Improved Detection and Eradication of Hawkweed (Hieracium)

Experiments and second-generation dispersal models

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Improved Detection and Eradication of Hawkweed (Hieracium)
Experiments and second-generation dispersal models

by Roger Cousens and Nicholas Williams

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Foreword

Orange hawkweed (*Hieracium aurantiacum*) and devil hawkweed (*H. praealtum*) are two stoloniferous perennials that have naturalised in a small part of the Victorian Alps. Both species have now been declared prohibited species at national and state and territory levels in Australia.

For invasive plant species to be eradicated it is necessary to exhaust or remove seed banks. In this research a range of glasshouse and field experiments were undertaken to fill knowledge gaps relating to the seed ecology and biology of *H. praealtum* and *H. aurantiacum*.

In a second part of the project a modelling tool was developed to assist in locating where the species are likely to occur in the landscape and plan effective and efficient action.

Eradication programs are now in progress for both species in Victoria and for *H. aurantiacum* in New South Wales and Tasmania.

This project was funded in Phase 1 of the National Weeds and Productivity Research Program, which was managed by the Australian Government Department of Agriculture, Fisheries and Forestry (DAFF) from 2008 to 2010. The Rural Industries Research and Development Corporation (RIRDC) is now publishing the final reports of these projects.

Phase 2 of the Program, which is funded to 30 June 2012 by the Australian Government, is being managed by RIRDC with the goal of reducing the impact of invasive weeds on farm and forestry productivity as well as on biodiversity. RIRDC is commissioning some 50 projects that both extends on the research undertaken in Phase 1 and moves into new areas. These reports will be published in the second half of 2012.

This report is an addition to RIRDC’s diverse range of over 2000 research publications which can be viewed and freely downloaded from our website [www.rirdc.gov.au](http://www.rirdc.gov.au). Information on the Weeds Program is available online at [www.rirdc.gov.au/weeds](http://www.rirdc.gov.au/weeds).

Most of RIRDC’s publications are available for viewing, free downloading or purchasing online at [www.rirdc.gov.au](http://www.rirdc.gov.au). Purchases can also be made by phoning 1300 634 313.

**Craig Burns**
Managing Director
Rural Industries Research and Development Corporation
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Additionally, we thank all the experts who contributed their knowledge of Hieracium to the questionnaire; Snowy Hydro for generously providing the weather data from the Cabramurra weather station; Parks Victoria, the Department of Sustainability and Environment and the National Parks Division of the Department of Environment and Climate Change for supplying the data required for modelling; and Dow Agrosciences for supplying Grazon.

The project would not have been possible without the financial and in-kind support of the Australian Weeds Research Centre, Parks Victoria, the Department of Sustainability and Environment, the Department of Primary Industries and the National Parks Division of the Department of Environment and Climate Change.
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Executive Summary

What the report is about

In this report a range of glasshouse and field experiments were undertaken to fill knowledge gaps relating to the seed ecology and biology of *Hieracium praealtum* (king devil hawkweed) and *H. aurantiacum* (orange hawkweed).

- For both species rapid germination of seeds is likely because most seed will germinate readily once temperature, moisture and light requirements are met—probably during spring–summer. Late-developing seeds will probably remain dormant during winter and germinate in the following spring.

- Buried seeds, even if they do germinate, are unlikely to emerge through the soil.

Where are the relevant industries located in Australia?

Two areas have been identified as at greatest risk of invasion by the two *Hieracium* species studied: the Bogong High Plains in the Victorian Alpine National Park, by both *H. aurantiacum* and *H. praealtum*, and the Round Mountain region (Jagungal Wilderness) of Kosciuszko National Park in New South Wales, by *H. aurantiacum*. These two regions have known invasive populations of *Hieracium* that are believed to have been present for at least 20 years.

Eradication of the populations is the aim of the land management agencies - Parks Victoria and the New South Wales Department of Environment and Climate Change - so this project aimed to help determine which areas should be the priorities for search and control activity in coming seasons.

On the basis of modelling using a plant growth index and climatic stresses to derive a ‘climatic niche’, the potential habitat for *H. aurantiacum* in Australia includes all of Tasmania, the highlands of eastern New South Wales and most of Victoria.

Background

*Hieracium aurantiacum* and *H. praealtum* (Asteraceae) are two stoloniferous perennials that have naturalised in a small part of the Victorian Alps.

Both species have now been declared prohibited species at national and state and territory levels in Australia, mainly because of their degradation of large areas of agricultural land and the reduction in amenity value and biodiversity in native tussock grasslands in New Zealand. Revenue lost as a result of invasion by several species of hawkweed in New Zealand was estimated at $45 million dollars in 1993.

Aims/objectives

This report investigates the effects of fire, herbicides and picking on seed production with a view to confirming the ecological responses of the seeds of *H. aurantiacum* and *H. praealtum* (Asteraceae).

Methods used

The use of fire as a management tool was explored by conducting a prescribed burn. Fire could be of use to remove seed around adult plants but not as a broad-area management tool or for adult plants.

The potential for production of viable seeds following hand-picking of flowers or herbicide application was also measured.
• Seed dispersal is possible from picked immature flowers, although this depends on the stage of maturity at the time.

• Depending on the flower’s stage of maturity, achenes can be produced after herbicide application, although their viability is yet to be determined.

• All flowering stems should be picked, bagged and destroyed before herbicide application.

Results/key findings

A previous model for predicting new occurrences of *H. aurantiacum* was adapted and applied to newly discovered infestations of that species in New South Wales and a population of *H. praealtum* in Victoria. Seed dispersal and site disturbance have appeared as the factors promoting increased likelihood of establishment.

Prediction maps were created and distributed to management agencies to guide surveillance and control activity for the 2009–2010 season.

• In Victoria the areas predicted to be at greatest risk of invasion by the *H. praealtum* population occur under the dispersal plume that stretches from the Rocky Valley dam bank opposite the quarantine area upslope in a southerly direction towards the Bogong High Plains road. This region occurs at the western edge of the known locations.

• In New South Wales the areas most at risk of *H. aurantiacum* establishment occur under the dispersal plume in the immediate vicinity of known populations. Areas subject to disturbance—for example, roads and Ogilvies Quarry—also appear to be a priority for search and control in coming seasons.

Implications for relevant stakeholders

In the course of the study we identified two primary areas for future research:

• modelling of improved dispersal by wind, changes in detectability over time, the simultaneous optimisation of surveillance for multiple species, and the impact of uncertainty on surveillance decision making

• quantifying detectability under differing conditions using novel field experiments.

Together with our industry partners, we put forward a successful bid for an Australian Research Council linkage grant worth $302 000 over three years. We have thus added considerable value to this current project and have begun to extend our knowledge of the management of *Hieracium* in Australia.
Introduction

Eradication of invasive plant species necessitates the exhaustion or removal of seed banks. Even high levels of plant mortality, reducing seed production considerably, can still leave populations to persist (Cousens & Mortimer 1995). The longer-lived the seeds, the longer eradication will take and the less likely eradication programs will succeed. For example, the main reason for the rapid eradication of the annual Kochia scoparia from Western Australia is considered to be the very brief lifespan of the plant’s seeds (Dodd 2004). Systematic and repeated searching and the use of herbicides ensured that no new seeds were added to the seed bank, which became exhausted as a result of high levels of germination. In perennials, an inconspicuous vegetative phase can make it harder to find and kill plants, but the long-term objective must be to remove the seed bank as well as plants. At the time a new invasion is discovered, however, there might be very little available information about the seed ecology and seed bank dynamics of the species.

Hieracium aurantiacum and H. praealtum (Asteraceae) are two stoloniferous perennials that have naturalised in a small part of the Victorian Alps (Natural Heritage Trust 2003; Williams & Holland 2007). Both species are reported to produce large amounts of viable seed (Koltunow et al. 1998; Makepeace 1985a; Stergios 1976). The fruits of Hieracium species are dispersed by wind and also have Velcro™-like spines that aid dispersal by animals, including humans (Blood 2001; Rinella & Sheley 2002). H. aurantiacum is known to be a facultative apomict (Williams & Holland 2007) and thus can produce seed both sexually and asexually, reducing its reliance on pollinators or on pollen from conspecifics (Williams & Holland 2007). This is also the case for H. praealtum (Chapman & Bicknell 2000). H. aurantiacum is believed to have been deliberately introduced into the Bogong High Plains at Falls Creek as a garden plant in the 1980s, although the first formal report on its presence did not occur until 1999 (Morgan 2000; Williams & Holland 2007). H. praealtum was first reported from near Falls Creek in 2003 (Carr et al. 2004). It has been suggested that this population was established in 2000 by seed inadvertently brought in on machinery from New Zealand (Williams & Holland 2007), where the species is widespread (Espie 2001).

Both species have now been declared prohibited species at national and state and territory levels in Australia (Williams & Holland 2007), mainly because of their degradation of large areas of agricultural land and the reduction in amenity value and biodiversity in native tussock grasslands in New Zealand. Revenue lost as a result of invasion by several species of hawkweed in New Zealand was estimated at $45 million dollars in 1993 (Espie 2001). On the basis of modelling using a plant growth index and climatic stresses to derive a ‘climatic niche’, the potential habitat for H. aurantiacum in Australia includes all of Tasmania, the highlands of eastern New South Wales and most of Victoria (Brinkley & Bomford 2002). In 2002 the potential production losses to Australia caused by H. aurantiacum’s effects on grazing and horticulture were conservatively estimated at $48 million (Brinkley & Bomford 2002). In New Zealand H. praealtum is more widespread than H. aurantiacum (Espie 2001); H. praealtum might thus pose even greater economic, environmental and ecological threats to Australia than those posed by H. aurantiacum.

Eradication programs are now in progress for both species in Victoria and for H. aurantiacum in New South Wales and Tasmania. Each summer there are extensive searches for flowering plants, which are sprayed with herbicides, and their locations are recorded by GPS; locations of plants sprayed in previous years are also visited. There are a number of questions that arise and that determine the efficacy of different control options and the level of effort that needs to be invested for eradication to be achieved:

- If a plant is killed, is there likely to be long-lived viable seed surrounding it?
- How long will the seeds survive—and hence for how long will locations have to be revisited?
- If plants are missed, how many seeds will they add to the seed bank?
- If the seeds land on the soil surface are they able to germinate?
- Can they germinate if they become buried by soil disturbance or under vegetation?
- Are there ways the seed bank can be reduced or destroyed completely—for example, by fire?
Containment or eradication action can be taken only after new populations and individual plants have been located. Knowledge of where a species is most likely to occur in the landscape is thus vital for planning effective and efficient action. The second part of this project therefore involved development of a modelling tool to help eradication teams target their search effort. We had previously developed an *H. aurantiacum* (Williams et al. 2008) model to help Parks Victoria in its search for that species on the Bogong High Plains. This combined knowledge of the spatial distribution of suitable habitats with a model of seed dispersal from a known source. By adapting and applying that model to *H. praealtum* on the Bogong High Plains in Victoria and *H. aurantiacum* in Kosciuszko National Park in New South Wales, we sought to improve our overall predictive ability and to present to our industry partners up-to-date maps showing predictions for the current year.

In the interest of clarity, the two distinct themes—species ecology and distribution prediction—are kept separate in this report. Part One describes experimental work on gaps in the ecology, seed biology and management of *H. aurantiacum* and *H. praealtum*. Part Two reports on the further development of models for directing search efforts for the species, along with predictions about known infestations in Victoria and New South Wales.
Part One  Experiments on the ecology and management of *Hieracium aurantiacum* and *H. praealtum*

JL Bear, RD Cousens and NSG Williams
Methods

The ecological gaps primarily concern *Hieracium praealtum* (king devil hawkweed) since we had previously conducted seed biology research on *H. aurantiacum* (orange hawkweed). The potential seed production of *H. praealtum* was determined in plants grown in the glasshouse. Germination of achenes of *H. praealtum* was examined under a range of light and temperature conditions in the laboratory and compared with that of *H. aurantiacum* (also previously studied). For both species, we described the emergence of pre-germinated seeds in relation to burial depth. As to management, we examined three factors identified by our industry colleagues as needing investigation—the effects of picking flowers on seed production, the effects of herbicides on seed production, and the potential of fire as a management tool.

Seed production: *Hieracium praealtum*

Seed production by *H. aurantiacum* had been measured in a previous study by our group. For the present study we grew 15 *H. praealtum* plants under quarantine conditions in a glasshouse (numbers are limited by the active eradication status of the species). Light levels ranged between 5200 and 6800 lux; maximum temperatures throughout the growth period averaged 36°C but reached 50°C on a few occasions. The plants were irrigated via a capillary bed; routine hygiene and protection against pests and disease were carried out on an ad hoc basis. Flowering began in early December 2008 and continued until early July 2009. Individual stems were harvested when the achenes in most of their capitula were mature (Koltunow et al. 1998) and were then stored in the dark at 22°C (± 2°C range).

Seed production was estimated by making a bulk collection of achenes from each stem and counting the number of capitula per stem. The achenes were then cleaned using a Zig Zag aspirator at the Victorian Conservation Seedbank, Royal Botanic Gardens, Melbourne, at fan speeds of 100 and 160 revolutions per minute.

Germinability was assessed for eight replicate samples of 25 randomly selected achenes, which were placed on two sheets of 8-centimetre Double Rings® Filter Paper 102 ‘Qualitative’ moistened with 3 millilitres of de-ionised water in 9-centimetre plastic Petri dishes. The Petri dishes were sealed with Parafilm® PM-996 and placed in a germination cabinet set to a constant 23°C and a 16:8-hour light:dark photoperiod. The seedlings were counted daily for 10 days. Unless otherwise stated, all further germination tests followed this method.

Achene viability was tested using a tetrazolium protocol described for *Taraxacum officinale* (Leist et al. 2003) with slight modifications. To minimise damage, embryos were not removed from their pericarps after they were cut; to ensure that staining was complete, achenes were soaked in tetrazolium chloride solution for 72 hours. They were then examined for intensity of colour.

Effects of environment on germination

Response to darkness: *Hieracium praealtum*

Various processes can act to bury achenes after they have dispersed: this experiment aimed to determine whether the resulting lack of light would inhibit germination. A previous study found that there is an obligate requirement for light for seeds of *H. aurantiacum* to germinate (Bear 2008). Samples of 25 *H. praealtum* achenes were placed on moist filter paper in Petri dishes under the diurnally alternating light:dark conditions just described for 10 days or under continuous darkness for 10, 20 or 30 days. There were four replicates of each treatment. Dark conditions were imposed by wrapping the Petri dishes in two layers of aluminium foil. Germination was assessed at the end of
each treatment; those incubated in the dark were then put in a diurnally alternating light:dark cycle for a further seven days.

Response to burial: both species

If achenes are buried and are able to germinate, from what depth would seedlings be able to emerge? Twenty-five achenes of each species were placed on 25 millilitres of sterilised technical agar in separate sterilised plastic Petri dishes 90 millimetres in diameter and 25 millimetres deep. The achenes had been surface-sterilised in 1 per cent sodium hypochlorite solution for 10 minutes and then rinsed in de-ionised water. The Petri dishes were sealed with Parafilm® PM-996, placed in a germination cabinet and incubated at 23°C under diurnally alternating light until at least 85 per cent had started to germinate (with the radical being visible); this occurred after four days. Light levels in the cabinet ranged between 660 and 3650 lux (BEHA Digital Lux Meter model no. 93408). Four treatments were then imposed, with eight replicates. Two treatments involved the addition of an artificial soil substitute either 4 or 8 millimetres deep. The soil substitute was a mixture of pine bark, coarse sand and sieved coir to which Osmocote® micro-prills and SaturAid® soil wetter had been added at a ratio of 1500 grams per cubic metre. This mixture was sieved through a 2-millimetre screen. The gravimetric moisture content of the medium was 10 per cent. The third treatment involved the addition of no soil and exposure to the light. The final treatment was again without soil, but the dishes were wrapped with two layers of aluminium foil to exclude light. Germination in the light and emergence in the buried seed treatments were assessed every 10 days for 30 days. Germination in the dark was assessed after 30 days.

Response to high temperatures: Hieracium praealtum

If fire has the potential to kill seeds, what is the minimum lethal temperature? An earlier study found that a temperature of between 90 and 110°C would kill all seeds of H. aurantiacum if exposed for 150 seconds (Bear 2008). Random samples of 25 H. praealtum achenes were wrapped in aluminium foil. Eight replicates were placed sequentially in an oven for 150 seconds at each of five temperatures (22, 70, 90, 110 and 130°C) and then maintained at room temperature (22°C, range ± 2°C) for 24 hours. Germination tests were then carried out, as already described. Germination was assessed after a further 10 days.

Effect of picking and discarding flowers on seed production and viability: both species

Will removing flowering heads and discarding them reduce the number of viable seeds that enter the seed bank? Could this also be a mechanism for long-distance dispersal through walkers picking flowers? To answer these questions we propagated 45 plants of each species. The plants were grown from stolon cuttings planted in Burnley General Mix potting medium in individual ‘squat pots’ and placed in a glasshouse until flowering began. Temperatures in the glasshouse were monitored using Thermochron ibuttons® (DS1921G-F5) set to record at two-hourly intervals. Maximum and minimum temperatures were 41.5 and 5°C. Once flowering had started, all plants were moved to a climate-controlled glasshouse where the temperature ranged between 35 and 12°C. Throughout the growing period the plants were watered via a capillary bed, and routine hygiene and protection against pests and disease were carried out. For H. praealtum, flowering began in early September 2009 and continued until February 2010, when the experiment was terminated. For H. aurantiacum, flowering did not begin until November 2010. There were two treatments and a control (see Table 1).
Table 1  Treatments for picked-flower experiments: stages of capitulum development when inflorescences were harvested

<table>
<thead>
<tr>
<th>Treatment label</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage A</td>
<td>Inflorescence harvested when at least one individual capitulum was fully open (Stage 9: Koltunow et al. 1998—see Figure 1). Any capitula that had developed beyond Stage 9 were removed (this occurred only on a few occasions, when capitula had developed a little faster than expected or if a harvest was missed over a weekend).</td>
</tr>
<tr>
<td>Stage B</td>
<td>Inflorescence harvested when at least one individual capitulum had closed and the corolla had fallen (Stage 13: Koltunow et al. 1998—see Figure 1).</td>
</tr>
<tr>
<td>Stage C</td>
<td>Inflorescence harvested when the achenes in most of its capitula were mature (Koltunow et al. 1998).</td>
</tr>
</tbody>
</table>

Individual stems were harvested with a scape length of 250 millimetres and were stored in the dark at 22°C (± 2°C range).

Seed production for *H. praealtum* was estimated by making a bulk collection of achenes from each stem and counting the number of capitula per stem for each of the three treatments. Achenes were then cleaned using a Zig Zag aspirator at the Victorian Conservation Seedbank, Royal Botanic Gardens, Melbourne, at a fan speed of 100 revolutions per minute.

Note: The pattern of capitulum development for *H. aurantiacum* and *H. praealtum* is the same. The position of the receptacle (r) in relation to the capitulum (ca) is shown.
Source: Koltunow et al. (1998).

Figure 1  Capitulum development in *Hieracium piloselloides*

Germinability was assessed for six replicate samples of 25 randomly selected achenes from Treatment A and eight replicate samples of 25 achenes from each of Treatments B and C. Achenes were placed on two sheets of 8-centimetre Double Rings® Filter Paper 102 ‘Qualitative’, moistened with 3 millilitres of de-ionised water in 9-centimetre plastic Petri dishes. The Petri dishes were sealed with Parafilm PM-996 and placed in a germination cabinet set to 23°C and a 16-hour photoperiod. Seedlings were counted after 10 days. Any ungerminated fruits were cut to determine whether embryos were present; viability was estimated as the percentage of filled achenes that germinated.

Because of *H. aurantiacum*’s relatively late flowering, seed production estimation and germinability testing for the species are still in progress. The results will be disseminated to our research colleagues as soon as they are available.
Herbicide efficacy: both species

Will spraying *Hieracium* plants with herbicide, without having removed and destroyed flowering heads, reduce the number of viable seeds that enter the seed bank? To answer this question, we grew 72 plants of each species to provide for four herbicide treatments and two flowering stages for the application of herbicide and three replicates of each. Methods for growing the plants were identical to those described for the picked-flower experiment just discussed. Table 2 shows the herbicide treatments.

Table 2  Herbicides used

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Herbicide</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lontrel 5 mL/L mixed with Pulse wetting agent, as per label</td>
</tr>
<tr>
<td>2</td>
<td>Glyphosate (as Roundup Biactive) 10 mL/L with no wetter</td>
</tr>
<tr>
<td>3</td>
<td>Water (control)</td>
</tr>
<tr>
<td>4</td>
<td>Grazon 5 mL/L mixed with wetter 1000 at 1 mL/L</td>
</tr>
</tbody>
</table>

The herbicides were applied using a misting aerosol, spraying individual plants until run-off occurred (similar to the spot-spraying applied in the eradication program). The plants were left to drip-dry before being returned to the capillary bed. The same two stages of capitulum development were used for the herbicide application as for the picked-flower experiments (see Table 3).

Table 3  Timing of herbicide application

<table>
<thead>
<tr>
<th>Stage</th>
<th>Timing of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Herbicide applied when at least one individual capitulum was fully open (Stage 9: Koltunow et al. 1998). Any capitula that had developed beyond Stage 9 were removed (this occurred only on a few occasions, when capitula had developed a little faster than expected or if a herbicide application was missed over a weekend).</td>
</tr>
<tr>
<td>B</td>
<td>Herbicide applied when at least one individual capitulum had closed and the corolla had fallen (Stage 13: Koltunow et al. 1998).</td>
</tr>
</tbody>
</table>

Inflorescences of *H. praealtum* and *H. aurantiacum* were harvested with a 250-millimetre scape in December 2009 and February 2010 respectively and then stored in the dark at 22°C (± 2°C range).

The effect of fire on mature plants: *Hieracium aurantiacum*

To determine the range of temperatures likely to be experienced during a fire and the effect of fire on mature plants of *H. aurantiacum*, a 0.8-hectare prescribed burn was conducted on 1 April 2009 at Falls Creek (36.87°S, 147.28°E). The site consisted of a mosaic of grassland, short open heath and tall dense heath within which there is a known infestation of *H. praealtum*. Temperatures were recorded every two seconds on the surface, 150 millimetres above the surface and 10 millimetres below the surface at three locations. Seventy potted plants of *H. aurantiacum* were ‘planted’ in their pots in a 2-hectare area at the site of the burn. Pots were buried in holes made by a soil corer so that the tops of the pots were level with the ground surface. The rim of each pot was hidden using litter and/or surface vegetation. Fifty-two of these plants were in the area to be burnt; the remaining 18 plants were in nearby vegetation that was not burnt. The diameter of the longest opposing leaf pair was recorded for each plant before planting (day 0) and 7, 26 and 60 days after the burn was carried out. Plant survival and number of stolons were recorded on days 7, 26 and 60. Plants were retrieved the day after the fire and returned to nursery conditions at Burnley Campus. During the fire it was
noted that 13 plants were in the direct path of a flamethrower used to ignite the vegetation. This was hot enough to kill the plants and melt the rims of the pots in which the plants were contained. These 13 plants were removed from the data.

**Statistical analyses**

ANOVA and Tukey’s multiple comparison tests were used to examine differences between heat treatments for each species and to ensure that cabinet number or shelf position did not interact as blocking factors. An arcsine transformation was used to normalise variance where necessary. Data are presented as means ± 1 standard error of the untransformed data. Two-tailed Student’s *t*-tests were performed on germination averages to test for differences between germination and viability tests, germination capability between *H. aurantiacum* and *H. praealtum* and to test for the effects of darkness and burial on germination and emergence. Minitab Release 15 was used for all analyses.
Results

Seed production

The results for seed production, germinability and viability of *H. aurantiacum* are from an earlier study but are presented here to allow direct comparison with the new *H. praealtum* data.

Sixty-nine per cent of the 6138 *H. aurantiacum* achenes were classed as filled; the remaining 31 per cent were discarded as chaff. A total of 4230 *H. aurantiacum* achenes were processed through the Zig Zag aspirator. Production was estimated at 31.2, 7.8 and 1.6 of high-quality, dubious and unfilled achenes respectively per capitulum. This translates to approximately 171, 43 and 8.8 respectively per stem. For *H. praealtum*, 4190 achenes were classed as filled (mean 10.63 per capitulum, 246 per stem). For *H. aurantiacum*, 44 per cent of the ‘dubious’ category were found to be viable.

*H. aurantiacum* achenes germinated rapidly and synchronously (see Figure 2): after four days 67 per cent had germinated and after 10 days 89 per cent had germinated (SE 1.5). *H. praealtum* achenes germinated at a similar rate, with mean percentage germination being 86.5 per cent (SE 2.48) at day 10.

**Figure 2**  Germination rate over 10 days for seeds taken from glasshouse-grown *Hieracium aurantiacum* and *H. praealtum*

Percentage viability measured by germination tests was similar to that from biochemical viability tests (see Figure 3) for *H. aurantiacum* (*p* = 0.29); in contrast, percentage viability for *H. praealtum* was significantly different between the two methods of testing (*p* = 0.024). There were no significant differences between *H. aurantiacum* and *H. praealtum* germination test results (*p* = 0.48), but there was a significant difference between biochemical viability tests for *H. aurantiacum* versus *H. praealtum* (*p* = 0.046).
Note: Error bars represent ± 1 SE of untransformed data. Viability as measured by germination testing is in solid colour; viability as measured by biochemical testing is hatched.

Figure 3  Results of viability tests for *Hieracium aurantiacum* and *H. praealtum*

**Effects of environment on germination**

**Response to darkness**

For *H. aurantiacum*, 95 per cent (± 2.51) of seed germinated in light compared with 14.67 per cent (± 3.86) in combined dark treatments; for *H. praealtum*, 74 per cent (± 4.0) germinated in light compared with 6.17 per cent (± 1.83) in combined dark treatments (see Figure 4). Interspecific differences for germination in light were also significant (*p* = 0.01). There were no significant differences between *H. aurantiacum* and *H. praealtum* when germinated in dark conditions (*p* = 0.06). Once replicate samples were removed from darkness and placed in diurnally alternating light–dark conditions, nearly all ungerminated seed germinated after seven days.
Note: Error bars represent ± 1 SE of the mean of untransformed data.

Figure 4  The effect of light and darkness on germination of *Hieracium aurantiacum* and *H. praealtum*

**Response to burial**

After 30 days more than 90 per cent of seed for each species ‘emerged’ when not buried, whereas less than 5 per cent of germinated (radicle visible) seed of each species emerged when buried at a depth of 4 millimetres and there was no seedling emergence from a burial depth of 8 millimetres (see Figure 5). Differences in emergence for buried seed compared with unburied seed were highly significant (*p* < 0.001). Pre-germinated seeds that were incubated in the dark but not buried proceeded to germinate. There was no significant difference between this treatment and unburied seed (*p* = 0.37).
Note: Lower-case letters indicate significant differences (Tukey’s multiple pairwise comparisons after arcsine transformation); error bars show ± 1 SE of untransformed data.

Figure 5  The effect of burial on pre-germinated seeds of Hieracium aurantiacum and Hieracium praealtum after 30 days

Response to high temperatures

The temperature responses of the two species were broadly similar. When exposed for 150 seconds, all H. aurantiacum seeds were killed at temperatures between 90 and 110°C and all H. praealtum seeds were killed at temperatures between 110 and 130°C (see Figure 6). For H. aurantiacum, temperatures below 90°C had no significant effect on germination; for H. praealtum, temperatures below 70°C had no effect on germination, but temperatures of 90 and 110°C significantly reduced germination.
The effect of picking and discarding flowers on seed production and viability: *H. praetaltum*

There were highly significant differences in the number of capitula per stem containing filled achenes across all three treatments: there were few capitula (11.2 per cent) containing achenes if picked at a late stage of capitulum development (when at least one individual capitulum has closed and the corolla has fallen) and very few capitula (1.4 per cent) containing achenes if picked at an early stage of capitulum development (when at least one individual capitulum is fully open). Almost all capitula (96 per cent) contained achenes if stems were not harvested (see Figure 7).
There were no significant differences for percentage germination or percentage of filled achenes between picking flowering stems at a late stage of capitulum development (Stage B) compared with not harvesting flowering stems until most capitula contained mature achenes (Stage C) (see Table 4). There were, however, significant differences in both the percentage germination and the percentage of filled achenes in each replicate sample for picking flowers at Stage A compared with picking at Stage B or at Stage C. There were no significant differences between any of the treatments for estimated viability (the number of filled achenes that germinated).
Table 4  Number of achenes per plant in bulked seed lots after cleaning, with germination capability of cleaned achenes and potential numbers of readily germinable achenes per plant capable of being dispersed and entering the seedbank for *Hieracium praetaltum*

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Stage at harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean number of achenes per plant after cleaning the bulked seed lots</td>
<td>A 15.5, B 80, C 1071</td>
</tr>
<tr>
<td>Germination capability (%)</td>
<td>A 5.33 (1.69), B 29.5 (3.46), C 32 (4.84)</td>
</tr>
<tr>
<td>Estimated number of readily germinable achenes per plant</td>
<td>A 0.83, B 23.6, C 343</td>
</tr>
<tr>
<td>Filled achenes (%)</td>
<td>A 9.33 (2.23), B 50.5 (4.72), C 57.5 (6.28)</td>
</tr>
<tr>
<td>Estimated number of filled achenes per plant</td>
<td>A 1.45, B 40.4, C 616</td>
</tr>
<tr>
<td>Estimated viability (% of filled achenes that germinated readily less than 8 weeks after harvest)</td>
<td>A 0.57 (13.21), B 58 (6.48), C 56 (4.54)</td>
</tr>
</tbody>
</table>

Note: The estimated number of filled achenes per plant and the percentage of filled achenes that germinated are given. Standard errors are in parentheses.

**Herbicide efficacy for seed production: both species**

Herbicides have been applied and seeds harvested. Seed production estimation and germinability testing for both species are still being completed. The results will be disseminated to our research colleagues as soon as they are available.

**The effect of fire on mature plants: *Hieracium aurantiacum***

As the fire passed, temperatures at the soil surface and at 150 millimetres above for a short period were highly variable (see Figure 8). The highest temperature measured was 695°C at the soil surface. Temperatures within a 4-metre radius of this varied between 30 and 230°C at or above the surface. Temperatures at 10 millimetres below the surface remained constant, at 16, 20 and 33°C for each of the three thermocouple locations.
Note: The highest temperature (695°C) was recorded at the soil surface at 14:39 hours.

Figure 8  Temperatures above and below the soil surface during a prescribed burn, 1 April 2009

Apart from the 13 plants that had no visible living tissue after exposure to the flamethrower, some green tissue was evident on all plants seven days after exposure. Twenty-six days after the fire 24 per cent of exposed plants had died; 30 per cent of plants had died by day 60. None of the unburnt plants died (see Figure 9).

Figure 9  Survival of *Hieracium aurantiacum* plants after exposure to fire
Exposure to both field conditions and fire had a significant effect on the size of plants as measured by rosette diameter (in the case of burnt plants, this was the diameter of the green area of the longest pair of opposing leaves that were not completely burnt). This effect was maintained throughout the 60-day post-fire period (see Figure 10).

**Figure 10** The effect of fire and exposure on size of *Hieracium aurantiacum* plants

Although exposure to fire had no initial effect on the number of stolons the *H. aurantiacum* plants produced, plants exposed to fire had produced fewer stolons by 26 days after the fire and significantly fewer stolons at 60 days compared with plants that were not exposed (see Figure 11).
Note: Error bars represent ± 1 SE of the means.

Figure 11  Stolon production per plant in burnt and unburnt *Hieracium aurantiacum* 7, 26 and 60 days after exposure to fire
Discussion

Seed production

Many Hieracium species are known to produce large amounts of seed, although estimates for different taxa differ widely—not only according to species (Koltunow et al. 1998) but also in relation to site factors (Makepeace 1985a) and flowering phenology (Stergios 1976). For example, in glasshouse conditions in New Zealand H. aurantiacum was shown to produce an average of 86 florets per capitulum (SE 7.16), of which 91 per cent comprised ‘dark seeds’ (Koltunow et al. 1998), whereas in the field it can produce a mean of 74 or 58 achenes per capitulum depending on when in the season flowering occurs (Stergios 1976). Our results—showing more than 170 and 246 pure seeds per flowering stem of glasshouse-grown H. aurantiacum and H. praealtum respectively—are not inconsistent with these findings. Indeed, this study is, as far as we are aware, the first to estimate the number of seeds per capitulum and per flowering stem for H. praealtum.

The high germination capability for three-month-old dry-stored seed for each species suggests that if there is any after-ripening requirement for H. aurantiacum and H. praealtum it was met before each seed lot was tested. Similarly, no dormancy breaking requirement was detected: close to 90 per cent of pure seed of each species germinated readily under standard test conditions within 10 days. The statistically significant differences between germination and viability tests for H. praealtum probably have no biological basis. We attribute the differences to difficulties associated with the manual removal of embryos from their surrounding pericarps to assess staining: embryos damaged by this process were counted as non-viable even if they were fully stained. We therefore found germination testing to be an accurate surrogate for assessing the viability of Hieracium seed lots and used it for all later tests rather than the more technically difficult and time-consuming biochemical method.

Effects of environment on germination

Response to darkness

Germination for both species was much reduced when dark conditions were imposed. The requirement for light to cue germination (photoblastism) or the inhibition of germination by darkness is a common trait in many small-seeded species, especially members of the Asteraceae (Fenner & Thompson 2005). If the seeds germinated at depth, they would lack the energy to reach the surface. Our results show, however, that a small percentage of seeds (approximately 15 and 6 per cent for H. aurantiacum and H. praealtum respectively) are capable of germinating in complete darkness. The ecological reasons for this are unclear—other than that darkness allows some flexibility to respond to different conditions. Field observations provide evidence in support of this: H. praealtum has been found growing under 100 per cent cover of Bossiaea foliosa, Prostanthera sp. and Kunzea muelleri (McDougall 2004; Thomas et al. 2008).

Response to burial

Because of the dramatic reduction in the germinability of seeds in response to darkness, we ensured that seeds for this experiment had begun to germinate before they were buried. Nothing emerged if they were buried at 8 millimetres; a few seedlings emerged from a burial depth of 4 millimetres. Since few seeds can germinate in darkness (that is, if buried below, say, 3 millimetres) and only a very few can push through soil if buried below 4 millimetres, buried seeds will be of major concern only at disturbed and cultivated sites—for example, Falls Creek village or where there are ski run renovations, such as Wombat’s Ramble.
Response to high temperatures

The study results demonstrate clearly that seeds of *H. aurantiacum* and *H. praealtum* are killed by short durations of temperatures between 90 and 110°C. This finding is consistent with a reported observation in Montana that the seeds of *H. aurantiacum* and *H. caespitosum* in burnt areas are either sterilised or burnt by heat (Bushey 1995). It is also consistent with findings for other perennial daisies. Morgan (1999) found significant reductions in germinability for surface-sown seed compared with seeds buried at a depth of 5 millimetres in three Asteraceae (*Hypochoeris radicata*, *Leucochrysum albicans* and *Rutidosis leptorrhynchoides*) after exposure to fire on the soil surface in *Themeda*-dominated grasslands.

Our results also suggest that temperature elevation during prescribed fire in the Australian Alps is short-lived and temperatures are relatively cool and very patchy: temperatures below the surface appear not to change at all. This means that prescribed fire cannot be used as a reliable means of killing or sterilising *Hieracium* seeds on or near the soil surface. Nevertheless, since the duration of elevated temperatures at and below the surface during lowland grassland fire is strongly correlated with fuel load (Bradstock & Auld 1995; Massman et al. 2008; Morgan 1999), it might be possible to manipulate fuel loads so as to maximise temperature change at and below the surface and to reduce temperature variability across a site infested with *Hieracium*, especially in the case of small infestations. Alternatively, flamethrowers could be used to heat material immediately around plants that have been treated with herbicides.

Effect of picking and discarding flowers on seed production and viability: *Hieracium praealtum*

The low fan speed required to ensure capture of filled seed, especially for the small seed lot in treatment A, resulted in a high proportion of unfilled achenes being retained. The study results suggest that picking and discarding whole scapes can disperse some seeds, possibly at long distances from the site of the infestation where inflorescences were picked. Despite this, a considerable reduction in the amount of seed entering the seed bank is likely if inflorescences are harvested before individual capitula produce mature achenes. Walkers are unlikely to pick stems with capitula all unopened. The period of seed storage in this experiment was short (less than eight weeks), which might may explain the low germination capability and low ‘fill’ rate. It might also be that there is an after-ripening requirement in these species, something that could easily be tested. Additionally, Stergios (1976) observed that late-harvested seeds required cold stratification.

The effect of fire on mature plants: *Hieracium aurantiacum*

Some *H. aurantiacum* plants were killed by flames, although only those in the path of the flamethrower were killed immediately. Exposure to fire reduced vigour in the short term, but most plants recovered. Fire is not sufficiently hot or homogeneous to use as the sole management tool for mature plants, although it could perhaps help as part of an integrated management plan.
Part Two  Modelling likely distributions of *Hieracium* species around current infestations in the alpine regions of Victoria and New South Wales

K Giljohann, AK Hahs, RD Cousens and NSG Williams
Introduction

Two areas have been identified as at greatest risk of invasion by the two *Hieracium* species studied: the Bogong High Plains in the Victorian Alpine National Park, by both *H. aurantiacum* and *H. praealtum*, and the Round Mountain region (Jagungal Wilderness) of Kosciuszko National Park in New South Wales, by *H. aurantiacum*. These two regions have known invasive populations of *Hieracium* that are believed to have been present for at least 20 years. Eradication of the populations is the aim of the land management agencies—Parks Victoria and the New South Wales Department of Environment and Climate Change—so this research was done to help determine which areas should be the priorities for search and control activity in coming seasons.

The work is a reaplication of Williams, Hahs and Morgan’s (2008) ‘dispersal constrained habitat suitability model’, which was developed to help Parks Victoria locate *H. aurantiacum* in the Bogong High Plains region. The model was found to be effective in predicting the occurrence *H. aurantiacum*, and many new colonisation sites have been identified since 2007.

The aim of the model is to predict sites where the species has a high likelihood of establishment given the suitability of the habitat (from a habitat suitability index) combined with the probability of seed dispersing from known populations to any location in the target area. This ‘seed shadow’ is calculated as the likelihood of seed travelling a given distance modified to reflect the direction of the prevailing wind. The predictions can be used to identify areas of likely future spread and to help with the search and control effort. Intensive searches can then be directed to the areas predicted to have a high probability of *Hieracium* establishment.

This part of the report is divided into three sections. The first section briefly introduces the species and details the methods used and the data required to implement the ‘dispersal constrained habitat suitability model’. The second section reports on the methods and model outcomes for the Victorian infestation of *H. praealtum*. In similar fashion the third section reports on methods and model outcomes for the New South Wales infestation of *H. aurantiacum*. 
Methods

The modelling was done in two steps for both infestations. The first step involved a model constructed using only the ‘source’ population to simulate seed dispersal; this allowed the prediction surface to be applied to the ‘recent’ location data to determine the plausibility of the model’s predictions. The second step involved simulating dispersal from all known locations to provide to the relevant management authorities up-to-date maps of the areas warranting the greatest attention in the search effort. With the exception of the sites for dispersal simulation, all methods applied to both models.

Expert elicitation

The intention was to apply the existing model to *H. aurantiacum* in a new location (New South Wales) and to a new species, *H. praealtum*, at the same location (Victoria), so the model had to be ‘re-parametised’ to reflect the conditions of the local environment and the local population.

Because of the limited amount of quantitative data pertaining to *Hieracium* biology and ecology in the Australian environment, the model relies strongly on expert opinion. If it were to reflect the current on-ground situation, this meant that elicitation of the knowledge base held by field practitioners, managers and other experts with field experience of the two populations was necessary. This was done using questionnaires circulated in October 2009. Appendixes A and B show the questionnaire results. Answers were weighted to reflect respondents’ level of experience; the weights were based on the number of hours spent in the field searching for the relevant *Hieracium* species. The models were re-parametised using weighted means from the questionnaire results.

Model data

GIS data and *Hieracium* spp. geographic location data, as required for model fitting, were obtained from Parks Victoria, the Department of Primary Industries and the Department of Sustainability and Environment in Victoria and the Parks and Wildlife Group of the Department of Environment, Climate Change and Water in New South Wales.

All modelling used the GIS software ArclInfo 9.2 (ESRI 2006). The resulting suitability predictions are therefore relevant to a predetermined grid cell size, as was dictated by the availability of the data—for Victoria a 20-metre grid; for NSW a 25-metre grid. The finest spatial resolution was chosen since this was best able to capture the heterogeneous nature of the local environment and provided results at a scale suitable for management action (Karl et al. 2000).

The habitat suitability index

A habitat suitability index is a predictive tool used to evaluate the quality of habitat for the species of interest. The index is based on a combination of available data together with expert opinion on the species’ biology and ecology. Through combining the independent analysis of several important habitat components in a logical and systematic manner, a single index is produced (Van Horne & Wiens 1991). This allows potential target sites to be compared on the basis of the resulting index.

Habitat components (variables) are selected for their importance to the species’ biology and ecology and are related to site suitability for the species by scaling each variable from 0 (unsuitable habitat) to 1 (optimal habitat). The variables can be linked in a number of ways, each reflecting a different relationship between the environmental variables—for example, multiplicative, additive or logical functions (Elith & Burgman 2003; Van Horne & Wiens 1991).
In this study three variables were chosen for their influence on the suitability of a site for *Hieracium* establishment and persistence: vegetation community; level of disturbance; and soil and site wetness.

- **The vegetation community index.** This provides an estimate of the suitability of each vegetation community in the region by taking into account factors such as structure, percentage cover and density. An assumption of this index is that there is no dispersal limitation; that is, all vegetation communities have an equal probability of seed arriving at the site.

  In New Zealand *H. aurantiacum* has naturalised in wasteland, grassland, scrub, tussock grassland, roadides, lawns, gardens and pastures (Webb et al. 1998). Disturbed areas are thought to have a higher susceptibility to invasion, with areas of vigorously growing grass more resistant (Natural Heritage Trust 2003). The species have, however, been found to be highly competitive and capable of displacing existing species in undisturbed sites (Espie & Boswell 2002).

  When the model was initially parametised in 2007 the short tussock grasslands of the Bogong High Plains were thought to be at the greatest risk of invasion; in New South Wales the species had also been found in snow gum woodlands, and in Tasmania it is thought to have established under mountain ash (*Eucalyptus regnans*) forest.

- **The disturbance index.** Although not essential for *Hieracium* invasion or establishment (Johnstone et al. 1999), disturbance has been found to increase the likelihood of seedling establishment by providing conditions that favour germination—for example, open spaces and low or reduced competition (Makepeace 1985b; Rose et al. 1998).

  The disturbance index incorporated landscape features known to have a high incidence of disturbance and spatially extensive disturbance events (fire and grazing) that might increase the likelihood of *Hieracium* establishment. The disturbances are considered cumulative rather than synergistic, so the parameters were combined additively using the following expression:

  \[
  D = \frac{(U + S + R + A + H + T + G + F + Da)}{9} + 0.001
  \]

  where U is urban areas, S is ski slopes, R is roads, A is aqueducts, H is huts, T is walking tracks, G is grazed areas, F is burnt areas and Da is other disturbed vegetation. To allow for establishment outside areas of disturbance, a value of 0.001 was added to each cell (= no zero cells).

- **The wetness index.** This was used as a surrogate for soil moisture in the absence of this variable being mapped across either region. The index is a topographically based estimation of overland water flow and accumulation that is weighted to reflect the suitability provided by different soil moisture conditions for *Hieracium* establishment and persistence.

  Because these three variables interact, they were combined multiplicatively using the following expression:

  \[
  HSI = (Vegetation \times Disturbance \times Wetness)^{\frac{1}{3}}
  \]
**Hieracium location data**

Geographic locations (x and y coordinates) were used for simulating seed dispersal. For each population seed dispersal was simulated as beginning on a set date (different for each species) and ceasing at the date of detection and control.

Methods of control differ between the two states. In Victoria flowering heads are removed to ensure that no viable seed is released from the known populations after control. In New South Wales flowering heads are not removed, allowing the possibility of viable seed being dispersed; this was accounted for by continuing all dispersal until 2009.

When information on population size was available this was used to weight the contribution made by each known *Hieracium* site to the spatial distribution of the seed shadow.

**The seed dispersal model**

In the seed dispersal model the probability of seed dispersal is calculated as the probability of seed travelling a given distance from its source multiplied by the proportion of time that wind blew from each of the cardinal directions during flowering and seed production.

- **The dispersal curve.** *Hieracium* seed dispersal was modelled so that the highest dispersal probability occurred within 100 metres of the source population but allowed for some dispersal up to 5 kilometres away. The data used to fit the curve are described in detail by Williams et al.(2007). The dispersal curve is illustrated in Figure 12 and is modelled using the following formula:

\[
Pr(\text{Dist}) = 1 - e^{-\left(\frac{d}{x}\right)^{a}}
\]

where Pr(Dist) is the probability of dispersal to that point, \(x\) is the average distance travelled by each seed, \(d\) is the distance from the source population, and \(a\) is a constant (−1.0385) fitted to describe the above conditions (highest dispersal probability within 100 metres of the source population while allowing for some dispersal up to 5 kilometres away).
Note: These values were used to assign the relative likelihood of seed arriving at a location in the Bogong High Plains, based on the distance from the location of a recorded \( H. \) \( \text{aurantiacum} \) population.

**Figure 12** Relative likelihood of \( H. \) \( \text{aurantiacum} \) seeds arriving at a location with increasing distance from the parent source

- **Wind and climate data.** The dispersal model was made more realistic by incorporating the prevailing wind direction during climatic conditions conducive to seed uplift. Wind and climate data were obtained from the weather station closest to the infestation site. Wind data were collated annually for the flowering and seed shedding season, when climatic conditions were most favourable for producing updrafts—thereby aiding in the dispersal of wind-dispersed seeds. Such conditions include warm, dry days that heat air close to the ground surface and lift seed above the turbulent boundary climatic layer (Tackenberg et al. 2003). Wind data were therefore selected from daylight hours (5 am to 9 pm) on days when there was less than 10 millimetres of rain and the maximum temperature exceeded 15°C (Williams et al. 2008). The proportion of records when the wind blew in each of 16 cardinal directions during these times was calculated: this was the probability of direction and was represented as \( \text{Pr(Dir)} \).

- **The dispersal plume.** The dispersal plume (seed shadow) was calculated by multiplying the dispersal curve (\( \text{Pr(Dist)} \)) by the proportion of time the wind blew from each cardinal direction (\( \text{Pr(Dir)} \)). This results in the areas in the direction of the prevailing winds having a higher probability of \( H. \) \( \text{aurantiacum} \) occurrence than other locations that are equally distant from the source site but in a different direction. Cumulative dispersal plumes for each species were created by adding the dispersal plume from each site containing \( H. \) \( \text{aurantiacum} \) using the following formula:

\[
\text{Pr(Disp)} = \frac{\sum_{i=0}^{n} \text{Pr(Dist)} \times \text{Pr(Dir)}}{n}
\]
The dispersal constrained habitat suitability model

The final model was constructed by combining the Hieracium spp. seed dispersal predictions with the probability of the species establishing in that location (the habitat suitability index, or HIS). This was done for each distinct period where the likelihood of establishment varied because of varying environmental conditions—for example, vegetation being unburnt or burnt. The following formula was applied:

$$Pr(Occurrence) = (Pr(Disp) \times Pr(HSI))^\frac{1}{2}$$

In Victoria this model has been found to be effective in predicting the occurrence of *H. aurantiacum*, and many new colonisation sites have been identified.

By reporting the standard errors associated with each value for the HSI variables we present the plausible limits (upper and lower) within which the true value is estimated to lie (Burgman et al. 2001). This allows for communication about the degree of certainty associated with each parameter.
Hieracium praealtum on the Bogong High Plains

Methods

The Bogong High Plains region of Victoria’s Alpine National Park consists of a series of alpine and sub-alpine plateaus surrounded by steep cliffs and montane forests. The known populations of Hieracium praealtum occur on the edge of the Rocky Valley hydroelectric dam adjacent to the ski resort village of Falls Creek. The study area is 34 by 28 kilometres in size (centroid coordinates 36°3’N and 147°14’W). Altitude ranges from 320 to 1985 metres above sea level; the known populations are contained in the sub-alpine vegetation at 1600–1650 metres. Cattle grazing was permitted in sections of the park until 2003 (see Figure 13). The climate is strongly seasonal, with high rainfall and persistent snow between June and September (Williams 2008).

Resolution

The base information for the prediction surface is a digital elevation map of the region that provides local topographic data. The format of the map is a grid of 20-metre cells that contain only one value per grid cell. GIS model outputs and predictions are dictated by the resolution (cell size) of this layer, so one suitability prediction applies to each grid. The coordinate system used was Australian Map Grid Zone 55, based on the Australian Geodetic Datum 1966.

Wind and climate data

Wind and climate data for 1999 to 2009 were obtained from the Bureau of Meteorology’s weather station above Falls Creek. The year when H. praealtum recruitment occurred is unknown, so all sites were modelled with seed dispersal beginning in 1999 and ceasing at the end of the month in which the site was detected and controlled.

Wind data were collated for all years during the periods when conditions are most favourable for producing uplift and thus dispersal of seed (see Figure 14). Dispersal was simulated annually for the four months from December to the end of March, when H. praealtum is in flower across the Bogong High Plains.

The habitat suitability index

The three habitat suitability variables were chosen for their influence on the suitability of a site for Hieracium praealtum establishment and persistence.

- The vegetation community index. A digitised version of McDougall’s (1982) classification and mapping described the spatial distribution of the alpine vegetation communities across the Bogong High Plains. The mapping of the sub-alpine and montane regions beyond the extent of McDougall’s map was a digitised version of the ecological vegetation classes of the Simplified Native Vegetation Map of Victoria—pre-1750 (DSE 2004). The pre-1750 mapping was supplemented with mapping done by Arn Tolsma, describing the bogs and wet-heaths of the sub-alpine region.

H. praealtum has as yet been detected only in the alpine and sub-alpine vegetation of the Bogong High Plains, although, because of concern that establishment might occur in lower altitude environments, the prediction region has been extended to include not only the alpine and sub-
alpine zones but also the montane regions (see Figure 15). Estimates of the suitability of montane vegetation communities were complicated by *H. praealtum* never having been observed in these communities. The suitability values that were applied for the montane vegetation communities are therefore the values estimated for New South Wales, where the related *H. aurantiacum* currently occurs in similar vegetation types.

- The **disturbance index**. This variable consists of nine elements—urban and ski resort areas (U), ski runs (S), roads (R), aqueducts (A), walking tracks (T), huts in the National Park (H), areas burnt by the 2003 and/or 2007 wildfires (F) previous grazing land (G), and disturbed areas independent of existing townships and ski runs that have had their vegetation cover removed or damaged (Da)—for example, Basalt Hill quarry (see Figures 12 and 16).

- The **wetness index**. This was used as a surrogate for soil moisture in the absence of this variable being mapped across the region. As can be seen in Figure 17, most soil moisture levels, barring the extremes of dry and wet, were deemed to provide suitable conditions for growth. This variable thus makes only a small contribution to the spatial variation in suitability (see Appendix A).

**Hieracium praealtum** location data

**‘Source’ dispersal**

In constructing the initial ‘source’ population model, seed dispersal was simulated from the 72 sites that occurred in the quarantine area. To account for differences in seed output, each site in the quarantine area was weighted (described shortly). The ‘recent’ location data (37 sites) were used to explore the veracity of the model’s predictions.

**‘All sites’ dispersal**

A total of 109 geographic locations were used to simulate seed dispersal; these were split between the source population of *H. praealtum* in the quarantine area on the north side of the Rocky Valley dam (72 sites) and the secondary populations on the north and predominantly south banks of the dam (37 sites) (see Figure 18). To account for site-based differences in population size, weights were assigned to reflect the relative contribution that each site made to the total seed dispersed (dispersal probability grids). This was done in order to place greater emphasis on those areas potentially receiving greater seed rain.

Weights were determined by two methods to reflect differences in record keeping. Both methods used rosette number as the weighting factor. The total number of rosettes from the entire ‘seeding’ *H. praealtum* population was 202 189.

Since the aim was to simulate seed dispersal as it occurred before detection and treatment in 2003, the initial estimate of population size (at least 200 000) was used to reflect the density of seed being dispersed from the quarantine area. This region is divided into a 5-metre grid and species presence or absence is recorded for each grid cell. The GIS mapping unit (a 20-metre grid) required that four 5-metre quarantine grids be merged into one 20-metre grid. The initial distribution of the population throughout the quarantine area is unknown, so a single value was assigned to each occupied 20-metre grid to denote species presence, regardless of whether single or multiple 5-metre grid cells had been recorded as occupied. Each occupied 20-metre grid contributed equally to seed dispersal; this equated to each of the 72 (20-metre) grid cells being assigned 2778 individual plants or rosettes.

In simulating dispersal from the secondary populations of *H. praealtum*, only those sites that had been recorded as flowering or with seed heads attached were included. Exceptions were made for sites with a minimum of 11–25 flower buds present and with 50 or more rosettes. These delimitations were selected as a conservative measure. Although an ‘individual’ or site with 50 or more rosettes is likely
to have been present at least one season before detection, and thus possibly dispersed seed, sites with as few as three or six rosettes were recorded as having flowered in the previous season (old flower stems still present).

Two sites were also included despite not meeting the prerequisites: KDHW008, recorded with 12 rosettes and 23 flowers in bloom; KDHW, with no rosette number recorded and 21 flowers in bloom.

Weights were assigned according to the number of rosettes at each site. The secondary populations had a total of 2189 rosettes distributed between the sites. When the rosette number was not counted or was entered as zero (despite a count of flowers, buds, and so on) the number defaults to one. When the rosette number was recorded as a range the average value was substituted. An exception is site KDHW007, which was recorded as having 190 flowers in bloom and more than 5000 flower buds. A rosette count of 200 was assigned to this site. A comparison with other sites of similar density in flowers and number of rosettes revealed KDHW049 (rosettes, 350; flowers, 200; buds, 1001–5000), KDHW061 (rosettes, 200; flowers, 175; buds, 751–1000) and KDHW093 (rosettes, 250; flowers, 200; buds, 1001–5000).

**Model testing: ‘source population’ dispersal**

Dispersal was initially simulated as occurring only from the quarantine area (the northern bank of the Rocky Valley dam). This allowed the suitability of the model predictions to be explored against the more recent data (2004 to 2009).

As can be seen in Figure 19, although the more recently detected sites are not associated with the highest prediction regions they are close enough to lend ecological plausibility to the model and are located under the main dispersal plume (light green; relative likelihood, 0.116–0.125). An exception is the site at Ruined Castle in the north-west, where it is thought seed was translocated by bushwalkers or ski machinery.

Because the areas targeted for *Hieracium* surveillance were guided by the model predictions for *H. aurantiacum* (Williams et al. 2008) these data cannot be used to independently validate the model since they are not a truly independent or systematic sample.

**Model prediction results: ‘all sites’ dispersal**

Model predictions reveal that the likelihood of *H. praealtum* establishment appears to be primarily driven by dispersal. The dispersal plume is concentrated towards the south-south-east, with a minor plume potentially directing seed north-west towards Falls Creek resort and the head lease (ski run) (see Figure 20).

The relative likelihood of seed establishment decreases as distance from the source population increases. The areas with the highest likelihood values are the sites closest to the source population (the quarantine area) in the direction of the prevailing winds. These sites occur on the south-west bank of the Rocky Valley dam and extend in a south-south-easterly direction for almost 2 kilometres (relative likelihood, 0.25–0.275), crossing the Bogong High Plains road. A total of 2.68 hectares is predicted to be at the highest likelihood of invasion (relative likelihood, 0.275–0.336); this area occurs on the south-western bank of the Rocky Valley dam, a minimum of 500 metres from the quarantine area as the crow flies. Also predicted to be at high invasion risk is the area stretching for about 450 metres upslope from the water’s edge.

Seeds dispersing predominantly from the quarantine area do not appear to be limited to the extent of the alpine vegetation on the Bogong High Plains, given the parameters of the dispersal model. The likelihood of dispersal and establishment is predicted to continue into the sub-alpine woodland and the upper reaches of the montane damp forest (relative likelihood, 0.225–0.25).
Disturbances that occur in the vicinity of the known populations are roads, walking tracks, aqueducts, former grazing land, and areas affected by the 2002–03 wildfire. Fire-induced disturbance is weighted to substantially increase the likelihood of *H. praelatum* invasion. Yet, of the 98 flowering and non-flowering sites on the southern side of the Rocky Valley dam, 54 sites are located in the unburnt region on and surrounding Basalt Hill (see Figure 21).

The influence of habitat on predictions is most evident under the main dispersal plume. Predictions reflect the pattern in the vegetation community’s composition, with higher likelihood values occurring where open heathland, bog and *Poa hiemata* grassland occur; this contrasts with areas of closed heathland. Soil moisture (the wetness index) has only a minor influence on the spatial distribution of suitable sites; this is possibly because almost all soil moisture levels (except for completely dry and running or standing water) are thought to provide suitable conditions for *H. praelatum*. Water was not included as a dispersal vector, so creek lines have a low relative likelihood (see Figure 22).

Figure 22 shows that the main dispersal plume lies to the west of the known populations. This is highlighted in Figure 14, showing that the predominant wind direction is south-south-easterly (darkest blue), whereas known populations occur further to the east (third- and fourth-darkest blue). This difference is of concern since it might point to an inconsistency in the wind records, which are collected uphill from the ‘source’ site, and could invalidate the results. Determining the cause of the misalignment will require a thorough search of the high-prediction zone because the mismatch might result from search patterns that are not reflective of the species’ actual distribution; it will also require that wind measurements be taken on site (for example, ‘source’ = quarantine area) to ascertain whether the wind and climate data are locally accurate. Another possibility is that the misalignment could be an artefact of the subset of wind records used in the modelling. Exploring the predictions from different subsets of wind data—for example, additions to or subtractions from the entire dispersal season (December to March) could be informative.

In summary, the area predicted to be at greatest risk of *H. praelatum* invasion occurs in the open heathland on the southern bank of the Rocky Valley dam. The highest priority for search and control efforts in the coming season would appear to be the area under the dispersal plume intersecting with the most westerly known *H. praelatum* locations and stretching upslope from the dam bank towards the Bogong High Plains road.
Note: Includes roads and walking tracks (grey), aqueducts (dark blue), ski runs (pink), the urban and resort area (bright blue), huts (white), areas of disturbed or cleared vegetation (red) and former grazing areas (green). The suitability values associated with each disturbance type are described in Appendix A. Water bodies are shown in blue. The red line delineated the extent of the alpine region as described by McDougall (1982).

Figure 13  Spatial arrangement of the disturbance elements
Note: Represents the proportion of time the wind blew in each of the cardinal directions during optimal conditions for seed uplift (that is, dispersal).

Figure 14  Cumulative wind direction data, 1999 to 2009
Note: Suitability ranges from high (pink) through medium (yellow) to low (green); water bodies are shown in blue. The vegetation communities and associated suitability values are described in Appendix A.

Figure 15  Suitability of vegetation communities for *Hieracium praealtum* establishment
Note: Shows water bodies (blue) and the extent of the alpine region as described by McDougall (1982) (white outline).

Figure 16  Area disturbed by wildfire in 2002–03 and 2006–07
Note: Topographic wetness index is a surrogate for the topographic variation in soil moisture. Highly suitable environments (light blue) are bounded by very dry areas or standing or running water (dark blue) which confer low suitability for establishment. Suitability values are listed in Appendix A.

Figure 17  Environmental suitability for *Hieracium praealtum*, as determined by the topographic wetness index
Note: The ‘source’ population for the initial model simulated dispersal from the tightly clustered points in the quarantine area on the northern bank of the Rocky Valley dam. Dispersal from ‘all sites’ was simulated as occurring from the locations that are known to have flowered (black points) but not from the sites where flowering had not been observed (white points). McDougall’s (1982) mapping shows the variation in vegetation across the site.

Figure 18 Known locations of Hieracium praealtum populations on the Bogong High Plains
Note: Relative likelihood of occurrence is shown as a sliding scale from red to orange to green and accords with a decrease in suitability for establishment. The accuracy of the model can be assessed by examining the recent populations (2004 to 2009; black points) in relation to their predicted occurrence.

Figure 19 Dispersal of Hieracium praealtum as simulated from the ‘source’ population in the quarantine area (yellow points)
Note: Illustrates the relative likelihood of *H. praealtum* occurrence; areas with the greatest likelihood of *H. praealtum* establishment are shown in red. A sliding scale from red to yellow to green accords with a decrease in suitability for establishment. The predictions use wind data from 1997 to 2009 and include all ‘seeding’ locations and the discrete disturbances of the wildfires in 2002–03 and 2006–07. Water storage areas are shown in blue; the red line represents the extent of McDougall’s (1982) alpine vegetation map.

**Figure 20** Predicted dispersal constrained habitat suitability for *Hieracium praealtum* across the Bogong High Plains
Note: Illustrating the relative likelihood of *H. praealtum* occurrence; the areas with the greatest likelihood of *H. praealtum* establishment are shown in red. A sliding scale from red to yellow to green accords with a decrease in suitability for establishment. Dispersal was simulated from the locations known to have flowered (black); non-flowering locations are shown in white. The Rocky Valley hydroelectric dam is shown in blue.

**Figure 21** Predicted dispersal constrained habitat suitability for *Hieracium praealtum* for the Falls Creek, Rocky Knobs and Basalt Hill areas of the Bogong High Plains
Note: Illustrating the relative likelihood of *H. praealtum* occurrence; a sliding scale from red to yellow to green accords with a decrease in suitability for establishment. Dispersal was simulated from locations known to have flowered (black); non-flowering locations are shown in white. The Rocky Valley hydroelectric dam is shown in blue.

Figure 22 Predictions for *Hieracium praealtum* for the Falls Creek, Rocky Knobs and Basalt Hill areas of the Bogong High Plains
**Hieracium aurantiacum** in Kosciuszko National Park: Mt Jagungal Wilderness – Round Mountain

**Methods**

The study area encompasses the montane, sub-alpine and alpine environments of the greater region surrounding Round Mountain in New South Wales, with the known populations at the centre (centroid coordinates: 36°3′N, 148°21′W). The boundary is a square 27 kilometres long, enclosing a square shape (total boundary 108 kilometres). Altitude ranges from 400 to 2045 metres above sea level, and the known populations are located between 1300 and 1550 metres above sea level. The vegetation of the region includes alpine, sub-alpine and montane communities; there are grazed lands in the north-western corner. The climate is strongly seasonal with high rainfall and persistent snow between June and September (Williams & Holland 2007).

**Resolution**

The base information for the prediction surface is a digital elevation map of the region that provides local topographic data. The format of the map is a grid of 25-metre cells that contain only one value per grid cell. GIS model outputs and predictions are dictated by the resolution (cell size) of this layer, so one suitability prediction applies to each grid cell. The coordinate system used was Australian Map Grid Zone 55, based on the Australian Geodetic Datum 1966.

**Wind and climate data**

Wind and climate data were obtained from the Snowy Hydro meteorological station at Cabramurra for 1997 to 2009; the station lies about 12 kilometres to the north of Round Mountain. The year when *H. aurantiacum* arrived is unknown, so all point locations—with the exception of the most southerly point on the Grey Mare fire track—were modelled as dispersing seed since 1997 and continuing through to 2009. The point location on the Grey Mare fire track was modelled as beginning dispersal in 2003, following the 2003 fire and the opening of the Grey Mare fire track.

Wind data were collated for all years during the periods when conditions are most favourable for producing uplift and thus dispersal of seed (see Figure 23). Dispersal was simulated for the five months from November to the end of March, when *H. aurantiacum* is in flower throughout the Round Mountain region of Kosciuszko National Park.

**The habitat suitability index**

The three habitat suitability variables were chosen for their influence on the suitability of a site for *H. aurantiacum* establishment and persistence.

- **The vegetation community index.** A digitised version of the New South Wales Forest Ecosystems Southern CRA (NPWS 2005) vegetation classification was used to describe the spatial arrangement of vegetation community types (see Figure 24).

- **The disturbance index.** This variable consists of nine elements—urban and ski resort areas (U), ski runs (S), roads (R), aqueducts (A), walking tracks (T), huts within the National Park (H), grazing areas (G), areas burnt by wildfires (F) and disturbed areas that are independent of existing
townships (Da)—for example, quarry sites and the airstrip at Ogilvies Creek (see Figures 25 and 26).

- **The wetness index.** This was used as a surrogate for soil moisture in the absence of this variable being mapped across the region (see Figure 27). It is a topographically based estimation of overland water flow and accumulation that has been weighted to reflect the suitability provided by different soil moisture conditions for *H. aurantiacum* establishment and persistence.

**H. aurantiacum location data**

The location data for *H. aurantiacum* consist only of geographic coordinates, so it was not possible to infer the size of the population from the data; as a result all points were treated as being of equal weight—that is, to represent the same size population.

Although it was not possible to accurately account for population size, the density of point locations (when more than one location point occurred in a single grid cell) was incorporated by weighting the relative contribution each occupied grid cell (number of point locations) made to the total seed dispersed (dispersal probability grids). This was done so as to place greater emphasis on areas potentially receiving more seed rain.

**‘Source’ dispersal**

The initial ‘source’ population model was constructed by simulating seed dispersal from 82 sites at the location of a former Snowy Hydroelectric Scheme town on Ogilvies Creek. The ‘recent’ location data (108 sites) were used to explore the veracity of the model’s predictions.

**‘All sites’ dispersal**

A total of 190 geographic locations were used to simulate seed dispersal; these included the source population at Ogilvies Creek; the second-largest population, at Round Mountain, 4.5 kilometres to the west; and smaller infestations at Cool Plain. A single plant was discovered at the junction of the Grey Mare and Farm Ridge fire tracks: it is thought this originated from the opening of the fire tracks for firefighting during the 2002–03 wildfire.

**Model testing: ‘source population’ dispersal**

Dispersal was initially simulated as occurring only from the source population at Ogilvies Creek since this is thought to be the population of longest duration (orange points, Figure 28). This enabled the suitability of the model predictions to be interrogated against the (chronologically) more recent data (black points).

As can be seen in Figure 28, the predictions show that the more recent populations are under the main seed dispersal plume, following the direction of the prevailing wind (light green; relative likelihood, 0.085–0.118). In this simulation, constructed using wind data from 1997 to 2009, the sites surrounding Ogilvies Creek and the nearby quarry are associated with highly suitable conditions for *H. aurantiacum* occurrence (yellow; relative likelihood, 0.144–0.296); the recently detected sites at Cool Plain are also associated with suitable conditions (orange–light green; relative likelihood, 0.131–0.085). Increasing distance from the source population reduces the likelihood of seed deposition, as can be seen in the prediction for the Round Mountain populations (E). The lone site on the Grey Mare fire track (SE) is thought to have been the result of vehicular transfer.
Model prediction results: ‘all sites’ dispersal

The predicted distribution appears to be primarily a consequence of wind and disturbance (see Figure 29). Dispersal plumes follow the prevailing westerly wind. The highest likelihood of seed dispersal and establishment is concentrated within 450 metres of known populations. A moderate likelihood of seed dispersal stretches out to 3 kilometres. As distance from the source population increases the relative likelihood of seed establishment decreases. Higher likelihood values are also related to population size (that is, the number of point locations). The predictions indicate that seed establishment is more likely to be associated with the Ogilvies Creek and Round Mountain dispersal plumes (relative likelihood, 0.125–0.2), as compared with those for the Cool Plain and Grey Mare fire track sites, which had substantially smaller populations (relative likelihood, 0.087–0.125).

Disturbance increases the likelihood of *H. aurantiacum* invasion; disturbed areas occurring near known populations are roadways, sites such as the old airstrip (relative likelihood, 0.158–0.25) and the quarry (relative likelihood, 0.225–0.272) at Ogilvies Creek, and areas affected by wildfires in 1998–99, 2002–03 and 2006–07. Since disturbance is thought to increase the likelihood of seedling establishment (whether the dispersal vector is wind or human), greater relative likelihood values are associated with these areas (see Figure 30).

Habitat does not appear to have a major influence on the potential spatial distribution of *H. aurantiacum*. The habitat suitability values suggest that, of those vegetation communities that occur in the dispersal plume, there is only a small variation in suitability (see Appendix B). Soil moisture is expected to have only a minor influence on site suitability. This is possibly because almost all soil moisture levels (except for completely dry and running or standing water) are thought to provide suitable conditions for *H. aurantiacum*. As can be seen in Figure 31, a lower likelihood of occurrence is therefore associated with hill crests and waterways. Water was not included as a dispersal vector, so creek lines have a low relative likelihood of occurrence.

In summary, the areas predicted to be at the highest risk of *H. aurantiacum* invasion occur in the immediate vicinity of known infestations and in areas subject to past and continuing disturbance. These areas would therefore appear to be the highest priority for search and control efforts in the coming season.
Note: Represents the proportion of time the wind blew in each of the cardinal directions during optimal conditions for seed uplift (that is, dispersal).

Figure 23  Cumulative wind direction data, 1997 to 2009
Note: Suitability ranges from high (pink) through medium (yellow) to low (green). Water bodies are shown in blue. The vegetation communities and associated suitability values are described in Appendix B.

Figure 24  Suitability of the vegetation communities for *Hieracium aurantiacum* establishment
Note: Includes roads, walking tracks and aqueducts (brown); Merae disturbances—sites such as the airstrip and quarry at Ogilvies Creek and other areas of disturbed or cleared vegetation (pink); urban areas (orange); and grazing areas (green). The suitability values associated with each disturbance type are described in Appendix B. Water bodies are shown in blue.

Figure 25  Spatial arrangement of the disturbance elements
Note: Shows roads (brown) and water bodies (blue).

Figure 26  The area disturbed by wildfires in 1997–98, 2002–03 and 2006–07
Note: Topographic wetness index is a surrogate for the topographic variation in soil moisture. Highly suitable environments (light blue) are bounded by very dry areas or standing or running water (dark blue), which confer low suitability for establishment. Suitability values are listed in Appendix B.

Figure 27 Environmental suitability for *Hieracium aurantiacum*, as determined by the topographic wetness index
Note: The relative likelihood of occurrence is shown as a sliding scale from pink to yellow to green and accords with a decrease in suitability for establishment. The accuracy of the model can be assessed by examining the recent populations (black points) in relation to their predicted occurrence.

Figure 28 Dispersal of *Hieracium aurantiacum*, as simulated from the ‘source’ population at Ogilvies Creek (orange points)
Note: Illustrates the relative likelihood of *H. aurantiacum* occurrence, the areas with the greatest likelihood of establishment being shown in red. A sliding scale from red to yellow to green accords with a decrease in suitability for establishment. Predictions use wind data from 1997 to 2009, all known locations, and the discrete disturbances of the wildfires in 1997–98, 2002–03 and 2006–07.

**Figure 29** Predicted dispersal constrained habitat suitability for *Hieracium aurantiacum* across the Round Mountain region
Note: Illustrates the relative likelihood of *H. aurantiacum* occurrence, the areas with the greatest likelihood of establishment being shown in red. A sliding scale from red to yellow to green accords with a decrease in suitability for establishment. Predictions use wind data from 1997 to 2009, including all known locations, and the discrete disturbances of the wildfires in 1997–98, 2002–03 and 2006–07.

**Figure 30** Close-up of the predictions for *H. aurantiacum* for the Ogilvies Creek and Round Mountain regions
Note: Illustrates the relative likelihood of *H. aurantiacum* occurrence given wind data from 1997 to 2009, known locations (white points) and the discrete disturbances of the wildfires in 1997–98, 2002–03 and 2006–07.

**Figure 31** Close-up of the predictions for the Ogilvies Creek and Round Mountain regions with 20-metre contour lines
Discussion and conclusions
Discussion

The dispersal constrained habitat suitability models produced for Hieracium praealtum in Victoria and H. aurantiacum in New South Wales broadly predict the recently detected populations. There remains, however, some lack of concordance between the current positions of greatest abundance and the highest predicted probabilities. Constraining the predictions of suitability to be highest under the dispersal plume is an effective way of minimising the extent of the potential search area. This method of combining a habitat suitability index with a prevailing wind dispersal model has now been tested on two new infestations and has proved to create ecologically plausible predictions. The model is therefore capable of providing immediate benefits for planning control action.

Modelling was done at a fine resolution, and this has resulted in prediction surfaces that have captured the heterogeneous nature of the environments and are of sufficient detail to be directly amenable to on-ground planning. The results of this research should help management agencies develop an effective eradication program that can be strategically tailored to achieve the greatest impact.

Interpretation of the predictions should, however, be subject to the caution that the wind dispersal model does not take into account the effect of local topography on wind direction. Advanced computer models built to simulate the influence of local topography on wind patterns have revealed complex interactions and effects (Chapman 2000) that are beyond the capabilities of a simple prevailing wind direction model. Nor, by focusing on prevailing wind direction, does the model take account of the influence of storm events on the chance of long-distance seed dispersal. Storms have been found to exert wildly different forces on the directions and distances travelled by seeds compared with what occurs under the majority of weather conditions (Cousens et al. 2008): the distances travelled far outstrip those of a ‘normal’ dispersal curve as a result of uplifting turbulence and gusting winds (Horn et al. 2001). This is an important stochastic factor that should be accounted for.

We are concerned about the simplicity of the dispersal-modelling approach as a result of the misalignment between the recently detected populations of H. praealtum on the Bogong High Plains and the modelled prevailing wind direction. The area predicted by the dispersal plume to have the highest likelihood of H. praealtum occurrence lies up to 900 metres further west from the most westerly known locations (see Figure 22). Unless, as noted, this disparity is a consequence of patterns of surveillance and control activity, rather than an accurate reflection of inhabited areas, the difference appears too great for the predictions to be considered useful for management purposes. Verifying the accuracy of the wind data is of crucial importance since it could mean that the chosen weather station is not close enough to the dispersal locations to accurately record local direction or that the topographic complexity of the Bogong High Plains calls for a more sophisticated modelling approach. Exploring how different subsets of wind data alter the direction probabilities would also be an interesting avenue that could help with refining our understanding of the duration of the seed dispersal season or the occurrence of ‘peak’ dispersal times, or both.

Accuracy of wind and climate data is of fundamental importance for the simulation of seed deposition. The placement of an anemometer at ‘source’ sites during the season of seed dispersal would allow for the collection of highly accurate wind and climate measurements against which the current data could be verified. An anemometer also offers the advantage of being able to record vertical wind speed, a necessary parameter in the construction of mechanistic models of seed dispersal. Recent advances in techniques for mechanistic modelling of seed dispersal (via wind) have produced high levels of accuracy in simulating deposition patterns (Tackenberg 2003). This should be the next step in creating more accurate predictions.

Because of the continuing lack of published data on Hieracium ecology in Australia, we were reliant on expert opinion for developing model parameters. The information gathered through the
questionnaires revealed particularly wide bounds to the experts’ judgment of the species tolerances—for example, the wetness index for H. aurantiacum (see Appendix B). By weighting the responses of each expert (in terms of hours spent searching for Hieracium) we tried to maximise the contribution made by those with more experience compared with the less experienced.

Nevertheless, we are unsure whether these results accurately reflect the species tolerances or are reflecting a risk-averse stance taken by the experts. When a species is in the initial stages of invasion not all places where it is observed will provide suitable conditions for long-term persistence (Pearson 2007). As a result, the wide bounds of the experts might actually be indicative of the current situation. Even so, the model might benefit from a refinement of the expert judgments with empirical data on the species known tolerances; this could be done using the environmental information associated with each known presence location (GIS data). Such an approach might assist in refining our understanding of Hieracium ecology because the increased precision of the parameters might lead to predictions that more closely replicate the species’ actual distribution.

A new addition to the model was included by weighting the contribution each site made to the spatial density of seed deposition. This step made the model more computationally intensive but was thought worthwhile because of the large variations in population sizes that are not represented by the point location. The weighting was most practicable for the Victorian infestation as a result of the detailed population records kept by Parks Victoria. Although the New South Wales infestations lack the detailed population data, the simplified weighting added a greater degree of realism to predictions. For example, the amount of seed potentially dispersed by the Cool Plain sites barely increased the likelihood of occurrence in that area, whereas the larger sites at Ogilvies Creek and Round Mountain were the main contributors to the dispersal plume (see Figure 31).
Conclusions

We achieved all project objectives:

- We have reduced the gaps in our knowledge of the seed ecology of the two species.
- We investigated the effects of fire, herbicides and picking on seed production.
- We extended our habitat constrained model to predict search areas for two species at sites not used to formulate the original model.

We confirmed that the ecological responses of the seeds of the two *Hieracium* species are likely to be similar—particularly with respect to burial and heat. Seed dispersal is possible from picked immature flowers, although this depends on stage of maturity at the time of picking. Fire could be of use to remove the seed bank around adult plants but not as a broad-area management tool or for adult plants.

We adapted the existing dispersal constrained habitat suitability model to reflect the local environmental conditions and the local population for both *H. praealtum* in Victoria and *H. aurantiacum* in New South Wales. Model predictions identify areas where *Hieracium* seeds are likely to spread and find suitable habitat. As a result, searches for new populations can be directed towards the areas with the highest relative likelihood since these environments are predicted to be at high risk of invasion.

In the course of the study we identified two important areas for future research:

- modelling of improved dispersal by wind, changes in detectability over time, the simultaneous optimisation of surveillance for multiple species, and the impact of uncertainty on surveillance decision making
- quantifying detectability under differing conditions using novel field experiments.

Together with our industry partners, we made a successful bid for an Australian Research Council linkage grant worth $302,000 over three years. We have thus added considerable value to this current project and have begun to extend our knowledge of the management of *Hieracium* in Australia.
Appendix A  Questionnaire responses: Hieracium praealtum, Victoria

Following are the combined response values for the 2009 questionnaire, which was designed to elicit experts’ opinions about the suitability of Victorian habitats and environmental conditions for establishment and growth of Hieracium praealtum. The probability values used to parametise the model are weighted means of the participants’ responses (weighting factor: number of hours of field experience).

<table>
<thead>
<tr>
<th>Victoria: Bogong High Plains</th>
<th>King devil hawkweed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QUESTION 1</strong></td>
<td></td>
</tr>
<tr>
<td>Vegetation communities</td>
<td>Probability</td>
</tr>
<tr>
<td>Bog</td>
<td>0.858</td>
</tr>
<tr>
<td><em>Celmisia sericophylla</em> herbland</td>
<td>0.998</td>
</tr>
<tr>
<td>Closed heathland</td>
<td>0.535</td>
</tr>
<tr>
<td>Disturbed areas</td>
<td>1.000</td>
</tr>
<tr>
<td><em>Kunzea</em> heathland</td>
<td>0.965</td>
</tr>
<tr>
<td>Late-lying snowpatch</td>
<td>0.898</td>
</tr>
<tr>
<td>Open heathland</td>
<td>0.999</td>
</tr>
<tr>
<td><em>Poa hiemata</em> tussock grassland</td>
<td>0.999</td>
</tr>
<tr>
<td><em>Poa costiniana</em> tussock grassland</td>
<td>0.998</td>
</tr>
<tr>
<td><em>Podocarpus</em> heathland</td>
<td>0.911</td>
</tr>
<tr>
<td>Relic bog</td>
<td>0.996</td>
</tr>
<tr>
<td>Rocky grassland</td>
<td>0.978</td>
</tr>
<tr>
<td>Rocky outcrops</td>
<td>0.998</td>
</tr>
<tr>
<td>Short turf snowpatch</td>
<td>0.999</td>
</tr>
<tr>
<td>Sub-alpine grassland</td>
<td>0.947</td>
</tr>
<tr>
<td>Sub-alpine woodland</td>
<td>0.809</td>
</tr>
<tr>
<td>Sub-alpine treeless vegetation</td>
<td>0.999</td>
</tr>
<tr>
<td>Montane wet forest</td>
<td>0.686</td>
</tr>
<tr>
<td>Montane damp forest</td>
<td>0.686</td>
</tr>
<tr>
<td>Montane dry woodland</td>
<td>0.677</td>
</tr>
<tr>
<td>Montane grassy woodland</td>
<td>0.773</td>
</tr>
<tr>
<td>Montane riparian woodland</td>
<td>0.677</td>
</tr>
<tr>
<td>Montane riparian thicket</td>
<td>0.686</td>
</tr>
<tr>
<td>Wet forest</td>
<td>0.686</td>
</tr>
<tr>
<td>Damp forest</td>
<td>0.686</td>
</tr>
<tr>
<td>Herb-rich foothill forest</td>
<td>0.773</td>
</tr>
</tbody>
</table>
### QUESTION 2

#### Disturbance

<table>
<thead>
<tr>
<th>Area</th>
<th>Weighted Mean</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban/resort areas (U)</td>
<td>0.999</td>
<td>0.021</td>
</tr>
<tr>
<td>Ski slopes (S)</td>
<td>0.998</td>
<td>0.042</td>
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<tr>
<td>Roads (R)</td>
<td>0.989</td>
<td>0.069</td>
</tr>
<tr>
<td>Aqueducts (A)</td>
<td>0.966</td>
<td>0.210</td>
</tr>
<tr>
<td>Huts (H)</td>
<td>0.995</td>
<td>0.157</td>
</tr>
<tr>
<td>Walking tracks (T)</td>
<td>0.998</td>
<td>0.063</td>
</tr>
<tr>
<td>Grazing areas (G)</td>
<td>0.995</td>
<td>0.157</td>
</tr>
<tr>
<td>Burnt areas: wildfire (F)</td>
<td>0.995</td>
<td>0.157</td>
</tr>
<tr>
<td>Disturbed areas (Da)</td>
<td>1.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### QUESTION 3

#### Topographic wetness index value

- Weighted mean
- SE

### QUESTION 4

Seed dispersal occurs during the months (i.e. flowering time) **Dec–March**
Appendix B  Questionnaire responses: *Hieracium aurantiacum*, New South Wales

Following are the combined response values for the 2009 questionnaire, which was designed to elicit experts’ opinions about the suitability of New South Wales habitats and environmental conditions for establishment and growth of *Hieracium aurantiacum*. The probability values used to parametrise the model are weighted means of the participants’ responses (weighting factor: number of hours of field experience).

<table>
<thead>
<tr>
<th>New South Wales: Mt Jagungal Wilderness Area</th>
<th>Orange hawkweed</th>
</tr>
</thead>
</table>

### QUESTION 1

<table>
<thead>
<tr>
<th>Vegetation communities</th>
<th>Probability</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpine wet herbfield &amp; sub-alpine wet herb/grass/bog</td>
<td>0.809</td>
<td>0.094</td>
</tr>
<tr>
<td>Disturbed areas (e.g. grazing)</td>
<td>0.999</td>
<td>0.007</td>
</tr>
<tr>
<td>Montane/sub-alpine dry rocky shrubland</td>
<td>0.523</td>
<td>0.234</td>
</tr>
<tr>
<td>Montane acacia/dry shrub/herb/grass forest</td>
<td>0.839</td>
<td>0.117</td>
</tr>
<tr>
<td>North-western montane dry shrub/herb/grass forest</td>
<td>0.695</td>
<td>0.047</td>
</tr>
<tr>
<td>Sub-alpine dry shrub/herb woodland</td>
<td>0.809</td>
<td>0.094</td>
</tr>
<tr>
<td>Sub-alpine herbfield</td>
<td>0.999</td>
<td>0.021</td>
</tr>
<tr>
<td>Sub-alpine shrub/grass woodland</td>
<td>0.809</td>
<td>0.094</td>
</tr>
<tr>
<td>Tableland acacia/herb/grass forest</td>
<td>0.686</td>
<td>0.140</td>
</tr>
<tr>
<td>Tableland tussock grassland/sedgeiland/woodland</td>
<td>0.868</td>
<td>0.327</td>
</tr>
<tr>
<td>Western escarpment dry shrub forest</td>
<td>0.677</td>
<td>0.234</td>
</tr>
<tr>
<td>Western escarpment moist shrub/herb/grass forest</td>
<td>0.686</td>
<td>0.140</td>
</tr>
<tr>
<td>Western montane acacia fern/herb forest</td>
<td>0.829</td>
<td>0.210</td>
</tr>
<tr>
<td>Western montane moist shrub forest</td>
<td>0.743</td>
<td>0.070</td>
</tr>
<tr>
<td>Western tablelands dry herb/grass forest</td>
<td>0.773</td>
<td>0.280</td>
</tr>
<tr>
<td>Western tablelands herb/grass dry forest</td>
<td>0.591</td>
<td>0.095</td>
</tr>
<tr>
<td>Rock</td>
<td>0.001</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### QUESTION 2

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Probability</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban/resort areas (U)</td>
<td>0.989</td>
<td>0.031</td>
</tr>
<tr>
<td>Ski slopes (S)</td>
<td>0.988</td>
<td>0.065</td>
</tr>
<tr>
<td>Roads (R)</td>
<td>0.795</td>
<td>0.047</td>
</tr>
<tr>
<td>Aqueducts (A)</td>
<td>0.7</td>
<td>0.000</td>
</tr>
<tr>
<td>Huts (H)</td>
<td>0.695</td>
<td>0.136</td>
</tr>
<tr>
<td>Walking tracks (T)</td>
<td>0.795</td>
<td>0.047</td>
</tr>
<tr>
<td>Burnt areas: wildfire (F)</td>
<td>0.929</td>
<td>0.210</td>
</tr>
<tr>
<td>Question</td>
<td>Value 1</td>
<td>Value 2</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Burnt areas - prescribed (none in region)</td>
<td>0.548</td>
<td>0.025</td>
</tr>
<tr>
<td>Disturbed areas (Da)</td>
<td>0.999</td>
<td>0.007</td>
</tr>
</tbody>
</table>

**QUESTION 3**

Topographic wetness index value

![Topographic Wetness Index Graph]

**QUESTION 4**

Seed dispersal occurs during the months (i.e. flowering time)  

Nov–March
References


DSE 2004, Simplified Native Vegetation Map of Victoria—pre-1750, Department of Sustainability and Environment, Melbourne.


Espie, P 2001, Hieracium in New Zealand: ecology and management, AgResearch Ltd, Mosgiel, NZ.


Improved Detection and Eradication of Hawkweed (*Hieracium*)

*Experiments and second-generation dispersal models*  Pub. No. 11/058

by Roger Cousens and Nicholas Williams

Orange hawkweed (*Hieracium aurantiacum*) and devil hawkweed (*H. praealtum*) are two stoloniferous perennials that have naturalised in a small part of the Victorian Alps. Both species have now been declared prohibited species at national and state and territory levels in Australia.

For invasive plant species to be eradicated it is necessary to exhaust or remove seed banks. In this research a range of glasshouse and field experiments were undertaken to fill knowledge gaps relating to the seed ecology and biology of *H. praealtum* and *H. aurantiacum*.

In a second part of the project a modelling tool was developed to assist in locating where the species are likely to occur in the landscape and plan effective and efficient action.

Eradication programs are now in progress for both species in Victoria and for *H. aurantiacum* in New South Wales and Tasmania.

This project was funded in Phase 1 of the National Weeds and Productivity Research Program, which was managed by the Australian Government Department of Agriculture, Fisheries and Forestry (DAFF) from 2008 to 2010. The Rural Industries Research and Development Corporation (RIRDC) is now publishing the final reports of these projects.

Phase 2 of the Program, which is funded to 30 June 2012 by the Australian Government, is being managed by RIRDC with the goal of reducing the impact of invasive weeds on farm and forestry productivity as well as on biodiversity. RIRDC is commissioning some 50 projects that both extends on the research undertaken in Phase 1 and moves into new areas. These reports will be published in the second half of 2012.

This report is an addition to RIRDC's diverse range of over 2000 research publications which can be viewed and freely downloaded from our website www.rirdc.gov.au. Information on the Weeds Program is available online at www.rirdc.gov.au/weeds.

Most of RIRDC’s publications are available for viewing, free downloading or purchasing online at www.rirdc.gov.au. Purchases can also be made by phoning 1300 634 313.

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