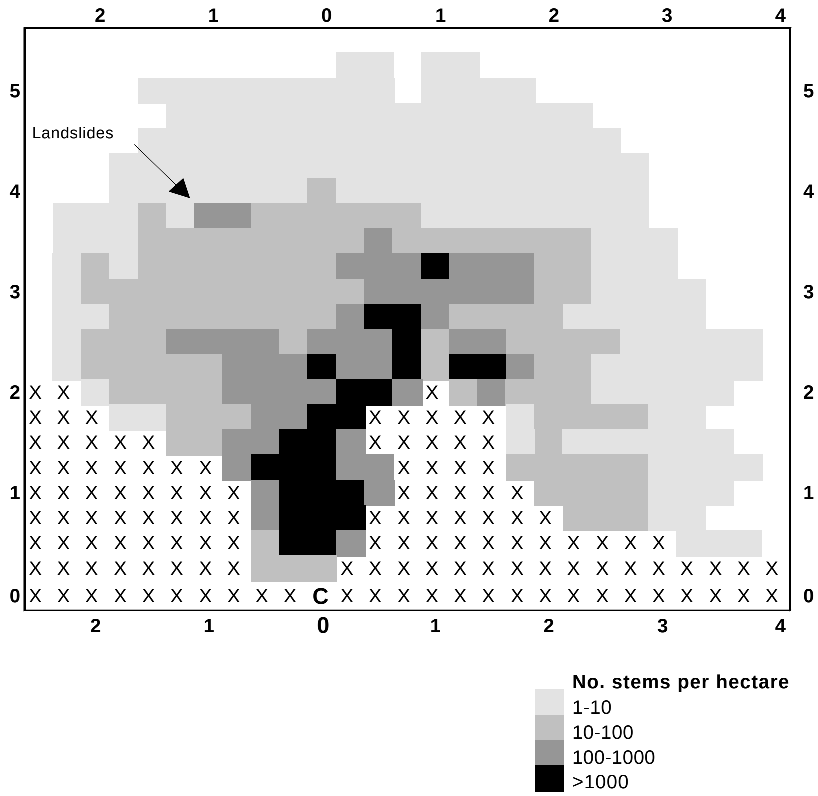

Figure 1. *The assessed density of* P. undulatum *trees in four hectare cells north of Cinchona (C). "X" indicates that the land is partially or wholly deforested. The distance from Cinchona along an east-west and a north-south axis (in kms) is shown around the perimeter of the map*.

To put this area in perspective, we have estimated the total area of forest in the Blue Mountains that we think is invadable by *P. undulatum*. For this estimation we assume that all forest above 600 m, the lowest height that *P. undulatum* is known to occur at in Jamaica (Adams 1972), is invadable. The forest area used is that shown on the 1984 edition of Map 13 of Jamaica's 1:50,000 series, based on aerial photographs taken in 1979-80. It is still reasonably accurate as to the extent of forest cover, most deforestation since then having being small scale or below 600 m. The area does not include the adjoining limestone massif of the John Crow Mountains. The planar area is thus estimated to be 28,140 ha of forest. An alternative method is to use the areas of different forest types given in Muchoney *et al.* (1994) and assume that all non-limestone montane primary and modified forest and scrub is invadable - a total of about 54,000 hectares. We estimate that a figure about halfway between these, approximately 40,000 hectares, is invadable, which would mean that about 3.3% of *P. undulatum's* potential range has already been "invaded".

1.2 Assessing the distribution more accurately

1.2.1 Visibility of *P. undulatum*

Pittosporum undulatum trees have an architecture that is more regular than perhaps any tree species native to the Blue Mountains. A straight bole, regular whorls of branches and a dense crown give the species a distinctive shape and texture (somewhat resembling a temperate spruce (*Picea*) from a distance). There is a pronounced seasonality to the appearance of *P. undulatum* trees also. Leaves flush early in the year and for a few weeks are a light green, but gradually through the year they darken, so by August/September their crowns are noticeably darker than those of most native trees, (this is accentuated by the density of *P. undulatum* foliage, which masks more of the lighter coloured trunk and branches). *P. undulatum* trees tend to be found in certain types of location, near landslides and in secondary forest most obviously, but more usefully for identification purposes, in certain locations, particularly on ridges or breaks in slopes.

We compared the usefulness of normal colour film (Kodachrome 24, with a neutral density filter) and colour infra-red film (Kodak colour infra-red film with a Wratten No. 12 filter) for recording the presence of *P. undulatum* and other weeds. Colour infra-red photographs have been used successfully in the identification of tree species, mostly in temperate countries where they are particularly useful for distinguishing conifers from broadleaved species, and for the detection of diseased trees. The characteristics of colour infra-red photography are that green healthy foliage (with a high concentration of chlorophylls) shows up as a vivid red, and haze is penetrated to a greater degree than normal film. On the other hand, different greens of different species can become more similar in colour infra-red photography (Kodak 1987). However, in our trial only a small proportion of the colour infra-red frames produced useful photos. This was probably because of the highly sensitive nature of infra-red film to the correct light exposure and the difficulties of keeping the film cold enough in tropical conditions (recommended storage temperatures are -18 to -21°C). *P. undulatum* trees were usually clearly visible on the few good colour infra-red photos, though only when lit from behind the camera; if side lit, the reflections of the leaves of all trees seemed to mask the appearance of *P. undulatum*. The resolution was not quite as good as on the normal colour transparencies. Both techniques show promise when a systematic attempt is made to map the distribution of the species.

1.2.2 Potential for aerial photographs

It was hoped that *P. undulatum*'s distribution might have been discernible on aerial photographs, but this has not yet been possible. Two sets have been taken, the first, funded by The Nature Conservancy, was taken in April 1992 and the second, funded by the Canadian International Development Agency, in August 1992. The Nature Conservancy aerial photographs were at the nominal scale of 1:22,500 and were generally cloudless, except for the western part of the range (mostly between John Crow Peak and High Peak), the area largely invaded by *P. undulatum*. The CIDA aerial photographs were at 1:18,500 nominal scale and showed the whole range cloud-free. However, the scale was not large enough for individual *P. undulatum* trees to be identified, although clumps of trees that were known previously from fieldwork could be distinguished. No new sets of aerial photographs have been taken since 1992, but the park management have indicated that they may commission a set at a larger scale, partly to map the distribution of *P. undulatum* and partly to detect illegal logging within the park (D. Lee, pers. comm., 1994). Jamaica is well endowed with air-photo cover, with 10 series of aerial photographs taken since 1941. Unfortunately, the largest scale used was only 1:10,000 (M. Rothery, pers. comm., 1994).

Detecting different tree species on aerial photographs is a well-developed practise in temperate forests, and guidelines given by Sayn-Wittgenstein (1978) provide a good idea of the scale that would be necessary to detect *P. undulatum* trees. At 1:500 most species can be recognised almost entirely by their morphological characteristics because twig structure and leaf arrangement can be seen; at 1:2,500 small and medium branches are still visible; at 1:8,000 individual trees can still be separated, except when growing in dense stands, but it is not always possible to discern crown shape. Therefore we estimate that the minimum scale that would be necessary to detect small *P. undulatum* trees would be about 1:5,000. Larger scales would allow for more certain identification of trees partially obscured by taller trees. Sub-canopy trees are almost undetectable on aerial photographs (J. Williams, pers. comm., 1994).

1.2.3 Ground survey

The systematic mapping of *P. undulatum*'s distribution by ground survey has not been attempted for a number of reasons. Ground survey's most useful role will be to make accurate assessments of the density of *P. undulatum* and other weeds in areas where they are known to occur. There are more extensive areas where alien weeds *could* occur, being within a plausible dispersal distance from known populations, but where the density is likely to be so low simple ground survey is likely to be unproductive, time consuming and rather hazardous. Some evidence of alien plants from remote sensing (from the air or vantage points) would be needed to justify speculative searching. There is a good case for using vantage points on the ground as an alternative (or complement) to aerial photographs. They could be taken when *P. undulatum* is most visible, (during September/October, which co-incides with the season when cloud cover is generally most frequent), and optimum time of day (when the sun is directly behind the observer). The slopes are sufficiently steep and disturbance of the canopy (particularly landslides and large treefall gaps caused by Hurricane Gilbert) sufficiently common for a network of vantage points to be set up covering most or all of the slopes threatened by *P. undulatum*, with the exception of some of the slopes on the north slopes, (although some of the gaps are becoming less useful as vegetation fills them). Photographs taken from the ground would however be less useful than aerial photographs, as they could not be taken stereoscopically, so making the plotting of detected trees onto a map or Geographical Information System more difficult.

1.2.4 Finding *P. undulatum* during clearance operations

Park management will need more detailed information on the location of isolated *P. undulatum* trees and populations than we have at present. Observation of hillsides being invaded by *P. undulatum* suggests that it would often be difficult to detect *P. undulatum* trees before they reach the canopy, by which time they may have already started producing seeds. There are two steps in using spatial data.

1. Obtain accurate locations for the trees or population foci. The best way to do this would be to use stereo aerial photographs.
2. Use this distributional data to find these population foci in the forest. It can be surprisingly difficult to find *P. undulatum* trees in the forest. However, a team of experienced people, at least one of whom can read a compass accurately, and walking apart in parallel lines, should be able to find nearly all *P. undulatum* trees in even the most difficult terrain. The presence of *P. undulatum* seedlings is usually the surest sign of *P. undulatum* trees. A longer term option is to use the Global Positioning System, together with accurate remotely derived distributional information, but from our experience with the system in the forests of the Blue Mountains, its usefulness beneath the forest canopy is limited.

2. Manual methods of killing *Pittosporum undulatum* plants

The desirable qualities of manual control are that it should be cost-effective, with minimal impact on the environment and workers, therefore we have explored every possibility of killing the species by physical means alone, as well as by using chemical methods. We have tried the following combinations of physical and chemical methods.

Uprooting. Seedlings are readily uprootable as they usually have a shallow root system and a strong stem which rarely snaps. The maximum height of *P. undulatum* seedling that can be uprooted is very variable, mainly depending on soil thickness and substate type. In thick soil individuals as tall as five metres can be uprooted, especially if the stem is rocked backwards and forwards to break the superficial roots.

Cutting (with and without herbicide). Cutting is quick, especially for smaller trees, and allows harvesting.

Girdling (with and without herbicide). For large trees, girdling can be quicker than cutting, and it does not open up the canopy as quickly as cutting does.

Injecting herbicide. The injection of herbicides into holes bored into boles had been found to be an effective method of killing some species, in Australia for example.

Bark stripping. Stripping the bark off the base of the invasive tree *Maesopsis emenii* in Tanzania is an effective way of killing that species without the use of herbicides (N. Geddes, pers. comm., 1993).

Herbicides. We thought that it was too early to test a large number of herbicides at this stage in control so we tested only two, Tordon (active ingredients picloram (10.2%) and 2,4-D (39.6%)), and glyphosate. An experiment carried out in Puerto Rico into the potency of different herbicides in the late 1960s found that picloram was much the most powerful of those tested (Dowler & Tschirley 1970). Glyphosate (not used in the Puerto Rican study) is widely used, effective against most dicotyledonous plants, and relatively safe against humans and the environment (Grossbard & Atkinson 1984).

We found out how effective each method or combination of methods is against different sizes of tree by use of a main experiment and three smaller investigations.

2.1 Methods

Uprooting. A simple experiment to test the effectiveness of uprooting was carried out in four forest types. *P. undulatum* seedlings were pulled up forcefully until 40 had been pulled up at each location that had at least one snapped root of one mm diameter. The exact location of the detached root was marked with a flagged pin. The height and diameter at 30 cm of all seedlings and the diameter of all snapped roots at the point of breakage was measured. 264 seedlings, ranging in height from 20-186 cm were uprooted, of which 60.6% had snapped roots.

Main control experiment. We set up a main experiment with different methods of treating *P. undulatum* trees and saplings in October 1992. The treatments were:-

NT	Control (no treatment)
C	Cut stems at 0.8 m above ground level
CH	Cut stems at 0.8 m above ground level and apply Tordon at a mean application rate of 0.1 $cm^3\ cm^{-2}$
G	Girdle stems between 0.8 m - 1.0 m above ground level
GH	Girdle stems at the same height and apply Tordon, also at a mean application rate of 0.1 $cm^3\ cm^{-2}$
CG	Cut stem at 0.8 m and girdle between 0.3 - 0.5 m

Girdling consisted of cutting off all the “bark” (the living xylem and phloem) with machetes and then cutting frills (or gashes) into the wood itself.

Four blocks were used, all moderately to quite heavily invaded by *P. undulatum,* (trees in lightly invaded forest are too widely dispersed and too difficult to relocate for inclusion in such an experiment). Not all treaments would be suitable against all sizes of *P. undulatum* (it would not be practical to girdle saplings or cut - by hand - the largest trees). Therefore, the number of replicates of each treatment in each size class are shown below.

			Treatment			
Size class	**NT**	**C**	**CH**	**G**	**GH**	**CG**
>3 m-3 cm DBH (Saplings)	2	2	2	0	0	0
>3-15 cm DBH (Small trees)	4	4	4	4	4	4
>15 cm DBH (Large trees)	1	0	0	1	1	0

This gave 33 saplings/trees in each block, 132 altogether. Small trees were selected so that their DBH was evenly distributed through the range 3-15 cm, not randomly (small trees were much more numerous than larger trees). Each individual had to be at least 5 m from any other treated tree. Girdles were frilled to increase the amount of herbicide absorbed. Measurement of the regrowth was carried out in March and December 1993, September 1994, and finally in August 1995, i.e. 5, 14, 23 and 34 months after treatment.

Injecting herbicide. In a second experiment, carried out in August 1995, 5 cm deep 12 mm diameter holes were drilled into 40 *P. undulatum* trees at breast height. They were drilled at two frequencies (either every 10 or 20 cm of stem GBH). Undiluted glyphosate was poured in, approximately 5 cm^3 per hole. For comparison there was a fourth treatment *Basal girdle and glyphosate* (applied to the exposed area). Half the trees were near New Haven Gap and the other half below the Spanish River Trail.

Bark stripping. In a third control experiment, in January 1994, the bark was stripped off the base of *P. undulatum* trees. There were two treatments, "Cut at 0.3 m and strip all the bark off to soil level below the cut", and "Girdle from 0.3 m to 0.5 m, and also strip all the bark off to soil level". Three trees of each treatment were selected at each of four locations near to Newhaven Gap, 24 trees altogether. The bark of *P. undulatum* trees can be removed readily except near the base where the roots start to splay out and the stem becomes convoluted.

2.2 Results

Uprooting. Despite about 60% of the roots of uprooted seedlings snapping, none of these detached roots resprouted. However, about half the uprooted seedlings left on the soil surface survived, so they would need to collected and disposed of, which would add time to the operation (and would perhaps be unlikely to be carried out diligently anyway). But the systematic uprooting of seedlings as a management technique may be useful in limited areas with a high priority for clearance. Such areas would need to be monitored for alien weeds establishing in the pockets of bare soil so created.

Main control experiment. Results on survivorship at August 1995 in the main experiment are given below. Initial analysis of the data found no indication of any block effect, (and none was likely as all sites were in rather similar forest), so it were not included in the analysis. Analysis of variance showed that treatment had a highly significant ($p<0.001$) effect, with girdling treatments causing significantly greater mortality than cutting. Size of tree had no significant effect.

Table 1. *Survivorship of stems by treatment, 34 months after treatment in the main control experiment.*

Treatment	**% Survival**
No Treatment	100[a]
Cut	72[a]
Cut + Herbicide	51[b]
Girdle	53[b]
Girdle + Herbicide	10[c]
Cut + Girdle	79[a]

Those treatments with the same superscripts are not different at the 5% level (using Scheffe's test)

Cutting. Although there was no significant difference in the survival after *No treatment*, *Cut* and *Cut + Girdle*, the results from the experiment clearly indicate that trees cut without the application herbicide can die. Those trees cut and treated with herbicide and still alive in August 1995 produced significantly fewer and shorter sprouts than those trees not treated with herbicide ($p<0.001$). However, the production of any sprouts by these herbicide-treated trees is surprising - Tordon is generally thought to be one of the most effective herbicides against woody plants. Sprouts from stumps treated with Tordon invariably had a distinctive appearance, with mottled, usually flat, leaves with mucronulate tips. The sprouts produced after cutting *P. undulatum* (without herbicide application) in the Heavily Invaded Forest Experiment (HIFE) sometimes have the same distinctive appearance, suggesting that the symptoms are indicators of general stress or ill-health in the species. Repeated cutting of *P. undulatum* eventually kills the species, though evidence from HIFE suggests that death occurs more quickly when the stumps are in the understorey than in more open areas. There may be a role for repeated cutting (without herbicide) along trails where cutting can be frequent and herbicide use would be less acceptable.

Girdling. Girdling by just peeling the bark off *P. undulatum* is not effective, as tissue readily regrows over the exposed surface, bridging the girdle. The xylem itself must be cut into. Cutting into the xylem hastened crown loss and therefore probably death of *Maesopsis emenii* in Tanzania, but at the cost of stimulating sprouting (N. Geddes, pers. comm., 1993). The comprehensive review of Noel (no date) makes it clear that most species produce shoots from just below the girdle, the part of the tree above the girdle always dies eventually (often taking a few years), and that in most cases (though it wasn't clear if in every case) these shoots eventually die also, i.e. the individual dies. About 90% of the trees that were girdled and had herbicide applied, died. We have since learnt that it may not be necessary, may even be disadvantageous, to cut off all the bark - the frills and herbicide alone being effective. We tried this method on 5 trees, as well as 5 trees frill girdled as before, in July 1996 (using glyphosate instead of Tordon), the results of this small trial won't be known until Tom Goodland returns to Jamaica. There is inevitably some wastage with frill girdling, with herbicide flowing out of the frills, possibly reaching the ground, and heavy rain soon after may wash out much of it. A better and more effective method of applying precise quantities of herbicide is to use a spot- or drench-gun. They are widely available and inexpensive (c. £30). (Analysis of the data on the seed production of girdled and control *P. undulatum* trees indicated that treated trees (either with or without herbicide) did not produce a large crop of capsules, although those that were produced were more visible because of leaf loss, so may have been more visited by seed-eating birds).

Stem injection. The results of the stem injection experiment was recorded in July 1996. Table 2 shows the number of living and dead trees for each of the four treatments as well as the percentage crown loss for those trees that were living.

Table 2. *Mortality, and percentage crown loss for living trees, in the stem injection experiment, 11 months after treatment.*

Treatment	Alive	Dead	Crown loss %
Cut and glyphosate	0	14	n/a
Holes at 10cm intervals	1	13	90
Holes at 20cm intervals	5	9	76
Basal girdle and glyphosate	14	0	9

Bark stripping. In the bark stripping experiment three of the cut trees and five of the girdled trees produced sprouts but these were clearly only coming from bark near soil level that had been left, unintentionally. Where all the bark was successfully taken off there were no sprouts.

2.3 Choice of herbicide

Clearly Tordon can kill *P. undulatum*. Since starting the project we have found out that Tordon was used to kill *P. undulatum* in Hawaii (Tunison 1992) and, more interestingly, that two other herbicides have been effective.

- A mixture of 2,4,5-T and diesel applied to stumps cut just above ground level was very effective at Jonkershoek in South Africa (Richardson & Brink 1985).
- Concentrated Roundup (glyphosate 360 g l^{-1}) has been effective when applied to cut stumps in Australia (I.K. Stephenson, quoted in Narayan (1993)).
- In the Dandenong Ranges in Victoria, Australia, *P. undulatum* is killed by drilling stems and filling with undiluted glyphosate using a Velpar gun. The holes should be 8-15 mm diameter, about 50 mm deep, 4-6 cms apart and 20-50 cm above ground level and below the lowest living branch. It is essential that holes are placed vertically below any main branches, otherwise they may not be killed (Gillespie 1991). Given that holes drilled 4-6 cm apart in Australia were presumably wholly effective, and that holes in Jamaica 10 cm apart were over 90% effective, the optimum spacing is about 6-8 cm.
- Also in Australia, to preserve the sclerophyll forest, “bush regenerators” are controlling *P. undulatum* by cutting trees and painting the stumps with glyphosate, either undiluted or 1:3, or injecting glyphosate into sapwood at the same concentrations (R. Buchanan, pers. comm, 1994).

Glyphosate is probably the best herbicide to use because of its effectiveness, and low environmental and human health impact. One problem with glyphosate is that a few rain-free hours are needed after application, estimates of 2-6 hours being given by the manufacturers and experienced users in the U.K. Given the frequency of rain in the Blue Mountains this is obviously a big limitation. A possible solution is to cut and strip the bark off small trees (no herbicide) during wet periods (if not at all times) and drill holes in large trees and plug after herbicide application. Another option would be to use a fast-acting contact herbicide, such as paraquat, but there are serious worker and environmental safety worries over the use of this herbicide.

Woody plants are commonly treated by cutting then spraying the regrowth a few months later, thereby getting larger quantities of translocatable herbicides such as glyphosate into the plant, as with *Rhododendron ponticum* in the UK (Forestry Commission 1990). This method has limited applicability in the Blue Mountains as many of the cut stumps would be widely scattered throughout remote forest and therefore would be very hard to find again, although in very heavily invaded forest regrowth spraying could be a useful technique.

2.4 Time needed to eradicate plants

The time, based on extensive experience, needed to treat various sizes of *P. undulatum* in different ways is shown below. They do **not** include any time taken to locate the plants.

Treatment and size	**Size of plant**	**Estimated time (secs)**	**Comments**
Uproot seedlings	<2 m tall	10 to 30	Uprooted seedlings should be either kept off the ground surface or collected and piled
Cut	>2 m tall	20 to 80	Using machete
Girdle	>6 m tall	30 to 150	Using machete, frilling as well
Hole drilling	Large tree	100 to 200	Using hand brace
Application of herbicide	Any cut or girdled surface	30 to 70	Time for transporting and handling herbicide not included
Strip bark from 30 cm to soil	Over 3 m tall	50 to 150	All bark must be removed

2.5 Environmental impacts and safety of manual control

There are serious worries about the environmental impact and persistence of Tordon. Picloram, a principal active ingredient of Tordon, was still present in soil twelve months after application in a tropical rain forest in Puerto Rico (reaching a maximum of 0.05 ppm at 12-30 cm deep) (Dowler & Tschirley 1970). As glyphosate appears to be effective, and has a very low toxicity to humans (Grossbard & Atkinson 1984), there seems to be little advantage in using Tordon, apart from its low cost. In Mauritius there is a large ongoing programme using herbicides to control many invasive species, and herbicide safety has become an important issue. Because of the strenuous work in humid heat it has not been possible to ensure that workers wear their protective clothing all the time, therefore glyphosate has found a greater role, in preference to more hazardous herbicides (W. Strahm, pers. comm., 1993). Some men in the Blue Mountains are familiar with the application of herbicides, because of their extensive use on the coffee plantations, and realise the potential danger to human health. We think that although herbicides may have significant environmental impact, the alternative of letting the invasion proceed could have considerably greater impact on the environment. The use of herbicides to kill woody plants is common in areas protected for nature conservation, such as national parks in the USA (OTA 1993).

There is the possibility that cutting rather than girdling *P. undulatum* trees could increase the probability of alien weeds establishing, but this much less likely in primary forest than in heavily invaded secondary forest. In primary forest *P. undulatum* trees tend to be smaller and to have a dense layer of native seedlings and saplings beneath, in contrast to heavily invaded forest. Additionally, the alien seed input is likely to be lower because of the distance from the highly invaded and disturbed land on the south slopes.

3. Non-manual methods of controlling *Pittosporum undulatum*

The second main way in which *Pittosporum undulatum* may be controlled is biologically, though the use of fire is briefly discussed later. Another method of control often mentioned in the literature is environment manipulation, though this is not relevant to the primary forests of the Blue Mountains, which are natural ecosystems essentially unaffected by human activities.

The Jamaican authorities have no policy directly related to the introduction and release of biological control agents, and park managers have expressed caution over its use (D. Lee, pers. comm., 1994). Nevertheless we have made a full review of the potential usefulness and risks of biological control, not least because many people think it will have wider applicability in natural vegetation in the future (D. Gardner, pers. comm., 1994; I.A.W. Macdonald, pers. comm., 1996). We are fully aware of the need for biological control programs to take all necessary precautions to ensure that any introduced agent will not attack or otherwise affect native or other economic species, and of the international protocols for screening potential biological control agents that have been developed to minimise these risks. Useful information has come from Hawaii, where there is the only active programme to control weeds in forests biologically, a programme that may have great relevance to the Blue Mountains (Markin and Gardner 1993; D. Gardner, pers. comm., 1994). The programme was started in 1982, has targeted over 10 weed species and has active programs underway for five of them, carried out by a team of seven full-time research scientists.

The principal objectives of this section are to provide the scientific information necessary to assess the potential effectiveness of biocontrol, targeted at different stages of the *P. undulatum* life cycle, and to consider the more general factors and issues that may affect its success. The most effective biological means of reducing the population of weeds such as *P. undulatum* is usually to target the reproductive stages in the life cycle of the species, from the initiation of flower buds to the time the capsules dehisce and expose the seeds. Most biological control efforts against plants have been directed towards this reproductive stage, especially against perennial plants (S. Neser, pers. comm., 1992), but the possibility of biological control against the vegetative stage of *P. undulatum* (by a predator or disease that harms or kills by eating or damaging leaves, stem or root) is examined first.

3.1 Biological control against vegetative growth of *P. undulatum*

Effects of defoliation

Small greenhouse grown *P. undulatum* seedlings are able to resprout following decapitation (Gleadow 1982). To determine if *P. undulatum* seedlings growing in the forests of the Blue Mountains are resistant to defoliation we carried out a simple test in April 1992, followed by a more ambitious experiment (carried out with a group of undergraduates from Oxford University, under the supervision of Tom Goodland) in 1995.

In 1992 thirty *P. undulatum* seedlings (from 20 to 300 cm tall) at each of two sites (heavily and lightly invaded forest) were completely defoliated by hand, about two months after most *P. undulatum* plants had produced new leaves, (i.e. the new buds were small). In January 1993 all these seedlings had produced new flushes of leaves from terminal buds, with only very rare shoot dieback (T. Goodland, unpublished data).

The objective of the 1995 experiment set up by the Oxford University group was to investigate the effect defoliation has on the growth and survival of seedlings of *P. undulatum*, and the three common native species closest to it in regeneration requirements. The species were *Palicourea alpina* and *Psychotria corymbosa* (both Rubiaceae) and *Hedyosmum arborescens* (Chloranthaceae). There were 3 treatments (cut off all leaves with scissors at leaf base, cut off half of each leaf, and no treatment), and three sites (all primary forest), with 10 replicates, giving 360 seedlings altogether. They measured the height of each seedling and recorded its number of leaves, and also sampled leaves to determine leaf area. In July 1996 Tom Goodland carried out an assessment of the experiment, recording which of the seedlings had died. About 90% of the seedlings completely defoliated had put out new leaves. Those that had not done so but still had green stems were considered to be still alive. All the dead seedlings, 20 seedlings altogether, had been given the Total defoliation treatment, none of the seedlings in the other two treatments had died. The number of seedling deaths was rather too few to draw firm conclusions.

Table 3. *Number of dead seedlings 12 months after complete defoliation*

	Site1	Site2	Site3	Total	% dead
Hedyosmum arborescens	4	3	4	11	36.6
Palicourea alpina	2	2	2	6	20.0
Psychotria corymbosa	1	1	1	3	10.0
Pittosporum undulatum	0	0	0	0	0.0

The ability of *P. undulatum* trees to resprout after being cut four times in HIFE indicates that large reserves in the stem or roots of the plant is probably a reason for its ability to produce new leaves following defoliation. Because of the ability of *Pittosporum* trees to produce resprouts after damage, and of small seedlings to resprout following decapitation (Gleadow 1982), it seems unlikely that the species could be controlled by an animal that just ate its leaves.

Predation in Australia

The following is a list of all the agents known to attack *Pittosporum undulatum* (or the genus more generally), none of them attacking flowers or fruit. Sources, in addition to the publications, are personal communications from Robin Buchanan, Peter Myerscough and Stefan Neser.

- *P. undulatum* is attacked by the Pittosporum longicorn larvae *(Strongylurus thoracicus)* if in a weakened condition. The larvae bore round tunnels in the sapwood just below the bark, usually concentrating on small to medium-sized branches. Individual branches are occasionally killed but otherwise the health of the plant remains unaffected.
- The larvae of a small (3 mm) fly, the Pittosporum leafminer *Phytobia pittosporphylli* (family Agromyzidae), commonly attack *P. undulatum* in certain areas, so that it is rare to see a fully expanded leaf undamaged. The larvae concentrate their feeding around the midrib causing discoloured sunken blotches about 1-3 mm across. Although most leaves on a single tree can be attacked, the plant is not seriously affected (Hering 1962; Jones and Elliot 1986; McMaugh 1985). *Phytobia pittospocaulis* sp. nov. lives in twig galls (Hering 1962). Together with S. *thoracicus,* the Pittosporum leafminer is the most common pest of *P. undulatum*.
- Scales, including soft scales such as the Cottony cushion scale (*Icerya purchasi),* the Pink wax scale (*Ceroplastes rubens)*, an alien, and the Chinese wax scale (*Ceroplastes sinensis),* another alien, can be common on *Pittosporum* species (McMaugh 1985; Jones and Elliot 1986).
- Gall thrips (*Teuchothrips* species, mainly *T. pittosporiicola)* commonly infest the leaves of *Pittosporum* species (especially *P. revolutum*) (McMaugh 1985), sometimes building up huge populations (Jones and Elliot 1986).
- Various "bugs" suck sap, including the Pittosporum bug (*Pseudapines geminata*) (oval in outline, about 8 mm long, and black with light markings) (Jones and Elliot 1986).
- The Pittosporum chermid or psyllid (*Trioza vitreoradiata*) causes small lumps on the leaves (Jones and Elliot 1986).
- The Pittosporum beetle (*Lamprolina aeneipennis)* can cause serious damage to leaves of *Pittosporum* species (particularly *P. hirtissimum* and *P. venulosum*) (Jones and Elliot 1986).

In the Sydney area these agents do not prevent trees being able to produce large numbers of seeds and, unless these agents are themselves controlled in the area, they do not hold much promise for the biological control of *P. undulatum* (P. Myerscough, pers. comm., 1994).

Anti-*P. undulatum* agents outside Australia

During the past twelve years a disease has been killing *P. undulatum* in the Cape Town/Stellenbosch area of South Africa (I.A.W. MacDonald, pers. comm., 1993). The "blight" had been devastating the species 8-10 years ago in gardens, affecting hedges in particular. But *P. undulatum* seems to be recovering now and is "really spreading all over the place" (D. Le Maitre, pers. comm., 1996). It is generally referred to as a viral disease but may be caused by a mycoplasm (M. Morris, pers. comm., 1993). It has not been investigated in depth and has apparently been welcomed by conservationists in South Africa (S. Neser, pers. comm., 1993). The disease may have originated on *P. viridiflorum* which is native to Southern Africa (I.A.W. MacDonald, pers. comm., 1993).

P. undulatum does suffer some herbivory in the Blue Mountains. We have compiled notes on the characteristics and distribution of all diseases and pest damage of *P. undulatum* that we have found in the area. So far we have identified seven different patterns of damage that we suspect are caused by seven distinct agents. Descriptions will not be given here as they are rather incomplete (it has proved very difficult to find any of these agents, despite examining hundreds of leaves), and a team of four Oxford University undergraduates, working in collaboration with us, investigated the subject in depth in mid-1995 (report not yet available). The most common type of damage appears to be caused by a leaf miner. This type of damage is common, and may be more common where *P. undulatum* is growing in lightly invaded forest and/or in gaps (T. Goodland, pers. obs., 1993). We do not yet know the identity of the causal agent for this or any of the other types of damage. This “leaf miner” damage is long-standing, as we have found a herbarium specimen from 1947 in the herbarium of the Institute of Jamaica, Kingston of *P. undulatum* with apparently the same kind of damage. Three of the types of damage were very localised (several square metres) in which all *P. undulatum* individuals were damaged, suggesting the possibility of future spread. All the responsible species are most likely to be local "generalist" species and none have lead to such extensive defoliation that death seems likely.

One potentially fruitful direction to follow in terms of biological control of *P. undulatum* could be a specific rust fungus (if one exists in its native range) (H. Evans, pers. comm., 1993). However, there is no existing knowledge of the rust fungus flora of *Pittosporum* species.

3.2 Biological control against reproduction of *Pittosporum undulatum*

Several aspects of the reproductive biology of *P. undulatum* will be dealt with here, not all directly related to biological control, though some of them provide necessary background information.

Phenology

Based on observations (by T. Goodland, P.J. Bellingham, J.R. Healey and E.V.J. Tanner) and Adams (1972), flowering starts in mid-November to December and is mostly over by late February to early March, though about 10% of trees produce flowers in May and June. Capsules start to mature (become orangy-brown) during July to October. Compared with the timing of the onset of flowering, there is considerable variation in the rate of capsule maturing with habitat and light environment. *P. undulatum* in Mor Ridge forest (or transitions between it and other forest types) and/or in gaps or on gap edges mature earlier than other plants (T. Goodland, unpublished data). Capsules start to dehisce in late October to early mid-November with some capsules dehiscing as late as January. There was a high degree of synchronicity within an individual, with a tendency for those more heavily shaded to be less advanced.

Monitoring of fecundity

Objectives. We collected detailed information on the fecundity of *P. undulatum* for the following reasons.

- As the high fecundity of *P. undulatum* is probably a key factor in its success it is useful to quantify it, so that it can be compared with the fecundity of native species, and with *P. undulatum* seedling recruitment.
- We wanted to see how fecundity varied in different environments, as observations suggested that degree of canopy openness may be an important influence on fecundity and phenology. The success of introduced agents in locating *P. undulatum* flowers or seeds may depend on their visibility, which could be lower in the understorey.
- The annual variability in seed production could affect the likelihood of a seed-attacking agent establishing.
- It could be important to know how fecundity varies with tree size, so increasing the precision with which managers could prioritise clearance (i.e. clearance of reproductive trees below a certain size could be delayed if their seed production was very low). A significant proportion of *P. undulatum* trees bear very few or perhaps no seeds at all each year. If these individuals consistently fail to do so year after year,

eradication of these could become a lesser priority, and the only way to investigate this is to label trees and monitor their fecundity for a number of years.

Methods. Thirty gaps and nearby understorey locations (i.e. 30 sites) in four areas were selected. The gaps in three of the areas were caused by Hurricane Gilbert in September 1988. The gaps in the fourth area were created in August 1992 by the selective illicit harvesting of large *Juniperus lucayana* trees by loggers. The variability between gaps (in terms of forest type and canopy height, which had a strong bearing on gap size and openness) within each of the first three areas is considerable, greater than that between areas, so they cannot be treated as blocks. There is less variability between the Juniper gaps. Only *P. undulatum* trees less than 25 cm GBH were chosen, as larger trees would have had a greater proportion of their crowns in the canopy, so reducing the likelihood that gap formation would have an effect. With larger trees it also becomes much more difficult to accurately assess the number of capsules, because of the denseness of their crowns, especially when the trees are in undisturbed forest. The fecundity and phenology was assessed each year 1992-96, in August to October as this was the ideal time as the capsules were orange and highly visible but they had not started to dehisce.

All *P. undulatum* plants >2 m tall but <25 cm GBH either in, with at least half their crown in, each gap were tagged and flagged for later relocation. For each of these, a *P. undulatum* in the understorey was selected. Understorey *P. undulatum* trees tend to have a different growth form, as well as a slower growth rate, from those growing in gaps, so are only comparable in a loose sense. They were selected by, firstly, subjectively choosing a nearby point in the understorey (one that had a sufficient density of *P. undulatum*, and a similar aspect and slope to the gap); and then selecting, for each of the *P. undulatum* trees in the gap, the nearest *P. undulatum* to that point within $^{+}/_{-}$ 20% of its GBH (Gilbert gaps) or $^{+}/_{-}$ 10% of its GBH (Juniper gaps).
For each individual the following were measured:

1. GBH (1.3 m).
2. Number of cymes, if any.
3. Number of capsules on ten cymes randomly chosen from throughout the crown.
4. Predominant state of maturity of capsules on the ten cymes.

Results. Six capsules were collected from 23 of the *P. undulatum* trees being monitored for fecundity (11 from gap trees and 12 from understorey trees). The number of seeds in each capsule was counted and the presence of eaten or diseased seeds noted, the results given below.

	No. capsules	Mean	SEM
Gap	66	33.1	0.71
Understorey	72	30.3	0.80
All	138	31.7	0.75

There was no significant difference in the number of seeds per capsule between trees in the understorey and in gaps. There was no sign of any insects having bored into capsules or any other loss due to biotic factors, though capsules have been found in other locations that had been gnawed on the ground (probably by rodents) and partially eaten on trees (probably by birds).

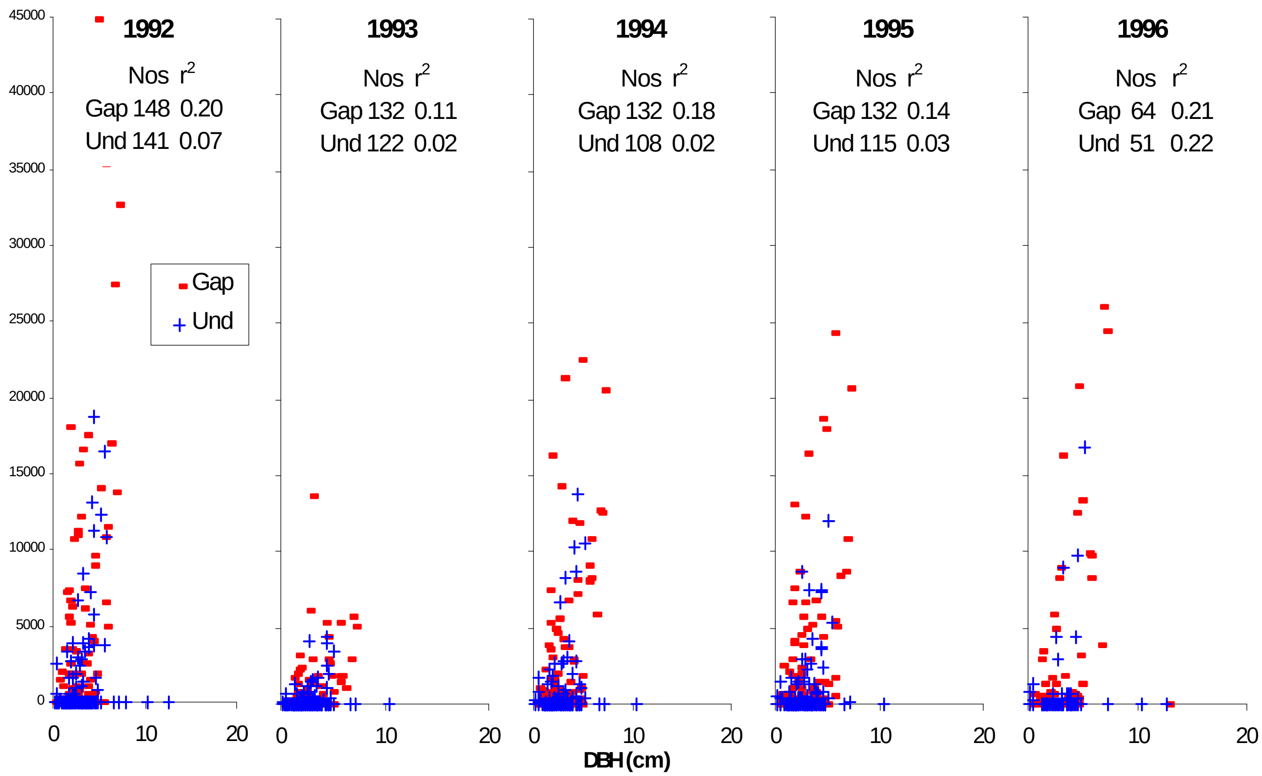

Figure 2. *The relationship between the DBH of* P. undulatum *trees and their fecundity (number of seeds, on the y-axis) for five successive years, 1992-96, and the effect of gap creation on fecundity. The data for the Gilbert and Juniper gaps have been combined.*

P. undulatum seed production was high, the regression relationship between DBH and fecundity giving a mean of 37,500 seeds for a 8 cm DBH tree in 1992, though there was very large variability in fecundity amongst trees of a similar size. It varied substantially through the five year period, so that in 1993 only one tree produced more than 7,000 seeds, there being no discernible relationship between DBH and fecundity. After five years the pattern of fecundity can be described thus: very high in 1992, only about half that in 1993, the seed production building up gradually between 1994-1996 to near 1992 levels. Whether this pattern is governed by extrinsic factors (such as weather) or intrinsic factors (for example within-plant food reserves) is not known. The seed production of trees in the generally more open Gilbert gaps was slightly but not significantly greater than in the Juniper gaps, likewise in the understorey of both areas. For the Gilbert sites, understorey trees were more likely to bear few or no cymes, compared with gap individuals. Individuals at the Juniper site started producing cymes at a larger size than those at the Gilbert sites. This may be because before August 1992 the forest was relatively tall and undisturbed, and therefore the smaller *P. undulatum* trees would have been growing in a relatively low light environment. Additional data collected in 1995 showed that the fecundity often falls to very low levels on larger *P. undulatum* trees.

Flower and fruit development

To assess the number of flowers that survive to produce capsules, in February 1993 we counted the number of flowers on six flower bearing cymes on 39 *P. undulatum* trees <25 cm GBH (20 in a gap and 19 in the understorey). The trees were revisited in early December 1993 and the number of capsules in each marked cyme was recorded. In summary, overall 17.0% of the flowers produced capsules, with the mean number of flowers surviving slightly higher in gaps than the understorey. Twenty one of the trees produced no capsules at all. Observations made of two branches on separate trees during January 1994 showed that *P. undulatum* flowers took between 2 and 3 weeks between flower opening and "withering" after fertilisation. Some of the flowers had already been eaten, probably by birds; the Greater Antillean Bullfinch, *Loxigilla violacea*, has been seen eating *P. undulatum* flowers (T. Goodland, pers. obs.).

3.3 Effectiveness of biological control

Type of biological control

Because of the widely scattered nature of *P. undulatum* in lightly invaded forest classical biological control is most likely to be effective. "Augmentation" - involving direct manipulation of established populations of natural enemies through mass production or colonisation, or "Conservation" - involving habitat manipulation to encourage populations of natural enemies which kill the invader or seriously reduce its competitive ability, are not feasible in this instance.

As for the use of anti-reproductive or anti-vegetative control, the former has three advantages over anti-vegetative control. Firstly, it would lead to a much more gradual opening up of heavily invaded forest, thereby avoiding the risks associated with the sudden death of most trees in large areas; secondly, it would not affect the potential for the use of *P. undulatum* as a woodlot / fuelwood species by local people, provided that an effective method for vegetative propagation was developed; thirdly, anti-vegetative control may be effective at reducing the vigour of *P. undulatum*, but is less likely to reduce population levels. However an anti-vegetative biological control agent would have advantages: seedlings are already widespread and locally common in primary forest so the reliance on an anti-reproductive biological control agent would allow many *P. undulatum* plants to grow and have a significant effect on parts of the forest for many decades; secondly, in lightly invaded forest rapid control is desirable, and is more likely with an agent that kills trees quickly; lastly it could be simpler and more predictable - assessing the effect a reduction in seed production would have on the population dynamics of the species is very difficult. A critical issue would be the reaction of the bird populations to such a change - if the fecundity of *P. undulatum* were reduced it does not necessarily follow that bird dispersal would decline proportionately, if at all (J. Wunderlie, pers. comm., 1993). Bird behaviour is of course a very complex issue which we have not had time to investigate.

Cost effectiveness

There are several reasons (given below) for thinking that biological control agents would be less than wholly effective. On the other hand, *P. undulatum* is likely to have a narrow genetic range in Jamaica, and this might mean that it is poor at adapting to new predators or environmental fluctuations greater than that in the Blue Mountains over the last 100 or so years.

- Although pests of forest trees can search for their host trees in a forest, where the target species is widely scattered, as *P. undulatum* is in the Blue Mountains, there may be an appreciable lag before the plant is found, by which time seed production could have already started.
- As the number of *P. undulatum* individuals (or seeds) is reduced, it becomes harder for the agent(s) to find its target and for its population to be supported in a fluctuating environment (S. Neser, pers. comm., 1993).
- The large annual variation in *P. undulatum* seed production may make it more difficult for a seed-attacking agent to establish and maintain a population and would very probably mean that in years of high seed production a large proportion of the seeds would survive.
- The difference in the climate between the Blue Mountains and *P. undulatum's* native range is appreciable (Healey *et al.* 1992b) and so may present an added difficulty in establishing a classical biological control agent.
- *P. undulatum*'s spread in Australia, often in areas close to or contiguous with its “natural” 19th century limits, suggests that its population level was held in check by factors other than native predators, factors such as lack of native dispersers and fire.

The likely cost of a biological control programme against *P. undulatum* could be US$1,000,000, and take about 7-10 years. Because of the fixed costs of building and equipping facilities in Jamaica the costs of attempting biological control against *P. chinense* or *H. gardneranum* could be considerably less than that against *P. undulatum* alone.

Environmental aspects

Introducing an exotic agent to Jamaica inevitably involves some risk to native species, though release of biological control agents is nowadays undertaken only after a rigorous screening programme. There are no native members of the Pittosporaceae in Jamaica which may mean that the risks of any introduced agent attacking native plants is reduced (S. Neser, pers. comm., 1993). However, if introduced agents did kill all *P. undulatum* it is possible that the agent(s) would attack native species, especially as the population of *P. undulatum* declined. Evidence from South Africa indicates that the disease which is attacking *P. undulatum* there does not affect other species, however this would clearly need to be fully tested in Jamaica before any introduction of it to Jamaica.

A major problem with the intentional or accidental release of an effective lethal agent in Jamaica is that the sudden death of all *P. undulatum* in heavily invaded forest could have serious ecological consequences. The light levels on the forest floor would be increased substantially, almost certainly enhancing the growth of *Hedychium gardneranum* and probably facilitating the germination and growth of *Polygonum chinense.* The large quantity of dead wood could, during an exceptionally dry period, leave these areas vulnerable to fire, either accidentally started, or by people deliberately taking advantage of the opportunity to clear forest for farming with the minimum of effort. The consequences would be very serious, with fire resistant weeds, such as *Melinis minutiflora,* benefitting. Perhaps a lethal, vegetative blight could be introduced eventually, once the dominance (and fuel load) of *P. undulatum* in heavily invaded forest had been reduced through management.

In summary, it may be able to reduce the rate of *P. undulatum* spread, and its final density, but would be very unlikely to eliminate *P. undulatum* from the Blue Mountains altogether. In addition, it may well be politically unacceptable to introduce a disease that kills *P. undulatum,* as any proposal that may lead to the loss of forest cover would be hard to justify in a country that has lost so much. The use of biological 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. Contact should be maintained with researchers in South Africa, because of the potential of the unidentified agent currently killing *P. undulatum* in the Cape Province to be used as a biological control agent in Jamaica. However, should further research into the potential for biological control become necessary full attention should be given to an assessment of its risks and the costs of a proper screening programme before any decisions are taken.

3.4 The use of fire as a way of controlling *P. undulatum* in the Blue Mountains

Controlled burning is being tried at present as a potentially cost effective way of controlling invading *P. undulatum* in Australia (Narayan 1993; R. Gleadow, pers. comm., 1993). For example, in New South Wales, a combination of fire and insect attack is used, where intense and moderate fire (100% leaf scorch) kills *P. undulatum*. If the fire is less intense, damage to the trunk is still severe and then borers (presumably longicorn) attack, killing the plant within a few months (R. Buchanan, pers. comm, 1994). Following a controlled fire in Victoria, Australia at a temperature of about 200-250^{0}C 20% of monitored *P. undulatum* individuals resprouted from basal buds, but all *P. undulatum* in areas suffering from higher temperatures were killed (Narayan 1993). A low temperature fire of 120^{0}C led to a net recruitment of *P. undulatum* seedlings (Narayan 1993). Twenty percent of two and a half year old *P. undulatum* seedlings exposed to 200^{0}C in laboratory conditions resprouted (Narayan 1993). The bark of *P. undulatum* trees is thin and resinous, reaching 6.5 mm thick on a trunk 30 cm DBH in its native range (Gleadow & Ashton 1981). It is more resistant to fire than many marginal rainforest tree species, but is still susceptible compared with fire resistant species such as *Eucalyptus* (R. Gleadow, pers. comm., 1993).

Fire is frequent in the Blue Mountains, especially on hillsides covered by the African grass *Melinis minutiflora* (Aldrich 1993). It is unlikely that heavily *P. undulatum* dominated forest would burn without disturbance even during an exceptionally dry period, partly because of the thin litter layer and small quantities of woody debris characteristic of these secondary forests. However, a scrubby area (which probably had more fuel due to a dense layer of shrubs and ferns as well as abundant *P. undulatum*) did burn in the dry dry season of 1989 and *P. undulatum* trees had been killed by a fire about 5-10 years ago in another area. This evidence, and what is known about *P. undulatum* in Australia, does suggest that *P. undulatum* would be partially or totally eliminated from an area suffering an intense fire. However, although there are some native species that can readily colonise burnt areas (such as a shrub *Dodonaea viscosa* and bracken *Pteridium aquilinum*) the main beneficiaries would probably be introduced weeds, particularly *M. minutiflora*. In addition, fires result in soil erosion and loss of soil fertility through oxidation and volatilisation, hence the use of fire as a cheap method of controlling *P. undulatum* in the Blue Mountains would be highly undesirable.

4. Strategy for *Pittosporum undulatum* control

If the primary objective is to slow or stop an invasion, modelling highlights the importance of eradicating small outlying populations before starting to eradicate the main original population, even if it is expanding slightly faster than the satellite populations (Moody & Mack 1988). Although it is less urgent to remove *P. undulatum* from heavily invaded forest than from lightly invaded forest, it should still be a long term objective, not least because of the value of *P. undulatum* wood. However, it is very important to discover ways of removing the species without leading to the forest becoming even more heavily invaded by alien weeds. The very high recruitment of *P. undulatum* and the generally low recruitment of other species following the removal of *P. undulatum* trees has been examined in the accompanying report.

As long distance dispersal of *P. undulatum* by birds is so prevalent it is essential that an integrated approach to its management in the Blue Mountains be adopted. This means that the management options for lightly invaded and heavily invaded forest and land outside the forest has to co-ordinated. For example, looked at on its own, it would seem to make little sense to try to eliminate *P. undulatum* outside the forest (where it probably does little harm and may even be beneficial), but if the ultimate objective were to remove all risk of the species re-invading the forest, its removal outside the forest may be essential. The various options as to which areas could be cleared of invasive plants are discussed below, in order of increasing ambitiousness. They are not strict alternatives, as easier options could be steps towards a more complete control of the species in Jamaica.

4.1 Restricted areas of forest

Areas to be kept weed free could include:

1. **Trails**. The invasion of all three main weeds may be hastened by the more open environment along trails. As it would be relatively easy to clear *P. undulatum* from them, this would be a cost effective way of reducing the invasion rate where they pass through little invaded forest. It would be essential if this were done to control *P. chinense* and *H. gardneranum* as well, otherwise they could be the main beneficiaries. Their rampant growth that can quickly make trails impassable.
2. **Areas near or highly visible from trails**, especially the Blue Mountain trail. To do this would decrease the rate of trail re-invasion and save remnants of natural uninvaded forest for visitors.
3. **Sites** (small areas of less than a hectare) **of particular scientific/archeological interest** or those with research uses. The act of removal itself is a disturbance, so for some of these areas it may be better to leave the invasion to proceed undisturbed.
4. **Representative areas of natural habitat**. These could be modelled on “Special Ecological Areas”, a concept originating from the Hawaii Volcanoes National Park in Hawaii (Tunison & Stone 1992). These are areas of a hundred to a few thousand hectares that make the removal and exclusion of alien plants particularly worthwhile. Areas are delimited because of such attributes as high conservation value, a low degree of invasion and easy accessibility. Such areas could either be incorporated into one of the existing Blue and John Crow Mountains National Park management zones, such as the Special Conservation Zones or could be established separately. Two obvious areas are the forest in the vicinity of Portland Gap and the Blue Mountain Peak trail (a more extensive area than in 2. above), and the forest along and close to the Grand Ridge of the Blue Mountains between Morces Gap and John Crow Peak, because of its great diversity of forest types, research interest and accessibility.

4.2 All primary forest

The removal of *P. undulatum* from lightly invaded forest should receive top priority. Almost all primary forest is much less invaded than secondary forest and generally has a higher conservation value. But there is about three times as great an area of it than heavily invaded forest, and it is mostly remote and inaccessible. A major problem with trying to remove weeds from all primary forest is that some of the slopes in the Blue Mountains are so steep and craggy - places in which *P. undulatum* thrives - that they are only accessible with rope, dramatically increasing the risk and cost of control. We have had to make a number of simplifying assumptions in order to calculate the cost of doing this:

- age/size at which *P. undulatum* starts to produce seed (a typical height of 3 to 5 m, age 5-10 years). Given the inaccessibility of much of the forest there is a clear case for removing *P. undulatum* plants significantly shorter than this. In follow-up clearance operations the target should be to ensure that all *P. undulatum* individuals are removed before they get to 3 m.
- persistence of the *P. undulatum* seedling bank.
- time period over which *P. undulatum* seedlings are recruited from any seedbank.
- maximum growth rate of *P. undulatum* seedlings.
- time needed to find and then kill different sized plants. As *P. undulatum* grows more rapidly in gaps, greater control effort will inevitably be needed there. These disturbed areas are localised, often small, and workers should be alerted to the importance of checking for *P. undulatum* in any gaps they encounter.

Our assessment of the cost of clearing *P. undulatum* from the 1020 ha with an estimated density of <100 trees per hectare, is in the range of US$110,000 and US$145,000. It would be highly desirable to remove the other two serious alien weeds in primary forest, *Hedychium gardneranum* and *Polygonum chinense,* at the same time, but we can estimate the cost of doing this with much less confidence. It could easily cost as much again in labour and material costs, but with little increase in fixed costs. Therefore the total costs of removing the three main weeds from lightly invaded forest would likely be in the range of US$220,000 to US$290,000. We must stress that these costs are not based on actual data on controlling weeds in lightly invaded forest, so may be very inaccurate, more likely to be underestimates than overestimates.

The Blue Mountains are different from almost all other areas where much effort has been expended on the control of alien plants in that there are many people who live locally who would be willing and able to work on a manual control programme. Elsewhere labour has either been expensive (such as Hawaii or New Zealand) or scarce (such as the Galapagos Islands or Mauritius, where labour is only available when the sugar cane is not being harvested (W. Strahm, pers. comm., 1993)). A manual control programme would be labour intensive and therefore clearly beneficial in an area with high unemployment and under-employment (R. Kerr, pers. comm., 1993). Rather than hiring local people on a casual basis as labourers, it would be preferable to build up a committed team of people and train them rather like forest rangers, so that they will be able to take a wide responsibility for protecting the forest and promoting it amongst local people.

4.3 Heavily invaded forest

As the harvesting of *P. undulatum* from heavily invaded forest has the potential to be self-financing it could be a policy that could be self-justifying and could be pursued independently of action in lightly invaded forest. The key issue in heavily *P. undulatum* invaded forest is the effect of *P. undulatum* management on the *degree* of invasion of alien weeds. The proximity of these areas to very heavily invaded land on the forest fringes could mean that the areas become heavily invaded within a few decades, mostly by *H. gardneranum* and *P. chinense* as well as *P. undulatum.* This could lead to a permanent loss of tree cover within a few decades. (Both *H. gardneranum* and *P. chinense* have already spread into non-*P. undulatum* invaded primary forest, (though the latter only in a few places), so management in heavily *P. undulatum* invaded forest would make little difference to their rate of invasion throughout the Blue Mountains).

We have found *H. gardneranum* surviving, if not growing, beneath the densest canopy of *P. undulatum*, an environment where very little else can grow. The species also benefits from canopy opening, by increasing its rate of vegetative spread, as displayed in natural gaps and man-created clearings in the upper Clyde valley. It would unwise to remove *P. undulatum* without removing *H. gardneranum* if the latter were beneath it. The potential effect of *P. undulatum* on *Polygonum chinense* is greater than that on *H. gardneranum*. *P. chinense* does not occur beneath dense tree canopies, as some disturbance is necessary for its establishment. A significant finding of the Heavily Invaded Forest Experiment in July 1995 was the presence of at least twelve healthy newly-established *P. chinense* plants, up to four metres long, in the *Remove all P. undulatum* treatment in a heavily invaded block. In that plot, *P. undulatum* had comprised only 9.5% of the total basal area (of stems over 3 m tall) so it appears that *P. chinense* is able to colonise sites after the removal of relatively minor amounts of *P. undulatum*. *P. chinense* can also get established in gaps created by the fall of large *P. undulatum* trees. The understorey of heavily invaded forest is sparser than lightly invaded forest, benefitting species that are recruited as a result of gap creation. On the other hand *P. undulatum* is a more aggressive coloniser of gaps than most native tree species, (not just in terms of height but also crown growth), so there is probably a greater chance that the *P. chinense* would be suppressed in gaps where *P. undulatum* regeneration is dominant. It is important to find out whether *P. chinense* will invade forest that is presently heavily invaded (by *P. undulatum*) faster if large *P. undulatum* trees are left to grow and eventually fall, creating gaps, or if they are killed standing and allowed to disintegrate without such pronounced gap formation. It might be possible to eliminate *P. undulatum* from heavily invaded forest by the gradual removal of trees taking care not to cause so much disturbance that *P. chinense* or *P. undulatum* are recruited (*H. gardneranum* can grow without such disturbance). As data from HIFE indicates the paucity of native seedling recruitment following *P. undulatum* removal, these areas could be replanted or resown with native species. There are likely to be major problems with the raising of large numbers of tree seedlings of some species in nursery conditions, and probably with the survival of planted seedlings. Lack of resources may mean that the re-planting of such areas would have to be an alternative to the planting of (mostly different) species outside the forest as part of efforts to restore tree cover to the denuded slopes. As some forest is so heavily invaded it could even be sensible to convert the less steep and most accessible land to non-forest tree cover, such as agroforestry or forest plantations. After the cutting and uprooting of all *P. undulatum,* the timber could be extracted, the abundant foliage left on the soil surface to provide some protection and help to suppress weed regeneration, care taken to prevent fire, then plant either native species or exotic N-fixing species.

4.4 Eradicate entirely from the Blue Mountains area

This would involve not only removing *P. undulatum* (and other weeds) from the heavily invaded forest around the less invaded core but also control of them outside the forest. Additionally, there are good reasons for control of the Hardwar Gap invasion as the area is much visited by tourists, with the main visitor centre for the park nearby, and it does contain a forest type not described from the Blue Mountains (the Very Wet Ridge forest of Grubb & Tanner (1976)) - the extent of *P. undulatum* there is apparently quite limited so the costs of its elimination would be low.

If eradication of the three main weeds were achieved there would be little chance of any of them ever reaching the area again, as we have no evidence that any of them occur in Jamaica outside the western Blue Mountains area. However, we have not attempted to cost this policy as it would be very expensive, unlikely to succeed, and of questionable merit, though it may be feasible in the long term.

4.5 Biocontrol

Recent correspondence with two leading experts on the control of invasive alien plants has lead us to consider that the potential of biological control (as much a method as a strategy) may be much higher than we had originally thought. On the Atlantic island of St Helena both *Pittosporum undulatum* and *P. viridiflorum* are exotic and invasive (as well as many other alien weeds). A joint South African/Australian project will be proposing biological control of these two species, as apparently there are already agents known to attack the species. Further details are lacking at the moment. The fact that there are no native members of the Pittosporaceae should make the process relatively straightforward and will thus require minimal work on specificity of natural enemies (S. Neser, pers. comm., 1996). Ian Macdonald, an authority on invasive plants, thought that the potential for biological control is greater than indicated in Goodland & Healey 1996. In particular, he thought biological control would be much less expensive than suggested in the report, and also that it would be safer (with little chance of an introduced agent attacking native plants, as long as the screening had been rigorous enough).

5. Recommendations

Clearance of *P. undulatum* from lightly invaded forest

Eradication of *P. undulatum* from lightly invaded forest is highly desirable and seems to be feasible, so trial control should start as soon as possible. Two topographically well-defined areas of 2-5 ha typical of those invaded should be cleared of all *P. undulatum.* There are good reasons for removing the other two serious weeds, *Hedychium gardneranum* and *Polygonum chinense,* as well, at least until we have a better idea as to the feasibility of their eradication. For convenience these areas should be in the forest north of Cinchona; two possible areas are the north facing hillside below Morces Gap and the northern slopes of Sir Johns Peak (areas highlighted on map).

The density of *P. undulatum* and % cover (to the nearest 10%) of the ginger and redbush should be estimated in these areas before treatment and, initially, one year afterwards to judge its effectiveness. The terrain will be too dificult to set up square plots, so a number (ideally 10) of circular plots (5.64 m in radius, giving 100 m^{-2} each) should be set up in representative areas. The centre should be marked with bright flagging.

All the *P. undulatum* trees in the lightly invaded forest in these two areas should be small enough to cut down with machete (or axe). Immediately apply sufficient undiluted glyphosate to thoroughly wet the cut surface without letting (much) glyphosate flow off the stump.

Killing ginger will be more difficult. The best type of herbicide is Escort together with Pulse. Assuming these are not presently available in Jamaica (and they are expensive) physical methods seem to be the best option: Slash stems and dig out all rhizomes, and pull out young seedlings. (N.B. old shade-suppressed plants may appear small but have a string of rhizomes attached to them). Stems and leaves may be left to mulch. Do not mulch or compost rhizomes because they always resprout. Keep out of ground contact or pile and later burn them. (NB Chemical: spray foliage or slash stems and spray cut stumps. Use Escort + Pulse and apply from spring to late autumn. Rates: handgun 25g Escort + 100 ml Pulse/100 litres water. Knapsack 5g Escort + 10 ml Pulse/10 litres water).

Killing redbush will also be difficult, but there may not be any in these areas (though it is present on the north slopes). A combination of cutting and glyphosate should work, but more trials are needed.

A record of the number of people employed on how many days plus how herbicide used will need to be kept.

The work would be suitable for a team of a park ranger, a knowledeable local man, and other local manual workers.

If results from the trials are encouraging, larger scale clearance of *P. undulatum* should proceed. The highest priority is control of the small "nucleus" population in the Whitfield Hall/Blue Mountain Peak area. A high priority should also be attached to the killing of the isolated *P. undulatum* trees in the north slope forests north of Cinchona and this could be commenced before the Whitfield Hall population is completely eliminated.

Assessing distribution

The commisioning of a set of aerial photographs will not be necessary until a widespread control programme is initiated. *P. undulatum* trees would be readily seen on aerial photographs at the scale of 1:5,000, so given the complex topography of the Blue Mountains, such a set of photographs would offer the best chance of mapping its distribution. Aerial photography should use normal colour photography, but, if possible, some colour infra-red photographs should also be taken for comparative purposes.

Methods of killing *P. undulatum*

As uprooting is effective and because of the lack of need of herbicide, this method should be used whenever individuals need to be killed. The high density of *P. undulatum* seedlings in some areas will preclude the eradication of the species at this size.

Small trees. Plants too large to be uprooted can be cut. There are then two ways of killing the stumps.

- Immediately apply herbicide. All stumps treated (in 1995) with sufficient undiluted glyphosate to thoroughly cover the cut surface had died by 1996. It would be sensible to find out if a less concentrated solution worked as well.

- Strip the bark off the stump. Our trial attempts at this seem to be completely effective *as long as all the bark down to soil level or lower is removed*. If any is left, the stump will resprout (but perhaps die if weak and in a heavily shaded location). It becomes very difficult and time consuming to successfully do this with larger trees, as the roots are often large and convoluted. It would be well worthwhile exploring this technique further.

Large trees. Large trees in remote areas (where harvesting is unlikely to be feasible) should be killed standing with the use of herbicide. Those trees that can be harvested should have their stump treated with glyphosate as with smaller trees. There are three methods of applying herbicide to standing trees that we think are potentially useful.

- Frill girdling. Further tests are needed to see if all the bark should be removed, as well as making the frills and applying the herbicide. The application of glyphosate to frills is certainly a method that we recommend.
- Drilling holes and pouring in herbicide. This is very effective, if at least one hole is drilled for every 10 cm of stem girth, but is slower than frilling. Its effectiveness as a way of applying herbicide cannot at present be compared with that of frill girdling, as we used glyphosate with the drilled holes and Tordon with the frill girdling. It should be possible to plug the holes after the herbicide has been poured (or syringed) in, allowing work to continue during the wettest periods.

- The third way is to use hypohatchets. We recommend that these be tried as they offer a way of quickly delivering a known dose of herbicide safely. They cost about £200, and should be tough and reliable as they are used in commercial forestry in the USA. Spare parts would be unavailable in Jamaica. If management has difficulty in locating suppliers we will be able to help.

Harvesting of *P. undulatum* from heavily invaded forest

Removal of *P. undulatum* from heavily invaded forest is less urgent, but harvesting could start also on a limited scale. Because of the very high recruitment of *P. undulatum* following canopy disturbance and the commoness of other serious weeds in more accessible forest, great care needs to be taken in any control or harvesting. It would be very difficult to manage forest for timber production which is threatened by three alien weeds with such different characteristics. If the overriding objective is to leave the slopes of the Blue Mountains forested there is the real possibility that not clearing *P. undulatum* from heavily invaded forest would be the best policy.

A moderately high priority is an investigation into ways to deal with large *P. undulatum* trees in heavily invaded forest. They are vulnerable to windthrow and when the next hurricane strikes this could provide many nuclei for the further spread of *Polygonum chinense* and *Hedychium gardneranum*. Harvesting the *P. undulatum* trees for timber may have a similar effect. Thus, if *P. undulatum* is to be controlled or harvested in heavily invaded forest, every effort must be taken to maximise the regeneration success of native species in the disturbed areas, rather than creating the conditions that favour exotic species. Therefore, the effect on the regeneration of exotic and native species of killing large *P. undulatum* trees by felling versus killing them while still standing should be experimentally tested. If the timber is harvested the effect on the regeneration of the resulting soil disturbance should also be investigated. We suggest an experiment with three control treatments:

- cut and treat stump with glyphosate
- girdle and treat girdle with glyphosate
- undisturbed control

and two levels of soil disturbance. At least six large (>25 cm DBH) *P. undulatum* trees should be included in each treatment. The most suitable area would probably be upper Clydesdale but other areas should be considered. The seedling bank around each tree should be recorded before and after treatment (but this need not be taken to the level of labelling of individuals). This would be suitable for an MSc project or similar.

Kill all *P. undulatum* (cut, harvest and apply herbicide) (or for larger badly formed trees girdle and apply herbicide); also remove larger seedlings (>2m tall) at same time. Go back in about 5-10 years, just before those *P. undulatum* seedlings left have started to produce seeds.

Planting trees should be a policy of last resort for the restoration of natural forest cover following control of *P. undulatum* because of the likely cost. However, should it be necessary, species suitable for planting in areas cleared of *P. undulatum* should preferably be native, fast growing and with a dense crown enabling the suppression of exotic invasive species. They would probably be a subset of the species that are successful in gaps in the natural forest. A wide range should be tested initially, the actual species selected for a particular area should be largely determined by the degree of canopy opening caused by the removal of *P. undulatum.* We have made an initial list, ordered in approximate order of decreasing requirement for gaps for establishment:

> *Brunellia comocladiifolia, Alchornea latifolia*, *Turpinia occidentalis, Clethra occidentalis, Symplocos octapetala, Juniperus lucayana, Podocarpus urbanii, Guarea glabra*.

The ease of propagation of bare root cuttings, survival after transplanting and subsequent growth of a number of these species is currently being tested at Cinchona Botanic Garden by M.A. McDonald in ODA FRP project R6290 and the results of this trial will provide further criteria for species selection.

In order to determine whether commercial use of harvested *P. undulatum* timber could make a contribution towards the costs of control in heavily invaded forest, more information is needed on the working properties, acceptability and market value of *P. undulatum* wood. Logs of *P. undulatum* should be distributed to a cross section of Kingston wood processors to obtain this information. It would also be valuable to obtain a better idea of the economic viability and environmental impact of making charcoal from *P. undulatum* than has been obtained so far; this could readily be carried out in the Cinchona area.

Management of other invasive species

Tests should be made of the effect of physical and chemical treatments on the control of *Polygonum chinense* and *Hedychium gardneranum*. These two invasive species should be eradicated from the Vinegar Hill Trail (and any other trails opened up). Existing contacts should be maintained, and new ones developed, with other organisations concerned with the control of *H. gardneranum (*e.g. in New Zealand, South Africa, Azores, Madeira and Réunion) and *P. chinense* and any other invasive species found to be problematic in the Blue Mountains. The two known *Syzygium jambos* populations should be eradicated because of the extent to which this species has become invasive in other countries.

Biological control

We do not recommend any action to investigate the potential of biological control at present. Steps towards it only need to be taken if the trial weed clearance shows that the feasibility of manual control is low. The next steps should be an exploratory visit to the native range of *P. undulatum* (New South Wales) and further consultations with biological control experts.

Use of *Pittosporum undulatum* outside the forest

Despite the local popularity of *P. undulatum* as a source of fuel-wood, charcoal and for other uses, the environmental damage being caused to the natural forests by harvesting of native species for these uses and the potential of community woodlots to alleviate this pressure, we cannot recommend the planting of *P. undulatum* outside the forest because of the risk that these trees will act as a source of seeds for the invasion of nearby forest. Park management favour the use of native species for planting in the park or the buffer zone (Kerr *et al* 1993). The ability of the great majority of native trees to establish outside the forest is likely to be poor (E.V.J. Tanner, pers. comm., 1991). However, this is currently the subject of trials by Dr Morag McDonald in ODA FRP project R6290.

The one location where trial planting of *Pittosporum* species (*P. undulatum* and *P. viridiflorum*) currently entails little risk to the forest is in the Cinchona area, because the species are already so well established there. However, even in this case uncontrolled planting by farmers should be discouraged; it is only in a smaller number of woodlots that management could ensure that trees are cut before they start to bear seed. In order to investigate the potential for a female sterile line to enable planting to be carried out without risking an increase in the invasion, it would be necessary to determine whether any of the standard, low-technology, vegetative propagation techniques (that can be used by farmers) will work for *Pittosporum*. Although sterile lines may have great potential to allow safer use of potentially invasive species in environments which might be vulnerable to invasion (C. Hughes, 1993), great care should be taken to consider all of the potential draw-backs of this approach so as to caution against such a high technology fix being seen, naively, as a fail-safe solution to a fundamental ecological problem.

In any case, given the local value of *Pittosporum* as well as its potential threat to the natural forests, local participation in decisions over its management and control is vital for their success.

Further research

The forest permanent sample plots established and recorded during this project represent one of the best networks in any area of tropical montane forest in the world. They must be maintained and re-enumerated at regular intervals (e.g. for the plots of E.V.J. Tanner and co-workers every five years, next due in 1999) in order to monitor the rate of invasion of exotic species, their impact on native species, the interaction of different disturbance events (e.g. hurricane impact), and the dynamics of the native forest community that control its vulnerability to invasion.

So far, our research on the impact of *P. undulatum* has concentrated on its effects on terrestrial plant biodiversity. New research is needed on the interaction of the invasion and animal biodiversity, especially birds. The attractiveness of *P. undulatum* fruit to native bird species has played an important role in the spread of the invasion. On the other hand, forest heavily invaded by *P. undulatum* has a greatly reduced diversity of types of fruit and a reduced structural complexity (which may greatly reduce the diversity of epiphytes and of invertebrates) with potentially serious negative effects for bird biodiversity. In the wake of the pioneering research work of Dr Andrew Lack, the Jamaican bird fauna (including many endemic species) has received international conservation interest. Dr Nigel Varty of Birdlife International carried out detailed studies of the impact of Hurricane Gilbert on the bird fauna of the Blue Mountains. These contacts should be developed to enable the necessary research to be carried out on the interaction of *P. undulatum* and animal biodiversity.

New research is needed on the impact of the other invasive exotic plant species (*H. gardneranum* and *P. chinense*) on biodiversity; the effects are likely to be severe.

Given the catchment protection importance of these forests new research on the impact of all three invasive exotic plant species on hydrological and soil parameters is justified. The high leaf area index and dense shade of *P. undulatum* may have a significant negative impact on water yield and slope stability. Nonetheless, such research would be costly to undertake properly (L.A. Bruijnzeel, pers. comm.).

Funding

No substantial progress will be possible with any of the main recommendations without external funding. The outputs of this project and the resulting trial clearance should be used to make a case to donor agencies/international conservation organisations for such funding. The case should be based on our assessment of the extent and severity of the threat posed by the invasion, information that will improve in quality with further analysis and monitoring of permanent sample plots, and a more accurate costing of control measures.

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