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A dispersal constrained habitat suitability model for Orange Hawkweed *(Hieracium aurantiacum)* on the Bogong High Plains, Victoria

N. Williams, A. Hahs, J. Morgan and K. Holland

October 2007

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Level 10, 535 Bourke Street, Melbourne Victoria 3000

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A dispersal constrained habitat suitability model for Orange Hawkweed (*Hieracium aurantiacum*) on the Bogong High Plains, Victoria

(incorporating a review of the ecology of introduced *Hieracium* species)

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October 2007

EXECUTIVE SUMMARY

Orange Hawkweed (*Hieracium aurantiacum*) is amongst a group of newly emerging exotic species in alpine landscapes of Australia that has the potential to become widely-established and threaten native biodiversity. Presently, alpine areas in Australia are largely weed-free so developing tools that help predict new invasions will be essential if such weeds are to be controlled before they become widespread. Currently such tools are not well developed in Victoria. This Technical Report provides background information on the biology of Orange Hawkweed (Chapter 2 – Literature Review) that is then used in to develop a dispersal constrained habitat suitability model to predict the dispersal and establishment of Orange Hawkweed at Falls Creek on the Bogong High Plains. We then tested the accuracy of the model by conducting a field survey using volunteers in areas predicted to carry Orange Hawkweed.

The Hawkweeds found in Australia are perennial, vegetatively-spreading herbs from the Northern Hemisphere that have become highly invasive in many ecosystems in New Zealand, Japan, Canada and the United States. They produce numerous wind-dispersed seeds that establish readily in a variety of habitats, including high mountain grasslands. Once established, they can form dense carpets many square metres in area.

To model the potential spread of Orange Hawkweed from Falls Creek, and provide improved opportunities for control of an expanding species that threatens alpine vegetation, we developed a dispersal constrained habitat suitability model. The model uses information on the suitability of a habitat to be invaded by Hawkweed (habitat suitability index derived from parameters such as level of disturbance, site wetness and vegetation community) and dispersal (likelihood of a seed reaching a location based on distance and direction from parent plant). The maps of the resulting model provide a basis for identifying areas of likely future spread in the Falls Creek area. We then intensively searched 172 ha at several locations on the Bogong High Plains to see if our model correctly predicted localities of new populations.

Large areas of the Bogong High Plains are suitable habitat for the establishment of Orange Hawkweed, and the 2003 fire is likely to have enhanced the potential for invasion. However, Orange Hawkweed invasion on the Bogong High Plains is currently limited by dispersal. Effective control measures to limit future dispersal, such as the identification and destruction of populations before they set seed, are extremely important in preventing *H. aurantiacum* from expanding its range, as is the prevention and rehabilitation of disturbances which favour establishment of the species.

This report provides the framework for coordinating future search efforts. Areas predicted to have a high probability of *H. aurantiacum* establishment should be intensely searched. In the absence of control *H. aurantiacum* may colonise large areas of the Bogong High Plains. The highest probability of establishment is in a south-easterly direction from the infestations initially recorded at Falls Creek, i.e. south and southeast of the Rocky Valley Storage, and on the north-facing slopes of the Rocky Knobs.

Extensive field searches undertaken to validate the model failed to detect new populations of Hawkweed in areas predicted to carry the species. However, time-step validation, using 1998-2000 species occurrence data, accurately predicted the occurrence of all post-2003 Orange Hawkweed populations. No Hawkweed was found in areas outside the dispersal plume of our model. Hence, the model seems to have good predictive power and provides an opportunity to improve our ability to detect emerging weed threats. Similar models could be applied to other weed species in the Alpine National Park such as King Devil Hawkweed (*Hieracium praealtum*) or Grey Sallow Willow (*Salix cinerea*).

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1. INTRODUCTION

Exotic species invasions are one of the greatest threats to the persistence of biodiversity in natural ecosystems throughout the world (Vitousek 1994), and much effort is made to control these species. Alpine areas in Australia remain largely free of exotic species due to limitations imposed by climate and dispersal (McDougall et al. 2005). With global warming and increasing recreational pressure anticipated, it is likely that alpine areas will be subject to invasions by exotic species. Consequently, developing tools to predict invasive spread, and rapid response to new incursions when they are detected, will be crucial to ensure these threats are minimised. Mack and Lonsdale (2002) highlight that the record of eradicating invasive species is poor, and that controlling new incursions is most feasible when small spatially dispersed satellite populations are targeted. By the time that dense stands form, the ability to control these infestations is drastically reduced. The need to detect and control new invasions is therefore clear.

In Australia, the need for information about the location of invasion and threat posed by exotic species in alpine areas has assumed some urgency. New weeds, such as Orange Hawkweed (*Hieracium aurantiacum*), Soft Rush (*Juncus effusus*) and English Broom (*Cytisus scoparius*), have established over the last two decades in subalpine and alpine areas in Victoria and begun to spread from their source populations with resultant negative impacts on the native biota (e.g. English Broom in herb-rich subalpine woodland; Wearne and Morgan 2004). To maximise their effectiveness, control efforts should be concentrated when exotic species populations remain small and isolated. To do this requires tools that can predict likely locations of the species occurrence.

Controlling new incursions presents a conundrum for land managers. By definition, satellite populations will be small and scattered and difficult to observe in the initial phases. To detect such invasions before their abundance threatens native biodiversity is a challenge that has rarely been attempted. There exist relatively few robust examples of models predicting weed spread in Australia or elsewhere. Why this should be the case is uncertain because the tools exist to predict the occurrence of rare animals and plants and this methodology could be utilised to predict the potential distribution of weed species.

Information on the biology of a weed species and its invasiveness in other ecosystems (or countries) can be used to parameterise models of invasion in new localities. GIS tools can be married with ecological information on habitats likely to be invaded while information on dispersal (mode and distance of spread) can be used to quantify rates and distances of spread from points of invasion. This simple approach could provide an objective basis for identifying areas of likely spread and provide opportunities for proactive weed management that targets new and emerging population outbreaks.

1.1 Objectives

This Technical Report has two parts, each of which has separate but complementary objectives. The first part reviews the general biology and ecology of two Hawkweed species that have recently become established in Victoria, *H. aurantiacum* and *H. praealtum* (Chapter 2). It also discusses the invasion of Hawkweeds both in Australia and overseas and examines their impact. The second part of this report utilises the information collated in Chapter 2 to parameterise a dispersal constrained habitat suitability model that has been constructed to predict the dispersal and establishment of *H. aurantiacum* at Falls Creek on the Bogong High Plains. The results of the model are maps of the probability of Orange Hawkweed occurrence that we believe should provide the basis for future searches, thereby leading to more effective detection and control of this invasive species.

In Australia, *H. aurantiacum* has been identified as a potentially eradicable ‘sleeper weed’ (Brinkley and Bomford 2002). This means that the species currently has a limited distribution because it is in the early stages of establishment, but has the potential to become a serious weed. Consequently, early eradication may prove highly cost effective in the medium to long-term (Brinkley and Bomford 2002). It is hoped that our research can contribute to this goal. *H. aurantiacum* is listed on the Alert List for Environmental Weeds (National Heritage Trust 2003) and is considered a significant threat to biodiversity and native ecosystems if it is not successfully managed (National Heritage Trust 2003, Morgan 2000). Left uncontrolled *H. aurantiacum* also poses a significant threat to Australian agriculture with potential production losses estimated to be in the order of $48 million (Brinkley and Bomford 2002).

2. A REVIEW OF THE BIOLOGY AND ECOLOGY OF INTRODUCED *HIERACIUM* SPECIES

Hawkweeds are perennial herbs of the very large northern hemisphere Asteraceae (daisy family) genus *Hieracium* (Webb *et al.* 1988). *Hieracium* comes from the Greek word for hawk and reflects the ancient Greeks' belief that the sap of Hawkweeds would make a person's vision as sharp as a hawk (Espie 2001). Several species of Hawkweeds have become weeds in many regions of the world. Quarantine regulations prohibit the importation of Hawkweeds into Australia (National Heritage Trust 2003, NSW Department of Primary Industries 2005) and they are listed as noxious weeds in Victoria, New South Wales and Tasmania (National Heritage Trust 2003).

2.1 Hawkweed species found in Australia

Four species of *Hieracium* have been found in Australia; *H. aurantiacum*, *H. praealtum*, *H. pilosella* and *H. murorum.* As the populations of *H. pilosella* and *H. murorum* are believed to have been eliminated these species will not be described in this technical report.

2.1.1 Hieracium aurantiacum

Orange Hawkweed (*H. aurantiacum*) is a small, perennial daisy (family Asteraceae) with distinctive bright, red-orange flowers (Blood 2001). The species is also sometimes known as *Pilosella aurantiaca* (Blood 2001 and Webb *et al.* 1988). It is native to the mountains of northern and central Europe (Morgan 2000 and Webb *et al.* 1988) where it occurs primarily in mountainous meadows and hillsides (Wilson and Callihan 1999).

H. aurantiacum grows 15 to 40 cm tall (Blood 2001). Plants grow a basal rosette of leaves, and a single erect stem that bears clusters of flowers at the top (Webb *et al.* 1988 and Blood 2001). The root system is shallow and fibrous (Callihan *et al.* 1997). The stems and leaves of *H. aurantiacum* secrete a dirty white milky sap when cut (Rinella and Sheley 2002) and are covered in numerous hairs, 3 to 5 mm in length (National Heritage Trust 2003, Webb *et al.* 1988). The leaves are spathulate in shape (Rinella and Sheley 2002), 10 to 15 am long and usually grow at an angle to the ground, but they may lie flat under grazing or harsh conditions (Natural Heritage Trust 2003). The leaves are darker green on the upper surface and paler underneath (Natural Heritage Trust 2003).

H. aurantiacum produces bright, red-orange flowers with square-edged petals. The flower-heads are about 15 mm in diameter and occur in clusters between 5 and 30 heads (Blood 2001). Plants are bisexual, often producing both seeds and pollen (Koltunow *et al.* 2000). *H. aurantiacum* seeds are 1.5 - 2 by 0.5 mm in size, and possess a bristly tuft up to 6 mm long (National Heritage Trust 2003, Webb *et al.* 1988). The seeds also possess small barbs that help them to stick to animal fur and clothing (National Heritage Trust 2003). The pollen of *H. aurantiacum* is (mean ± SE) 22.8 ± 0.9 µm in diameter (Murphy and Aarsen 1995).

Orange Hawkweed (*Hieracium aurantiacum*)

Orange Hawkweed is distinctive due to:

- Bright, orange flowers which do not resemble any other species likely to be found in Australia's alpine regions. Flowering occurs from January to March
- The presence of leafy runners, i.e., horizontal, creeping stems like those of a strawberry plant.

Flowers

- Bright red-orange, dandelion-like, square-edged petals
- Up to 15 mm in diameter
- In clusters of 5-30 flower-heads at the top of the erect stem

Stems

- 15-40 cm tall
- Covered in 3-5 mm hairs
- Secrete a milky sap when cut
- Usually only a single stem per plant

Leaves

- 10-15 cm long
- Broad with a rounded end and narrow at the base
- Occur in a rosette at the base of the stem
- Dark green on the upper surface and lighter underneath

King Devil Hawkweed (*Hieracium praealtum*)

King Devil Hawkweed is superficially similar to a variety of yellow-flowered daisies. It is most-easily distinguished from them by:

- Long, spreading hairs covering the stems and leaves; and
- The presence of leafy runners, similar to those of orange hawkweed

Flowers

- Yellow, dandelion-like, square-edged petals
- Up to 20 mm in diameter
- In clusters of 3-35 flower-heads at the top of erect stems

Stems

- Up to 60 cm tall, shorter on poor or shallow soils, or in exposed areas
- Covered in sparse, long spreading hairs
- Secrete a milky sap when cut
- Stems may bear up to two small leaves

Leaves

- Up to 20 cm long
- Most occur in a rosette at the base of the stem
- Blue-green to red, darker on the upper surface and lighter underneath
- Usually have scattered, coarse hairs 2-4 mm long on the upper surface

Box 1. Identifying features of Orange and King Devil Hawkweeds.

2.1.2 Hieracium praealtum

Another *Hieracium* species in Victoria is King Devil Hawkweed (*H. praealtum*), which also grows as a weed in New Zealand, Canada and the United States (Blood 2004, Carr *et al.* 2004). It is native to Europe and Asia.

H. praealtum is a taller species than *H. aurantiacum*, and can reach a height of 60 cm (Webb *et al.* 1988), but grows smaller on poor or shallow soils, or in exposed areas (Blood 2004). The majority of leaves also occur in a basal rosette, but up to two leaves may occur along the stem (Webb *et al.* 1988). The leaves are erect, and usually grow 3 to 5 cm long but may grow up to 10 cm in shady areas; they are blue-green to red, and paler on the underside, often have inrolled margins (Espie 2001) and usually have scattered, coarse hairs 2 to 4 mm long on the upper surface (Webb *et al.* 1988) . The stems of *H. praealtum* are covered in sparse, long spreading hairs (Webb *et al.* 1988) and secrete a pure white milky sap when cut (Espie 2001). The species has yellow, dandelion-like flowers in clusters of 3 to 35 at the top of the stem (Webb *et al.* 1988).

The seeds are a similar size to those of *H. aurantiacum*, and also bear a bristly tuft that aids in wind dispersal (Webb *et al.* 1988).

2.2 Hawkweed taxonomy and nomenclature

There is some debate about the taxonomy of Hawkweeds, with *Hieracium* and *Pilosella* sometimes classified as separate genera, and sometimes as subgenera (Coşkunçelebi 2003). For the purposes of this report we consider that all Hawkweeds belong to the *Hieracium* genus. The number of species in the genus is also questioned, with Hawkweeds showing enormous variability. Consequently, there are a large number of subspecies, varieties and forms (Mráz and Szelag 2004, Zidorn *et al.* 2002). There is also considerable variation in chromosome numbers both between and within species (Morgan-Richards *et al.* 2004, Mráz and Szelag 2004). It is thought the large variation among Hawkweeds is due to frequent hybridisation events, and the associated transfer of genes between different Hawkweed species during their evolution (Mráz *et al.* 2005). This theory comes from many species possessing morphological characters that appear to be intermediate between other species (Mráz *et al.* 2005, Webb *et al.* 1988). Based on morphology and hybridisation studies, *H. aurantiacum* and *H. praealtum* are thought to be most closely related to a group of predominantly orange-flowering Hawkweeds, including *H. lactucella*, *H. caespitosum*, *H. pilosella* (Krahulec *et al.* 2004, Morgan-Richards *et al.* 2004).

The genus *Hieracium* is commonly split into two groups: the stoloniferous species (i.e., possessing ‘runners’), known as the *Pilosella* group, and a larger group of non-stoloniferous species (*Hieracium* sensu stricto) (Makepeace 1985a, Webb *et al.* 1988). In addition to morphological separation, these taxa also show some biochemical (Zidorn *et al.* 2002) and reproductive (Makepeace 1985a, Webb *et al.* 1988) differences. *Pilosella* contains approximately seventy species, and includes most of the Hawkweeds that are considered weeds worldwide (Makepeace 1985a), including *H. aurantiacum*, *H. pilosella* and *H. praealtum* (Webb *et al.* 1988).

2.3 The biology and ecology of *Hieracium* species

Hieracium species have a number of reproductive and life history characteristics that have enabled them to become successful weeds.

2.3.1 Reproductive biology

Hieracium species show high variation in reproductive strategies, both within and between species (Morgan-Richards *et al.* 2004). Among species in the *Pilosella* group, plants employ a combination of vegetative spread and seed production (Makepeace 1985a, Webb *et al.* 1988). Vegetative reproduction occurs via stolons and rhizomes. This strategy leads to dense communities expanding clonally, while seeds allow medium and long-distance dispersal. Clonal spread allows higher survival of daughter plants but requires a high investment by the parent (Makepeace 1985a).

Most members of the *Pilosella* group, including *H. aurantiacum*, are facultative apomicts (Bicknell and Borst 1994, Bicknell *et al.* 2003). This means that they can produce seeds without sexual reproduction or pollination (Koltunow and Grossniklaus 2003). *Hieracium* species are often used as a model system for the study of apomixis (Bicknell *et al.* 2003), including the molecular mechanisms involved and inheritance studies (e.g., Bicknell *et al.* 2000, Bicknell *et al.* 2001, Koltunow *et al.* 1998, Koltunow *et al.* 2000).

Facultative apomicts can take advantage of sexual reproduction, producing genetically diverse offspring, but can also produce seed asexually, allowing for long-distance dispersal in the absence of pollen from conspecifics.

Many different Hawkweed species are capable of interbreeding (Chapman and Bicknell 2000, Rinella and Sheley 2002), although this has rarely been observed occurring naturally (Mráz *et al.* 2005). In some cases evidence for hybridisation comes from differences in genome size (Morgan-Richards *et al.* 2004), chromosome counting, pollen fertility estimation, observations of seed production, allozyme analyses or DNA sequencing (Mráz *et al.* 2005, Trewick *et al.* 2004, Tyler 2005). *H. pilosella* and *H. aurantiacum* are thought to hybridise to form *H. stoloniflorum* (Webb *et al.* 1988). It has been suggested that hybridisation, probably with *H. praealtum*, has led to increased genetic variation, and subsequent colonisation success, of *H. pilosella* in New Zealand (Chapman and Bicknell 2000).

2.3.2 Life history of Hieracium species

Dispersal

Hieracium species disperse primarily by wind. The genera have small seeds, with a bristly tuft, assisting them to disperse long-distances via wind-dispersal. Despite this, Stergios (1976) found that the majority of *H. aurantiacum* seeds were deposited within 2 m of the source patch. This suggests that long-distance wind dispersal is a rare event, but may still occasionally result in seeds falling a long distance from the source population.

H. aurantiacum can also be dispersed by water, animals and humans (National Heritage Trust 2003). The seeds have minute barbs along their ribs that enable them to stick to hair, fur, clothing and vehicles. Hikers, road maintenance and ski equipment have been implicated in the species dispersal (National Heritage Trust 2003). Dispersal of seeds and plant fragments by water downslope has also been demonstrated for populations in Hobart.

Establishment

In New Zealand, *H. aurantiacum* is naturalised in wasteland, grassland, scrub, tussock grassland, roadsides, lawns, gardens and pastures (Webb *et al.* 1988). In Australia, short tussock grasslands are thought to be at the greatest risk of invasion (National Heritage Trust 2003) but the species has also been found in Snow Gum Woodlands. Disturbed areas may have higher susceptibility to invasion (Treskonova 1991), with areas of vigorously-growing grass more resistant to *H. aurantiacum* establishment (National Heritage Trust 2003). Despite this, the species is also thought to be highly competitive, and may displace existing species rather than occupying an unused niche (Espie and Boswell 2002).

A number of studies in New Zealand have found that soil moisture is an important predictor of *Hieracium* invasion. Rose *et al* (1998) found that *H. pilosella* cover tended to peak on sites with intermediate soil moisture, such as slopes of about 15 degrees. Soil moisture was the only variable that significantly predicted the presence of *H. praealtum* with the species tending to establish on sites with a higher moisture index (Svavarsdottir *et al.* 1999). This finding was repeated by Duncan *et al* (1997), who, after controlling for elevation, found that the cover of *Hieracium* species in Canterbury and Otago was lower at more xeric sites.

Although not essential for *Hieracium* invasion (Johnstone *et al.* 1999), evidence suggests that *Hieracium* species are more likely to establish in areas that have been disturbed (Rose *et al.* 1998, Treskonova 1991). Experiments have found that soil disturbance is essential to the successful establishment of *H. pilosella* (Jesson *et al.* 2000) and that *H. piloselloides* germinates most readily on bare soil (Johnson and Thomas 1978). King Devil Hawkweed (*H. praealtum*) also germinates readily on bare soil (Makepeace 1985b). Sites colonised by *H. pilosella* in eastern Otago, New Zealand tended to be degraded with a higher percent cover of bare ground and a lower cover of grass tussocks (Johnstone *et al.* 1999).

Growth and spread

Once established *Hieracium* species are capable of rapid increase, but the rate and magnitude of increase will depend on the biotic barriers present in the invaded community (Rose and Frampton 1999). *Hieracium* species can rapidly increase because they possess rhizomes and stolons that enable the species to spread vegetatively and allow plants to survive cold winters (Espie 2001, Rinella and Sheley 2002). In Australia, *H. aurantiacum* germinates year-round, with peak germination from March to May (National Heritage Trust 2003). The species can form dense mats, dominating the ground-layer vegetation and excluding other species (Morgan 2000). Under ideal conditions a plant can form a 0.5 m^2 mat in its first year from asexual growth (National Heritage Trust 2003). Plants generally form stolons early in the growing season, before establishing leaf rosettes at the base of the stem (Stergios 1976). A plant produces between four and eight stolons in a growing season (King County Noxious Weed Control Program 2005). A square-metre mat of *H. aurantiacum* can produce up to 40,000 seeds per year (National Heritage Trust 2003). Mowing can delay seed production, but plants soon send up shorter stems and flower again (King County Noxious Weed Control Program 2005). Additionally, mowing encourages further vegetative growth (Rinella and Sheley 2002). Any activities that disturb plants, such as digging or grazing, can stimulate the growth of new plants from fragmented roots, stolons and rhizomes (Rinella and Sheley 2002).

H. aurantiacum flowers from January to March in Australia, with seed formation and drop continuing into April (National Heritage Trust 2003). Flowering is thought to be influenced by altitude, with higher altitude plants flowering later, although on the Bogong High Plains plants can flower in December and are often finished by late January (Craig Hore pers. com.). In New Zealand, Boswell and Espie (2002) found a 7 - 10 day difference in the timing of flowering over a 500 m increase in altitude for other *Hieracium* species. In Michigan, Stergios (1976) found that most *H. aurantiacum* plants did not flower in their first year of establishment. Reproductive output was greatest early in the season, with a gradual decline observed (Stergios 1976). Seeds are normally dispersed within days of maturation (Makepeace 1985a) but may remain viable in the soil for up to seven years (Rinella and Sheley 2002).

In New Zealand, *H. praealtum* begins growing in early August, and begins flowering in November. The seeds mature from December to mid-January (Makepeace 1985a).

2.4 *Hieracium* invasions worldwide

Globally, *H. aurantiacum* has become naturalised in New Zealand, Japan, parts of Europe, Canada and the United States (Blood 2001). *H. praealtum* is a weed in New Zealand, Canada and the United States (Blood 2004, Carr *et al.* 2004).

Eleven exotic Hawkweed species have become naturalised in the United States (Rinella and Sheley 2002). *H. aurantiacum* was introduced as an ornamental and herbal remedy before 1818 (King County Noxious Weed Control Program 2005). The species has since spread throughout the Eastern Seaboard and into the Midwest (Rinella and Sheley 2002). This spread was assisted by cultivation in gardens, with planted populations then escaping into nearby fields or roadsides (Callihan *et al.* 1997). The largest infestation of *H. aurantiacum* in the United States is in northern Idaho (Callihan *et al.* 1997). Infestations also occur at low to mid-elevations throughout British Columbia, Canada (British Columbia Ministry of Agriculture 2002).

In New Zealand, *H. aurantiacum* is widespread and has the potential to become a large problem (National Heritage Trust 2003). Other Hawkweed species, including *H. pilosella* and *H. lepidulum* are serious weeds of the South Island. They are most problematic in montane and subalpine areas, where they are replacing the inter-tussock vegetation (Morgan 2000, National Heritage Trust 2003). At least ten Hawkweed species have become naturalised in New Zealand (Webb *et al.* 1988). It is thought they arrived in the mid-1800s in contaminated grass seed, with populations supplemented by the plantings of acclimatisation societies (Trewick *et al.* 2004).

2.5 *Hieracium* invasions in Australia

Hieracium species have been found in four Australian states: New South Wales, Victoria, Tasmania and South Australia (Blood 2004, Carr *et al.* 2004, Spencer 2005). However, there are very few details available regarding the South Australian infestation. Most introductions originated from ornamental garden plants as the species can be valued for their hardiness in harsh environments and attractive floral displays (National Heritage Trust 2003). Despite the ban on importing Hawkweeds into Australia they are still sometimes sold to gardeners (Blood 2004, Morgan 2000) and may be found as part of wildflower seed mixes (National Heritage Trust 2003). *H. aurantiacum* and *H. pilosella* have been found available for sale in nurseries on the South Coast and Southern Highlands of New South Wales (Burton and Dellow 2005) while *H. aurantiacum* was propagated at nurseries in South Gippsland, Victoria (Michael Hansford pers. com.).

The largest populations of *H. aurantiacum* occur in Tasmania (National Heritage Trust 2003) *H. aurantiacum* was grown as a garden plant in the Central Highlands and now occurs as a weed throughout the Central Highlands and Southern Midlands (National Heritage Trust 2003). The largest infestation of *H. aurantiacum* is at Fern Tree, a suburb located on the foothills of Mount Wellington, on the outskirts of Hobart. This area has an annual mean daily maximum temperature of 11.6°C and average rainfall of over 1300 mm per year. Soils are shallow and free-draining (National Heritage Trust 2003). *H. aurantiacum* populations were established from escaped garden plantings some time before 1963 (National Heritage Trust 2003). Mapping shows that the population expanded down-slope due to wind and water dispersal and is spread over 500 ha. There has been an obvious spread along watercourses. It is also thought that slashing road sides helped to spread the species, including to one site at Snug 20 km from the nearest known population (National Heritage Trust 2003). Recently concern has been expressed that seed and plant parts may be dispersed by mountain bike riding which is a popular recreation activity on Mt Wellington (Andrew Crane, pers. com.). The species now occurs on roadsides, public open spaces, walking tracks and in private gardens (National Heritage Trust 2003). It generally shows a preference for disturbed areas but may also occur in open woodland (National Heritage Trust 2003).

In New South Wales, *H. aurantiacum* was first recorded naturalised on the Round Mountain Fire Trail in the Jagungal Wilderness, Kosciuszko National Park (Burton and Dellow 2005, McDougall 2004) in December 2003 (Carr *et al.* 2004). It was found growing in *Eucalyptus pauciflora* woodland with a grassy understorey (McDougall 2004). It is thought that this population has been eradicated, although the area continues to be monitored for the species (David Lawrence, pers. com.). More recently, a well-established population of *H. aurantiacum* was found near Ogilvies Creek, 7 km to the southwest. The population is at approximately 1450 m in elevation. It is thought that this population was the source of the previously discovered plants. This area is a former Snowy Hydro Scheme town site, and includes the remains of plantings, such as fruit trees. *H. aurantiacum* may have been present here for 25 years, but is thought to have spread after the January 2003 fires. It is now established in an area up to 500 m long, and forms a monoculture in some areas (David Lawrence, pers. com.).

In New South Wales another Hawkweed species, Wall Hawkweed (*H. murorum*), has also been found growing at Katoomba, covering an area of less than one hectare. This population consisted of approximately 1000 plants when it was discovered in 1998 (Hosking *et al.* 2003). This had been reduced to around 100 plants by 2000 (Hosking *et al.* 2003). Control measures may now have eradicated the species (Hosking 2003). *H. murorum* has not been recorded as naturalised in any other Australian states (Hosking *et al.* 2003).

2.6 *Hieracium* invasions in Victoria

2.6.1 Hieracium aurantiacum

H. aurantiacum (Orange Hawkweed) was first recorded naturalised in Victoria in January 1999. It was found growing 1600 m above sea level in disturbed roadside and ski-field vegetation, and *Eucalyptus pauciflora* heathy woodland, in the Falls Creek Village during a Melbourne University field class (Carr *et al.* 2004, Morgan 2000). The species was identified as *H. aurantiacum* subspecies *carpathicola* (University of Melbourne Herbarium 1999). It had been growing unidentified as a garden plant in Falls Creek Village since at least 1985 (Jill Dawson, pers. com.). The species is thought to have been deliberately introduced from seed brought back illegally from Europe.

At least ten populations were present in 1999, each of more than 500 individuals, some more than 1 km from the presumed source (Morgan 2000). The majority of these populations were located in or near Falls Creek Village (Morgan 2000). One population was discovered inside the Alpine National Park, at Heathy Spur, a few kilometres from the Falls Creek Alpine Resort (Carr *et al.* 2004). Since this time *H. aurantiacum* has been spreading south and east from Falls Creek. Field surveys conducted in January and February 2004 showed that *H. aurantiacum* was present in Falls Creek Village and on some ski slopes south of the village (Carr *et al.* 2004). The species has not been found at Heathy Spur since the 1999 record (Carr *et al.* 2004) but isolated populations have been found in the Basalt Hill area (N. Williams and Lynise Wearne, pers. obs.).

In the summer of 2002-2003 a population of *H. aurantiacum* was discovered by bushwalkers in a remote area of the Mt. Buller ski resort along a narrow black ski run. Although bushwalkers were initially suspected as the source of the infestation it is now thought that seed was brought to Mt Buller on ski machinery transported from Falls Creek. After prompt control efforts, that removed seed heads and sprayed the area with herbicide, only a few plants were found on the site of the initial infestation in 2004-2005. However, two additional plants, that were also subsequently destroyed, were found along a track leading from the ski run. In the summer 2005/2006 surveys revealed that original infestation had spread onto a batter and downslope into native vegetation (predominantly *Eucalyptus pauciflora* with *Podolobium alpestre* understorey and scattered boulder field with *Podocarpus lawrenceii*) (Louise Perrin, pers. com.). Control efforts are continuing.

H. aurantiacum has also been recorded in a garden bed containing alpine and arid plants at the Ballarat Botanic Gardens. The size of this infestation was about 15 metres square and consisted of 20 - 50 plants. It was originally planted in the Gardens, and attempts to eradicate the species have so far been unsuccessful.

2.6.2 Hieracium praealtum

In December 2003, King Devil Hawkweed (*H. praealtum* ssp. *bauhinii*) was found by Department of Sustainability and Environment fire fighter Rudi Pleschutschnig in the Alpine National Park (Blood 2004, Carr *et al.* 2004). The 0.8 ha infestation of over 200,000 plants was discovered close to the Falls Creek Alpine Resort boundary, just north of Rocky Valley Dam (Blood 2004, Carr *et al.* 2004). The area consists of natural vegetation with some disturbed areas, such as a ski chair lift, vehicle track and picnic area (Blood 2004). This was the first record of *H. praealtum* in Australia (Blood 2004). During field surveys in 2004 two satellite infestations were also found (Carr *et al.* 2004). The original source of these populations is unknown, but seeds may have been introduced on contaminated bushwalking, camping or ski equipment from New Zealand or other overseas visitors (Carr *et al.* 2004). In 2006, two *H. praealtum* plants were found close to the track to Wallaces Hut, approximately 2700 m from the original infestation (Craig Hore, pers. com.).

3 IMPACT OF HAWKWEEDS

The introduction of *H. aurantiacum* and other Hawkweeds can have significant ecological impacts on indigenous plant communities. In Australia, the bright, showy flowers can also have a large visual impact on the character of our unique alpine regions (Carr *et al.* 2004). *H. aurantiacum* also threatens gardens, agriculture and roadside vegetation in Australia (NSW Department of Primary Industries 2005, Brinkley and Bomford 2002). Ecologically, *H. aurantiacum* and other Hawkweeds can have a large detrimental impact due to their ability to form dense mats and exclude other species from an area. In grassy, alpine areas *H. aurantiacum* may dominate the inter-tussock spaces that are necessary for the survival and recruitment of indigenous herbs (Blood 2001, Morgan 2000).

Soils under patches of Hawkweed often have different properties to that under surrounding vegetation, for example higher acidity (McIntosh *et al.* 1995). This suggests that *Hieracium* species may be modifying the soil, which could alter the suitability of habitat for other species and give *Hieracium* a competitive advantage. Modifying the soil organic matter cycle is also thought to allow *H. pilosella* to survive in nitrogen-deficient soils, such as those found in invaded areas of the South Island of New Zealand (Saggar *et al.* 1999).

Under patches of *H. pilosella* the soil is more acidic due to a higher concentration of exchangeable cations (McIntosh *et al.* 1995). In New Zealand, an increase in organic carbon and nitrogen content was observed (Knicker *et al.* 2000, Saggar *et al.* 1999). There was a higher carbon turnover occurring, but reduced N mineralisation because the organic N was present in a different form (Saggar *et al.* 1999). There were also lower potassium levels due to high uptake by *H. pilosella* and leaching, and higher levels of exchangeable magnesium due to the acidity (Knicker *et al.* 2000). The soils may also have lower base saturation, for example 80% compared to 97% in the surrounding herbfield (Knicker *et al.* 2000), and higher microbial biomass (Saggar *et al.* 1999).

In addition to the soil modifications mentioned above, some *Hieracium* species have allelopathic interactions with other species (Connor 1992). Allelopathy is the effect of chemicals from one organism on another (Murphy 2000). Dawes and Marvolo (1973) demonstrated that *H. aurantiacum* secretes compounds into the soil that can inhibit germination, growth and survival of other plants. This may assist the species to become dominant and exclude other species from an area. There is also evidence of allelopathy in other *Hieracium* species, including *H. pilosella* and *H. praeltum* (Makepeace and Dobson 1985). The impact of inhibitory compounds is greatest for germinating seedlings, and is unlikely to have a significant impact on established plants (Makepeace and Dobson 1985). In the field, allelopathic compounds are difficult to detect and may only be present for a short period of time (Makepeace and Dobson 1985).

In the laboratory, pollen from *H. aurantiacum* and *H. pratense* that landed on the stigma of other species secreted allelochemicals that reduced pollen germination (Murphy and Aarsen 1995). One to five *Hieracium* pollen grains were sufficient to reduce reproductive success in Fabaceae (Murphy and Aarsen 1995). This may be a rare event naturally (Murphy and Aarsen 1995), but Murphy (2000) demonstrated that *H. pratense* pollen can have a negative impact on sympatric Asteraceae in the field.

Hieracium species are palatable to cattle and sheep (Boswell and Espie 2002, Rinella and Sheley 2002) and have moderate to high nutritive values (Rinella and Sheley 2002). The utilisation of Hawkweeds by grazing animals is unknown, but Hawkweeds can displace other vegetation under intensive grazing (Rinella and Sheley 2002).

Hawkweeds have lower nutritional quality than pasture species, meaning invasion reduces the productivity of grazing areas (National Heritage Trust 2003).

4. A DISPERSAL CONSTRAINED HABITAT SUITABILITY MODEL FOR ORANGE HAWKWEED ON THE BOGONG HIGH PLAINS VICTORIA

4.1 Overview: Predicting the establishment of *H. aurantiacum*

The probability that a site will be invaded by *H. aurantiacum* is a function of the suitability of that site for *H. aurantiacum* establishment, a reflection of environment and past management, and the size of the *H. aurantiacum* propagule rain (Duncan *et al.* 1997). We have modelled *H. aurantiacum* invasion by combining a habitat suitability index for the species with a dispersal model that quantifies the size of the propagule rain at distances from the source population. This has produced a dispersal constrained habitat suitability model that predicts the relative likelihood that *H. aurantiacum* will become established at a particular point on the Bogong High Plains.

4.2 Study area

The Bogong High Plains are a series of uplifted, gently undulating, alpine and subalpine plateaus bounded by dissected valleys in the highlands of northeast Victoria. They range in altitude from 1600 m at Falls Creek to 1986 m on Mt Bogong and have a bedrock of Ordovician gneiss (Williams and Ashton 1987, Conn 1993). The climate of the region is strongly seasonal and is characterised by high precipitation, persistent snow between June and September, low average temperatures and frequent frosts in any month. Maximum summer daily temperatures rarely exceed 28°C and winter minimums do not fall below -10^{o} C. Mean annual precipitation is 2555 mm but there is strong monthly variation (Williams and Ashton 1987).

The only settlements in the area are at Falls Creek, Mt Hotham and Dinner Plain. These villages are on the margins of the high plains and have been developed as ski resorts. Extensive cattle grazing occurred in the past, but following the 2002/03 wildfires cattle grazing was restricted to assist post-fire vegetation recovery. In May 2005 the Victorian Government made the decision (after a review by the Alpine Grazing Taskforce) that grazing would no longer be permitted in the Alpine National Park. Land use in the Bogong High Plains is now largely for nature conservation and as a water catchment.

The boundary of the study area is the extent of the alpine vegetation communities mapped by McDougall (1982).

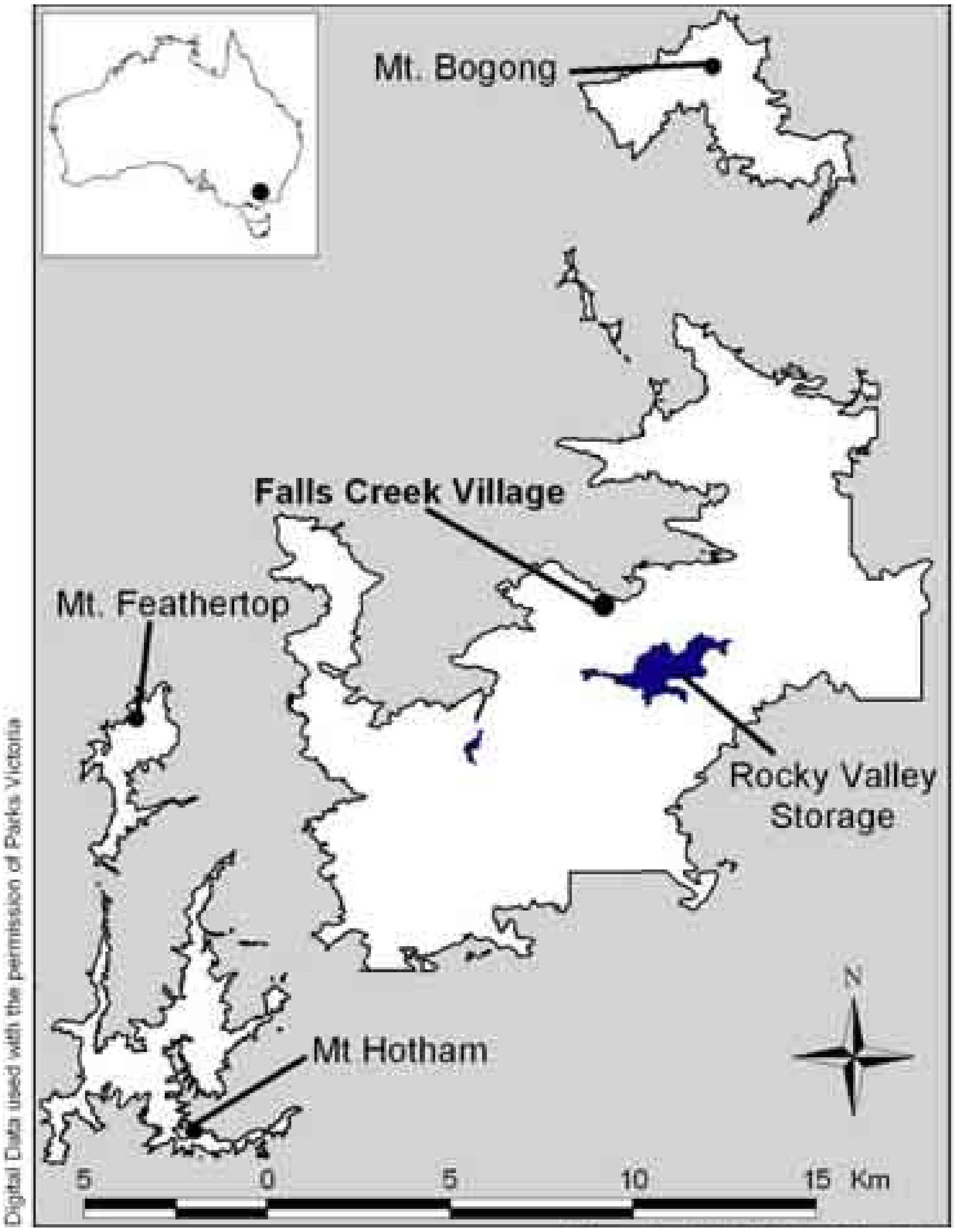


Figure 1. Map of the study area. The white area represents the study area. The insert shows the location of the study area (●) within Australia.

5 METHODS

5.1 Habitat suitability index

Habitat suitability indices (HSI) are conceptual models of expert opinion that have become an important tool for ecological assessment and conservation planning (Elith and Burgman 2003). They relate each relevant, measurable variable of the environment to the suitability of a site for the species of interest, by scaling the variable from 0 (unsuitable habitat) to 1 (optimal habitat). Each variable is represented by a single suitability index. These are linked by additive, multiplicative or logical functions that reflect relationships among variables to calculate the HSI (Elith and Burgman 2003, USFWS 1981).

The HSI we have developed for *H. aurantiacum* has three variables that are likely to influence the probability of successful establishment; the vegetation community (V), level of disturbance (D) and wetness (W) of each point in the landscape. Because these variables interact we combined them multiplicatively using the expression.

$$\mathrm{HSI} = (V \times D \times W)^{1/3}$$

Information that has informed the assigning of probabilities to each of the variables and their constituent parameters has been obtained from the scientific literature and expert opinion. Where data on the habitat preferences of *H. aurantiacum* were not available, information regarding closely related *Hieracium* species was utilised.

5.1.1 Vegetation community

In New Zealand, *H. aurantiacum* is naturalised in wasteland, grassland, scrub, tussock grassland, roadsides, lawns, gardens and pastures (Webb *et al.* 1988). In Australia, short tussock grasslands are thought to be at the greatest risk of invasion (National Heritage Trust 2003) but the species has also been found in Snow Gum Woodlands. Disturbed areas are likely to have higher susceptibility to invasion (Treskonova 1991), with areas of vigorously-growing grass more resistant to *H. aurantiacum* establishment (National Heritage Trust 2003). Despite this, the species is also thought to be highly competitive, and may displace existing species rather than occupying an unused niche (Espie and Boswell 2002).

McDougall (1982) classified and mapped the vegetation communities on the Bogong High Plains. We obtained a digitised GIS layer of this map. The vegetation classes were assigned a probability between 0 and 1 of *H. aurantiacum* establishing (Table 1; Figure 2). The probabilities were based on expert opinion, which took into consideration the height and density of the vegetation, the nature of the physical environment where that vegetation community was found and whether *H. aurantiacum* had previously been recorded in that vegetation type.

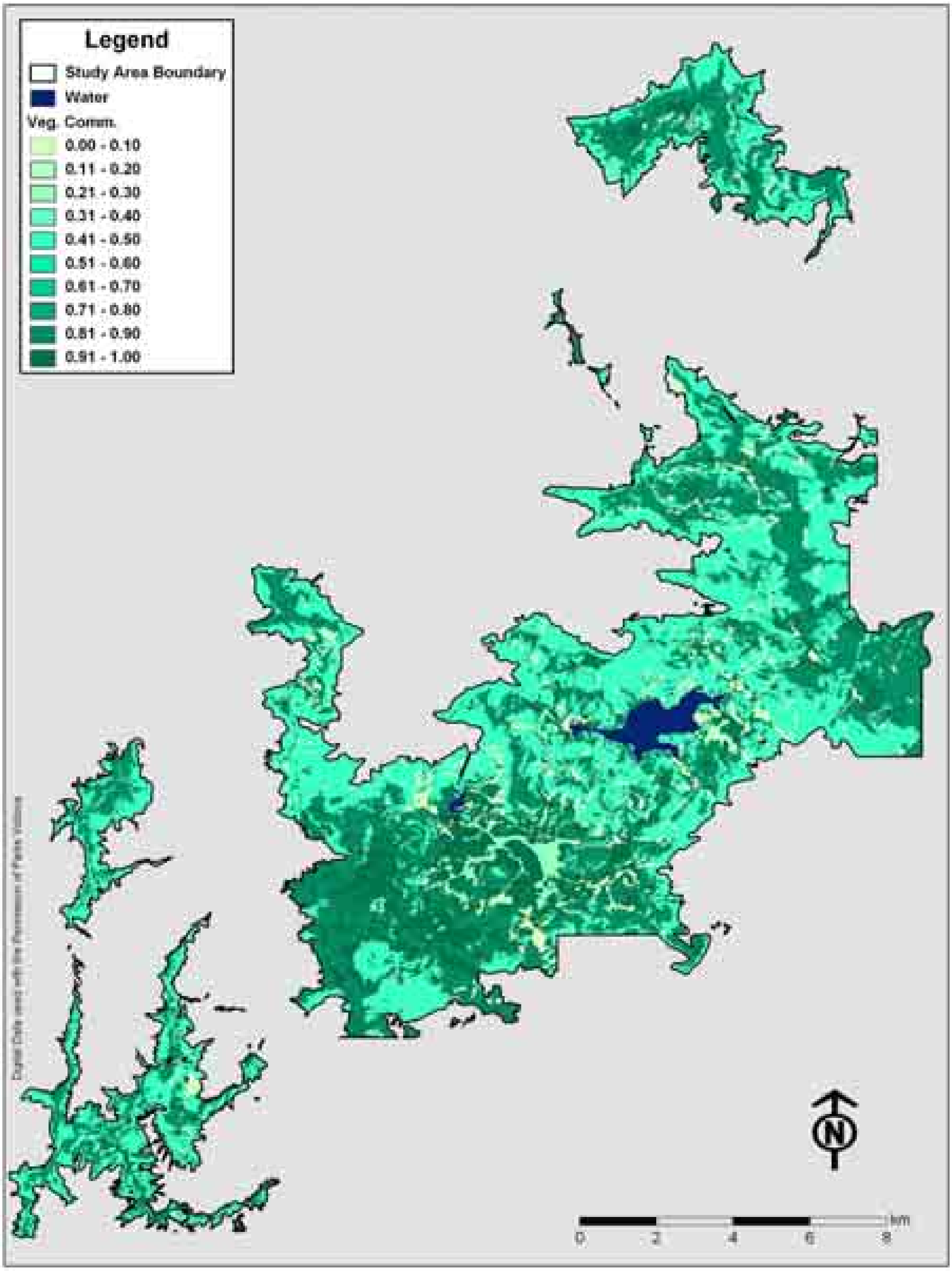


Figure 2. Probability values for the vegetation community component of the Habitat Suitability Index for *H. aurantiacum* on the Bogong High Plains.

Table 1. Probability values for the establishment of *H. aurantiacum* in the plant communities of the Bogong High Plains defined by McDougall (1982).

Plant community	Probability
Bog	0.01
Celmisia sericophylla herbland	0.01
Closed Heathland	0.50
Disturbed areas	1.00
Kunzea Heathland	0.50
Late - Lying Snowpatch	0.10
Open Heathland	0.90
Poa hiemata tussock grassland	1.00
Poa costiniana tussock grassland	1.00
Podocarpus Heathland	0.01
Relic Bog	0.20
Rocky Grassland	0.50
Rocky Outcrops	0.01
Short Turf Snowpatch	0.30
Sub alpine grassland	0.90

5.1.2 Wetness Index

A number of studies in New Zealand have found that soil moisture is an important predictor of *Hieracium* invasion. Rose *et al* (1998) found that *H. pilosella* cover tended to peak on sites with intermediate soil moisture, such as slopes of about 15 degrees. Soil moisture was the only variable that significantly predicted the presence of *H. praealtum* with the species tending to establish on sites with a higher moisture index (Svavarsdottir *et al.* 1999). This finding was confirmed by Duncan *et al.* (1997), who, after controlling for elevation, found that the cover of *Hieracium* species in Canterbury and Otago was lower at more xeric sites.

We incorporated the greater likelihood of *Hieracium* establishing on sites of intermediate soil moisture into the HSI by using a wetness index created using ANUCLIM (Houlder *et al.* 2003) from a digital elevation model of the Bogong High Plains. This calculated the relative wetness of 20 m x 20 m cells based on the total upslope catchment area. The Wetness Index values were then translated into a probability of *H. aurantiacum* establishing there based on previous values in the literature. The probability values used for the Wetness Index are presented in Figure 3 and the map of habitat suitability based on the Wetness Index is shown in Figure 4.

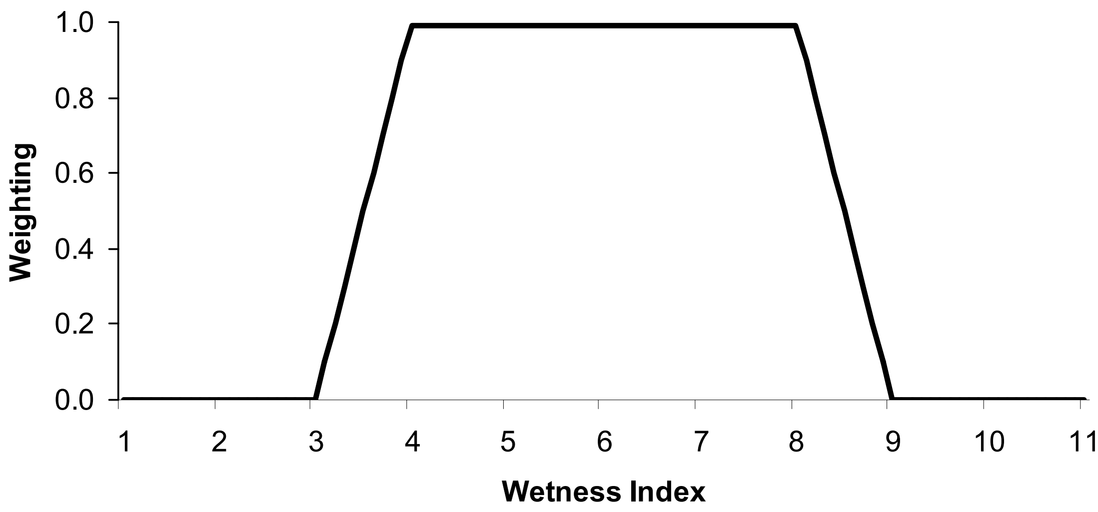


Figure 3. The weighting given to values of the Wetness Index.

5.1.3 Disturbance Index

Disturbance is often cited as an important precursor to invasions of alien species (Hobbs and Huenneke 1992). Although not essential for *Hieracium* invasion (Johnstone *et al.* 1999), evidence suggests that *Hieracium* species are more likely to establish in areas that have been disturbed (Rose *et al.* 1998, Treskonova 1991). Experiments have found that soil disturbance is essential to the successful establishment of *H. pilosella* (Jesson *et al.* 2000) and that *H. piloselloides* germinates most readily on bare soil (Johnson and Thomas 1978). King Devil Hawkweed (*H. praealtum*) also germinates readily on bare soil (Makepeace 1985b). Sites colonised by *H. pilosella* in eastern Otago, New Zealand tended to be degraded with a higher percent cover of bare ground and a lower cover of grass tussocks (Johnstone *et al.* 1999).

Based on the literature cited above, the disturbance component of the HSI incorporated landscape features known to have high incidences of disturbance and two spatially extensive disturbance events that may increase the likelihood of *Hieracium* establishment; fire and grazing. Because we consider disturbance (D) to be cumulative rather than synergistic, these parameters were combined additively using the expression:

$$D = \frac{(U+S+R+A+H+T+G+F)}{8} + 0.001$$

where U is urban ski resort areas, S is ski slopes, R is roads, A is aqueducts, H is huts, T is walking tracks, G is grazed areas and F is burnt areas. To allow for the case where *Hieracium* may establish outside areas of disturbance, a value of 0.001 was added to each cell in the final disturbance theme (so that there were no ‘zero’ cells).

Ski resorts and slopes

H. aurantiacum was reportedly first introduced to the Falls Creek village via seed illegally brought back from Europe and planted in the garden of a ski lodge. Ski resorts are well known as focal points of exotic plant species introductions to the Australian Alps (Johnston and Pickering 2001, McDougall *et al.* 2005), with 59 weed species, 29 of which also occur in native vegetation, recorded from Falls Creek (McDougall and Appleby 2000). The majority of *H. aurantiacum* records on the Bogong High Plains are from the Falls Creek village and nearby ski slopes. We were unable to obtain spatial datasets for the location of the urban village areas or ski runs so these areas were manually digitised from an aerial photo of the Falls Creek resort (Figure 5). Ski runs and the Mt Hotham ski resort on the southern edge of the Bogong High Plains were not included as information on their spatial location and extent were not available. Because we know the species can establish in these urban areas and along the ski runs we assigned a probability of 0.99 to each. The areas outside the urban areas and ski runs were assigned a probability value of 0.001.

Roads, aqueducts and hiking trails

Many Australian and international studies have found that exotic species are more prevalent along roads and hiking trails in mountainous national parks. Research in the northern United States has found that *H. aurantiacum* is more likely to establish on vegetation edges close to roads, hiking trails and other areas experiencing human disturbances (Dickens *et al.* 2005, Bullock and Clarke 2000). Observations at Falls Creek also indicate that *H. aurantiacum* was more likely to occur along the disturbed edges of roads and the aqueducts feeding into Rocky Valley Storage reservoir (N. Williams pers. obs., Morgan 2000). These disturbances also affect an area immediately adjacent to the feature of interest. Paved roads and a 20 m buffer either side of them were assigned a disturbance probability of 0.7. Aqueducts and little used four wheel drive vehicle tracks and a 10 m buffer either side of them were also assigned a disturbance probability of 0.7. Although hiking trails and huts have been shown to be sites of alien species establishment (Jesson *et al.* 2000), the degree and extent of disturbance could be expected to be less than that of roads. We therefore assigned hiking trails and huts, and their respective buffer areas of 10 m and 50 m, a disturbance probability of 0.3.

Fire

In January 2003, extensive wildfires burnt large areas of the Australian Alps (Cheal 2003, Worboys 2003). Fires in Australian alpine environments consume most of the vegetation and the litter layer, leaving extensive areas of bare soil (Wahren *et al.* 2001) that can take decades to return to pre-fire vegetation cover (Bridle *et al.* 2001). Concern has been expressed that these conditions may favour the invasion of exotic species (Cheal 2003, Johnston and Johnston 2003). To account for the increased habitat suitability for *Hieracium*, all areas on the Bogong High Plains within the boundary of the 2003 fires were assigned a probability of establishment of 0.5 (Figure 6). Because the fire occurred in 2003 this disturbance layer was only included in the expression for calculating HSI after this date.

Cattle Grazing

Prior to the 2003 fires, areas of the Bogong High Plains had been grazed by cattle since the 1850's (Williams and Ashton 1987). Cattle grazing creates bare ground due to feeding, trampling, urine scalds and dung (McDougall 1982). It has been shown to facilitate weed invasion and is considered a factor predisposing tussock grasslands to *Hieracium* invasion in New Zealand (Rose *et al.* 1998) possibly by increasing soil phosphorous levels (Svavarsdottir *et al.* 1999). Accordingly, areas licensed for cattle grazing on the Bogong High Plains (Figure 7) were assigned a probability value of 0.1.

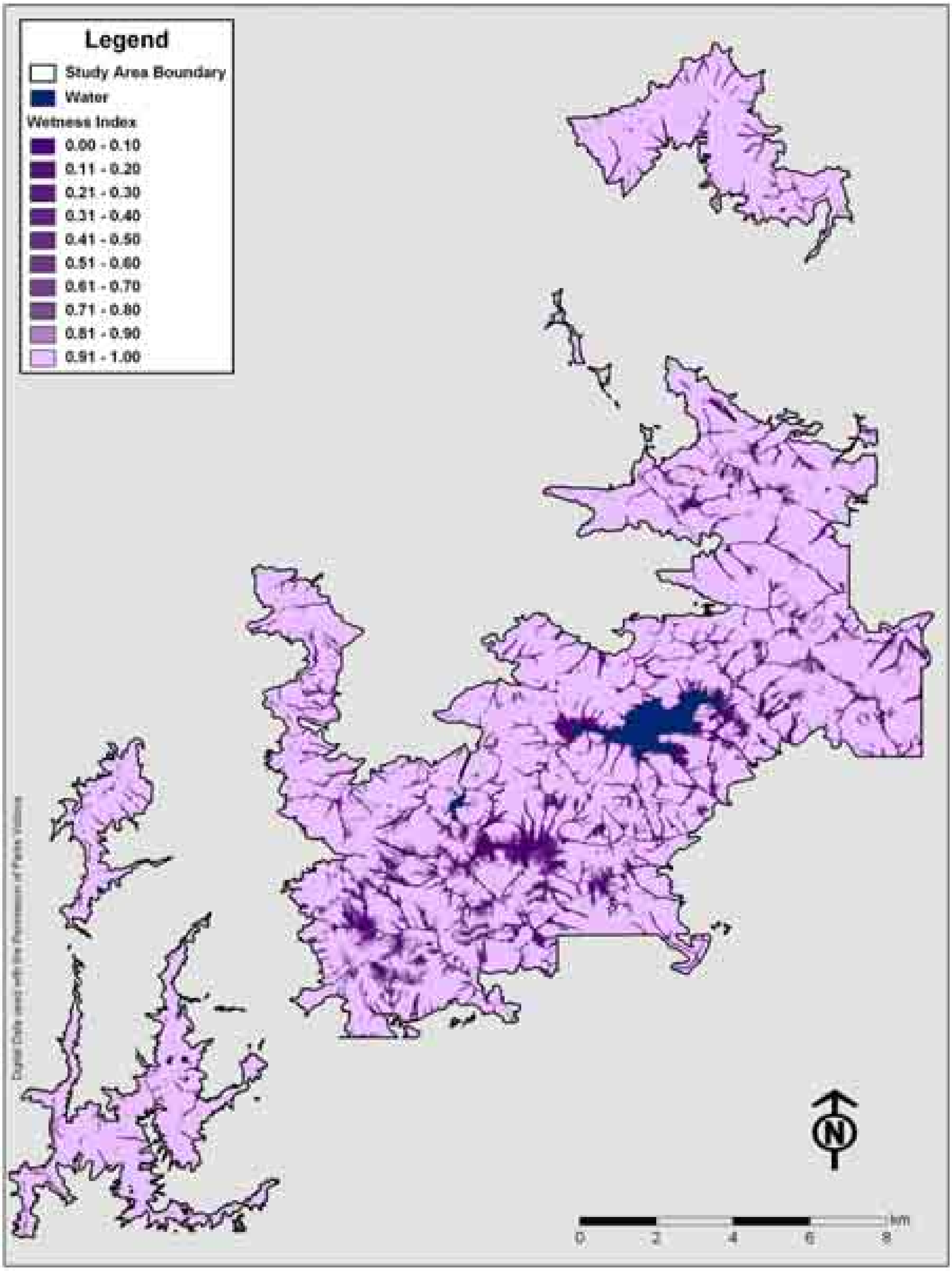


Figure 4. Probability values for the Wetness Index component of the Habitat Suitability Index for *H. aurantiacum* on the Bogong High Plains.

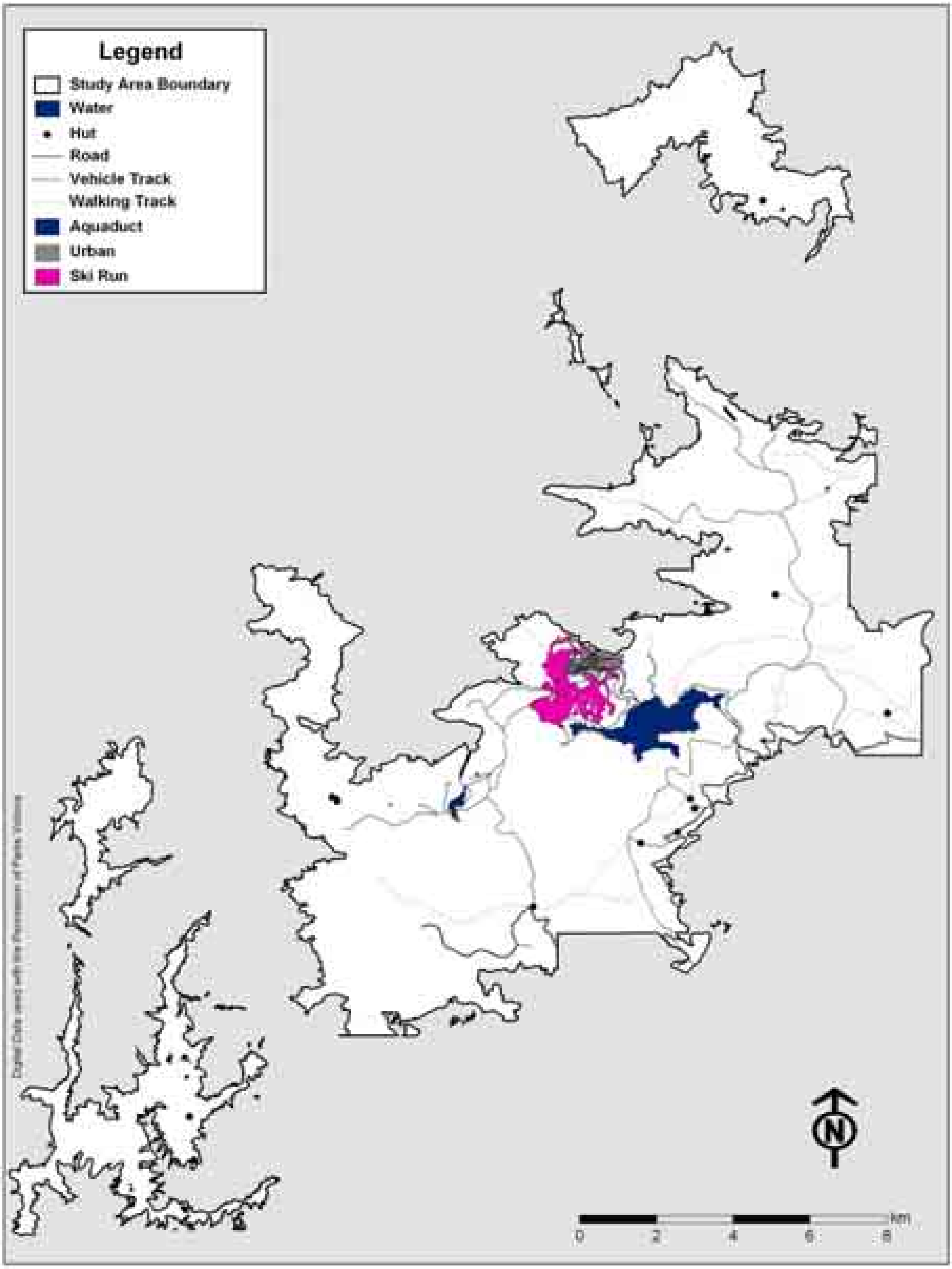


Figure 5. Location of the Falls Creek village, ski slopes, roads, aqueducts, huts and walking tracks included in disturbance components of the HSI for *H. aurantiacum* on the Bogong High Plains.

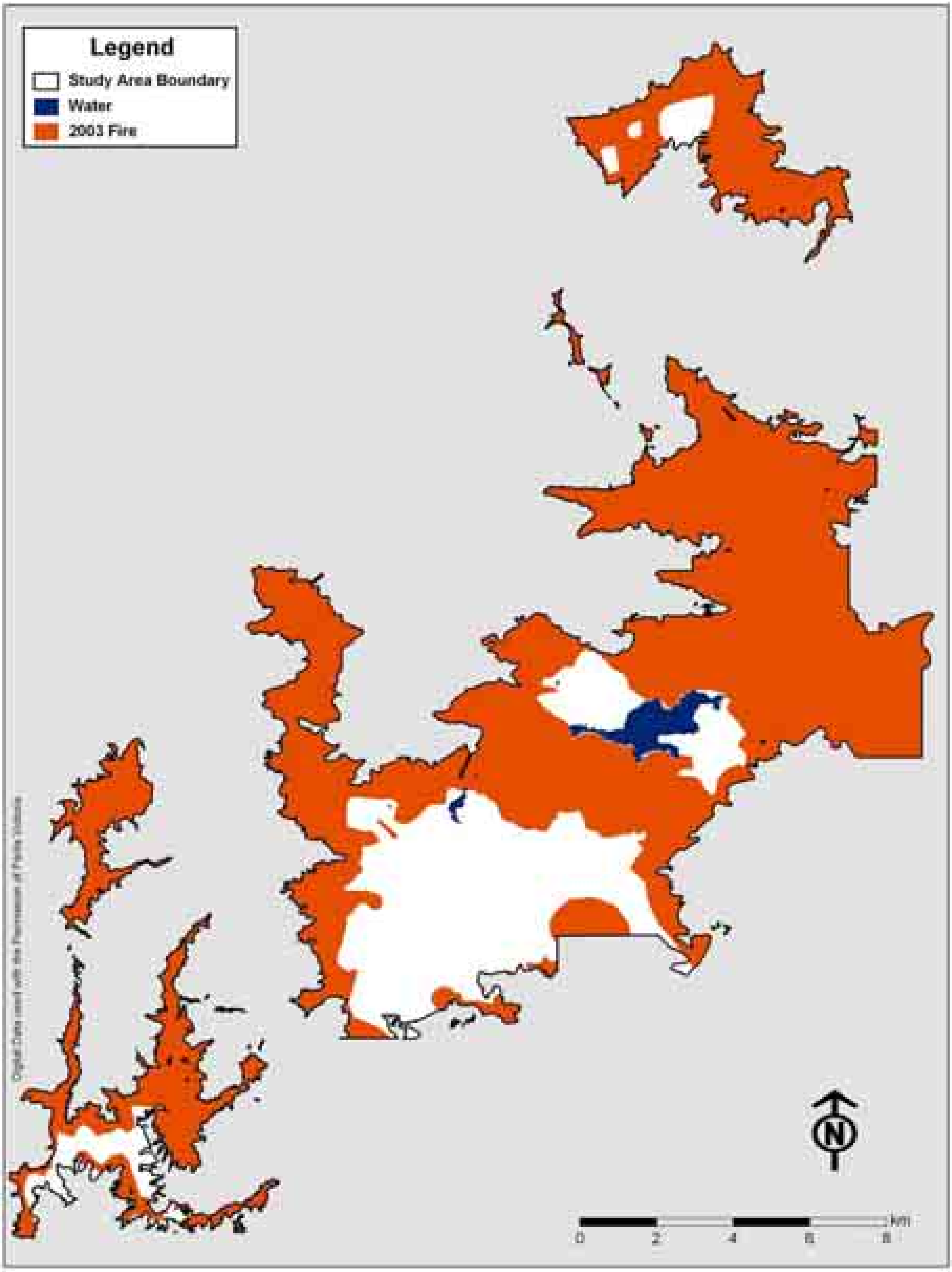


Figure 6. Extent of the 2003 wildfire included in the disturbance component of the HSI for *H. aurantiacum* on the Bogong High Plains.

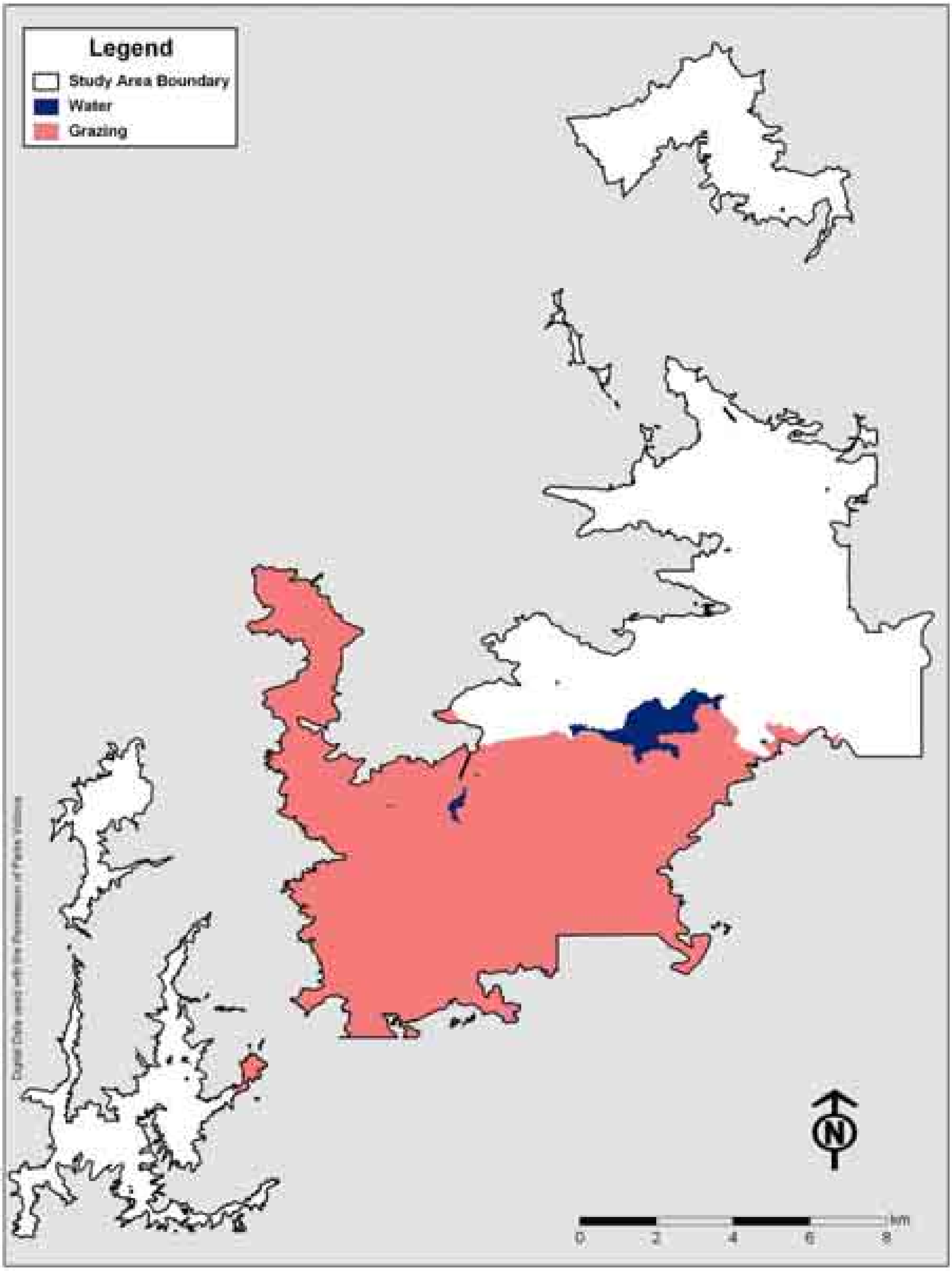


Figure 7. Extent of the area licenced for cattle grazing prior to 2003 that was included in the disturbance component of the HSI for *H. aurantiacum* on the Bogong High Plains.

5.2 Dispersal models

Two complementary approaches are commonly used to model the long distance dispersal of plant propagules. Phenomenological models fit a mathematical function to observed or hypothesised dispersal data but ignore the details of the dispersal process (Nathan *et al.* 2003). Mechanistic models use data from diaspore terminal velocities, wind speed and other physical variables that affect dispersal and describe the resulting dispersal distances mathematically, independent of actual dispersal data (Nathan *et al.* 2003, Bullock and Clarke 2000). We investigated both approaches to model the dispersal of *H. aurantiacum* in the Falls Creek area but were unable to develop a mechanistic model due to the resource constraints, inadequate data (i.e. vertical wind speed is not measured by the weather station at Falls Creek) and lack of stochastic modelling expertise. Consequently, only the phenomenological model is presented in this report.

Phenomenological models have traditionally used variations on the negative exponential and inverse power law distributions to fit dispersal curves to observed data. These curves often have long fat tails that drop off with distance less rapidly than the negative exponential curve implying high levels of long distance dispersal (Nathan *et al.* 2003). Although we could not measure the dispersal of *H. aurantiacum* seeds in the field, data were available to fit a curve. North American experiments found that 83% of *H. aurantiacum* seeds were dispersed within two metres of the parent plant and closely followed negative exponential functions (Stergios 1976). The distribution of populations at Falls Creek and Kosciousko National Parks suggests that most seeds land within 50 - 100 m but rare long distance dispersal events can disperse seeds at least 5 km. Detailed mechanistic modelling for the closely related *H. pilosella* in Germany supports this. In a flat open landscape, Takenburg (2001) found that most seeds would land within 50 m, 8% of seeds would travel greater than 100 m and 2% would travel several kilometres.

To incorporate this knowledge we modelled the probability of dispersal from a known *Hieracium* population with the formula:

$$\Pr(Dist) = 1 - e^{-(d/x)^{\alpha}}$$

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 α is a constant (-1.0385) fitted so that the highest dispersal probability occurred within 100 m of the source population but there was still some dispersal up to 5 km away. The dispersal curve is illustrated in Figure 8.

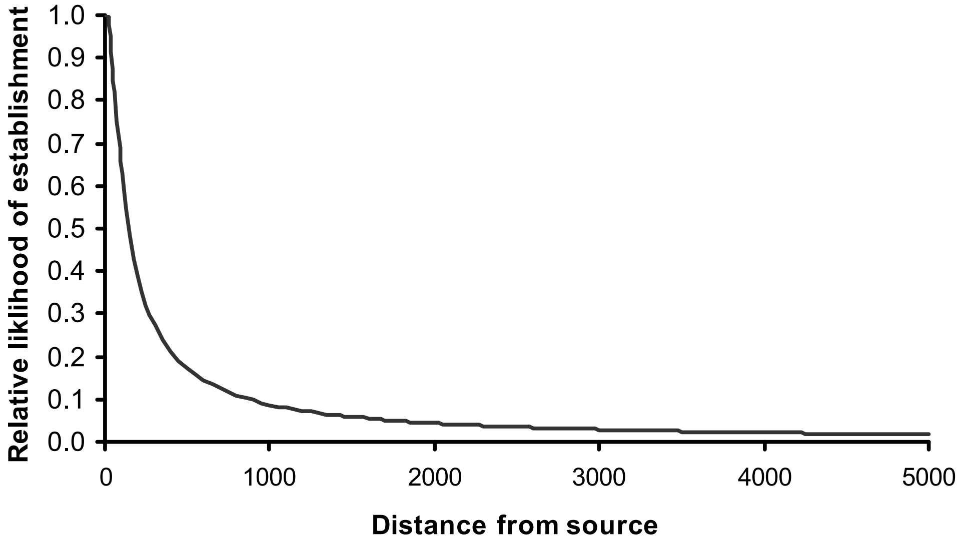


Figure 8. The dispersal curve used for the phenomenological dispersal model.

5.2.1 Making the phenomenological model more realistic

Although we were not able to consider dispersal of *H. aurantiacum* using true mechanistic models, the phenomenological model was made more realistic by incorporating wind direction. Wind data were obtained from the Falls Creek weather station located immediately north east of the village. Data was obtained for the months December to February from 1998 to 2006, when *Hieracium* populations are known to have been present, and were likely to be shedding seed. Dispersal of wind dispersed seeds is more likely to occur in climatic conditions conducive to the creation of updrafts which lift seeds above the turbulent boundary climatic layer (Tackenberg *et al.* 2003b). Such conditions include warm dry days which heat air close to the surface. Consequently, we selected only wind data from daylight hours (between 5 am and 9 pm) on days where there was less than 10 mm of rain and when the maximum daily temperature exceeded 15°C. The proportion of wind records when the wind blew in each of 16 compass directions during these times was calculated (Figure 9a and 9b).

The dispersal plume of seeds from sites containing *H. aurantiacum* was obtained by multiplying the dispersal curve from the phenomenological model by the proportion of time that the wind blew from each compass direction. This results in areas in the direction of the prevailing winds having a higher probability of *H. aurantiacum* occurrence than other locations that are equal distance from the source site, but in a different direction. Cumulative dispersal plumes from each of the six *H. aurantiacum* localities recorded between 1998 - 2003 and the 47 known occurrences between 2003-2006 were created by adding the dispersal plumes from each record for each time step.

$$\Pr(Disp) = \frac{\sum_{i=1}^{n} (\Pr(Dist_i) \text{ x } \Pr(Dir_i))^{1/2}}{n}$$

The first set of *H. aurantiacum* locations were used for the time step analysis and the larger second group were used for the final dispersal constrained HSI.

5.3 Dispersal constrained habitat suitability model

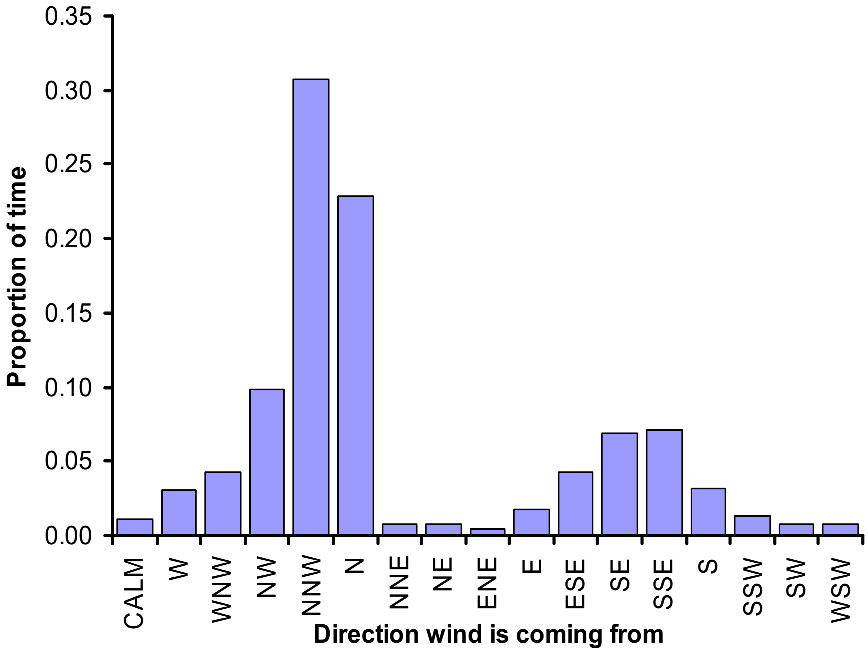
All of the component data themes were converted to a 20 m resolution grid theme using the Spatial Analyst extension in ArcView 3.2 (ESRI, Redlands, CA, USA). The coordinate system used was Australian Map Grid Zone 55, based on the Australian Geodetic Datum 1966. The map calculator function in ArcView was used to combine the values for each grid cell using the formulae identified above. Information on the spatial resolution and the data source for each of the grid themes used is presented in Appendix 1.

The final dispersal constrained habitat suitability model for each time step was constructed by combining the predictions for *H. aurantiacum* seed dispersal (Pr(Disp)) with the probability of *H. aurantiacum* establishing in that location (Pr(HSI)) using the geometric mean

$$\mathrm{Pr(Occurrence)} = \left(\mathrm{Pr}(Disp) * \mathrm{Pr}(HSI)\right)^{1/2}$$

The model was developed and refined by changing the weights and ways of combining the various components of the habitat suitability model so that it made ecological sense and reflected our knowledge of the distribution and habitat preferences of *H. aurantiacum* on the Bogong High Plains.

a)



b)

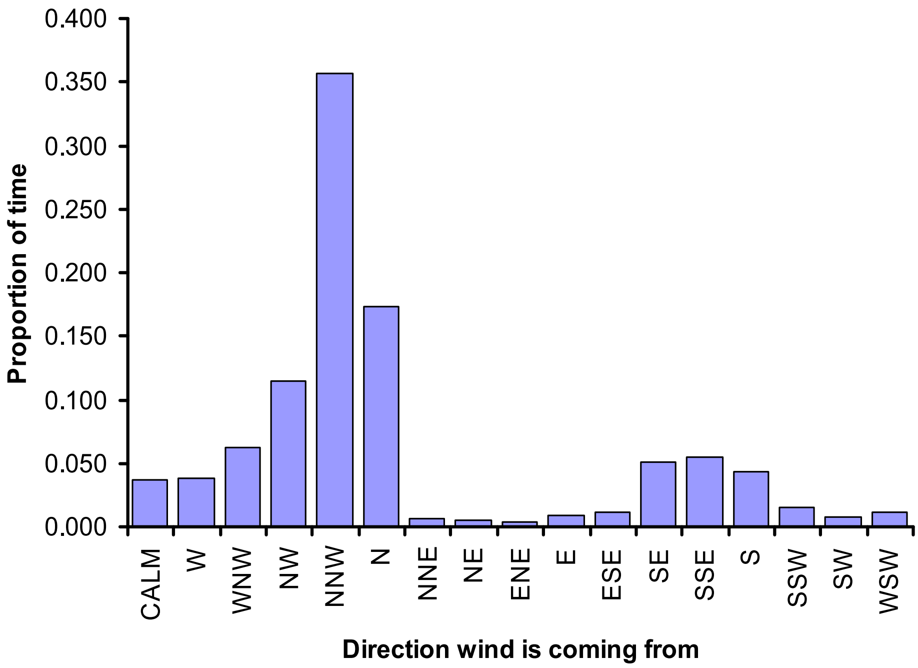


Figure 9. The proportion of time the wind was blowing from each compass direction at Falls Creek on days between December and February that were above 15°C and rainfall was less than 10 mm for a) the first time step (1998-2003) and b) the second time step (2003-2006).

5.4 Verifying the model

The model was verified in two ways. We conducted intensive field searches for the species in areas the model predicted *H. aurantiacum* would occur and also validated the model by using a time-step approach.

5.4.1 Field Survey

Field searches were conducted by the authors and trained student and staff volunteers from The University of Melbourne and La Trobe University third year Botany courses which are held annually on the Bogong High Plains. Field searches were conducted between the 28th January and 3rd February, and 21st to 25th of February 2006.

Figure 10. Participants in the University of Melbourne's Field Botany class search for *H. aurantiacum* on Basalt Hill.

Surveys involved systematically searching randomly selected localities from the mapped outputs of the model and other areas utilised during the teaching of the two university courses. Random search localities were stratified based on the relative area of the Bogong High Plains in each of ten probability classes. Consequently, more localities which had a lower predicted probability of *Hieracium* occurrence were searched compared to localities with a higher probability of occurrence. At each locality volunteers conducted a line search for the species, spacing themselves 5 - 10 m apart and slowly walking through the area examining the vegetation for the highly distinctive flowers and hairy stems and leaves of *H. aurantiacum* (Figure 10).

5.4.2 Time step validation

The time step validation of the model visually assessed how accurately it predicted the distribution of 47 recent *H. aurantiacum* records (2003-2005) from six earlier (1998-2000) records. The initial time step did not include fire in the disturbance component of the HSI. A map of the probability of *H. aurantiacum* occurrence in 2002 was created by modelling dispersal using the six locations of the early records and a subset of the wind data between 1998-2002 (Figure 9a). Recent records were overlain on the map to give an indication of the accuracy of the model.

6 RESULTS

6.1 Model Predictions

The Habitat Suitability Index indicates that large areas of the Bogong High Plains are suitable habitat for *H. aurantiacum* (Figure 11). Apart from disturbed areas around roads and Falls Creek village, the most suitable areas for *H. aurantiacum* establishment are the large areas of tussock grassland in the vicinity of Mt Nelse and Mt Bogong. These areas are also suitable habitat because they were burnt in the 2003 wildfires and the HSI is sensitive to the fire parameter.

The phenomenological dispersal model adjusted for wind direction and frequency (Figure 12) indicates that the areas where *H. aurantiacum* had a high probability of dispersing to between 1998 and 2005 were in a south-easterly direction from recorded infestations. Seeds are most likely to have been dispersed within the village, on to the north facing ski slopes and within one kilometre of the southern shore of Rocky Valley Storage. Limited dispersal may have occurred in a north-west direction due to occasional south-easterly winds during the dispersal period.

The dispersal constrained HSI (Figure 13) suggests that the majority of the Bogong High Plains south and southeast of Rocky Valley Storage is suitable habitat for *H. aurantiacum* that may have received seeds dispersing from known populations in the Falls Creek area. Apart from Falls Creek village and ski slopes the areas with the greatest likelihood of successful *H. aurantiacum* establishment are the north-facing slopes below Rocky Knobs and disturbed areas along the Bogong High Plains Road. There is also an area of suitable habitat on Spion Kopje that may have received seeds dispersed on southerly winds.

6.2 Model Testing

6.2.1 Field searches

University of Melbourne and La Trobe University botany course participants spent a total of 360 person hours searching 172 ha of the Bogong High Plains (Figure 14) for *H. aurantiacum*. Despite the substantial amount of time spent searching no populations were found. Consequently, it was impossible to validate the model using field searches. Nevertheless the search methods are thought to be robust and should be replicated in future searches for *Hieracium* species on the Bogong High Plains. Searching multiple locations of differing likelihood of *Hieracium* occurrence more than once to account for flowering differences is particularly important.

6.2.2 Time Step Validation

Figures 15 and 16 show the location of *Hieracium* populations found since 2003 in relation to the predicted probability of occurrence modelled from the 1998-2000 records. The maps indicate that the model accurately predicts the occurrence of *Hieracium* populations as all of the post-2003 records north of Rocky Valley Dam occurred in or very close to areas predicted to have a high probability of occurrence. Two populations recorded on Basalt Hill are in areas predicted to be suitable habitat for the species. No populations have been found outside the dispersal plume, which suggest that the dispersal component of the model accurately reflects the movement of *Hieracium* seed.

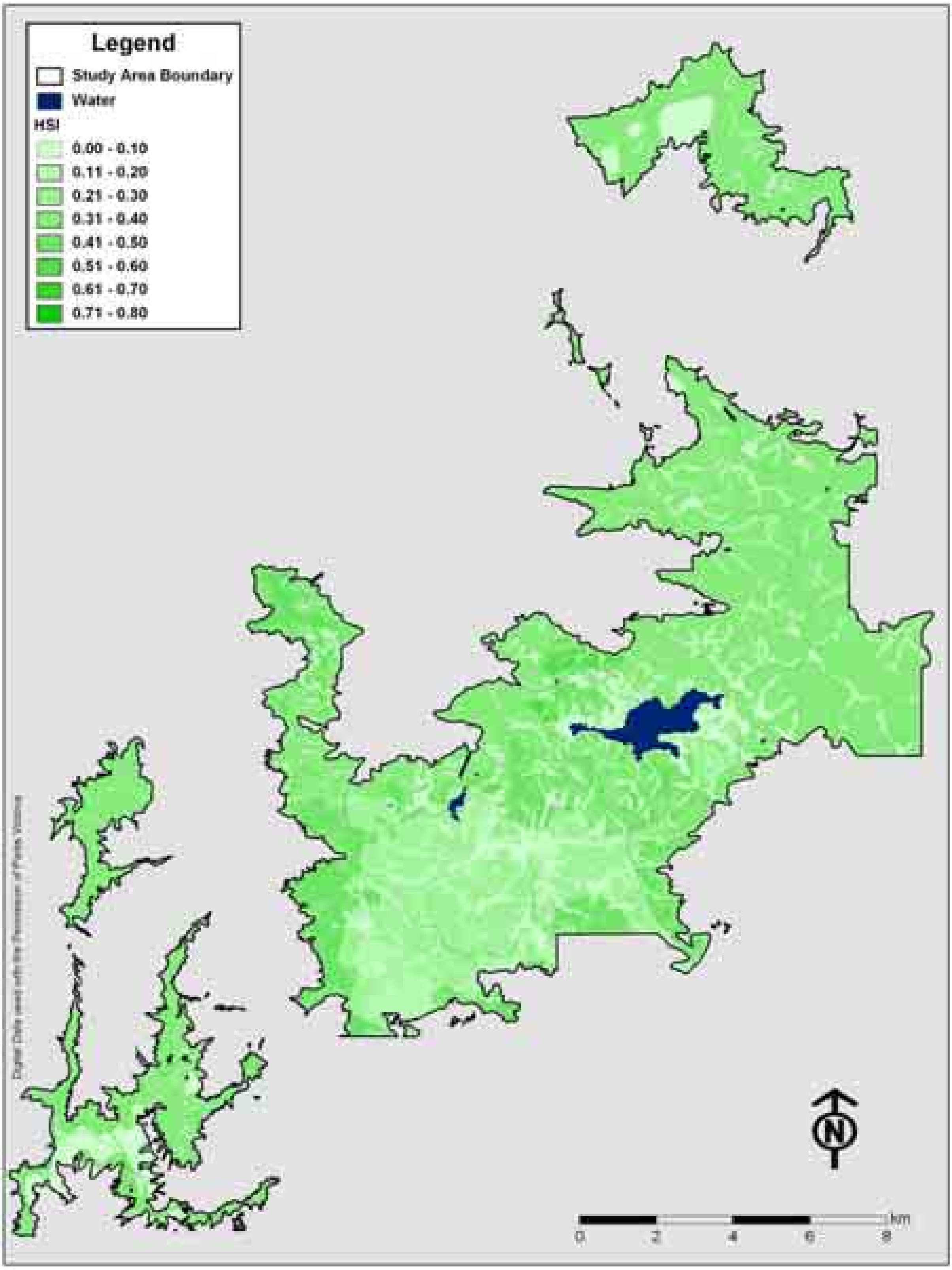


Figure 11. Map of the Bogong High Plains illustrating the habitat suitability index (HSI) for *H. aurantiacum* after the 2003 wildfire. Darker colours indicate more suitable habitat.

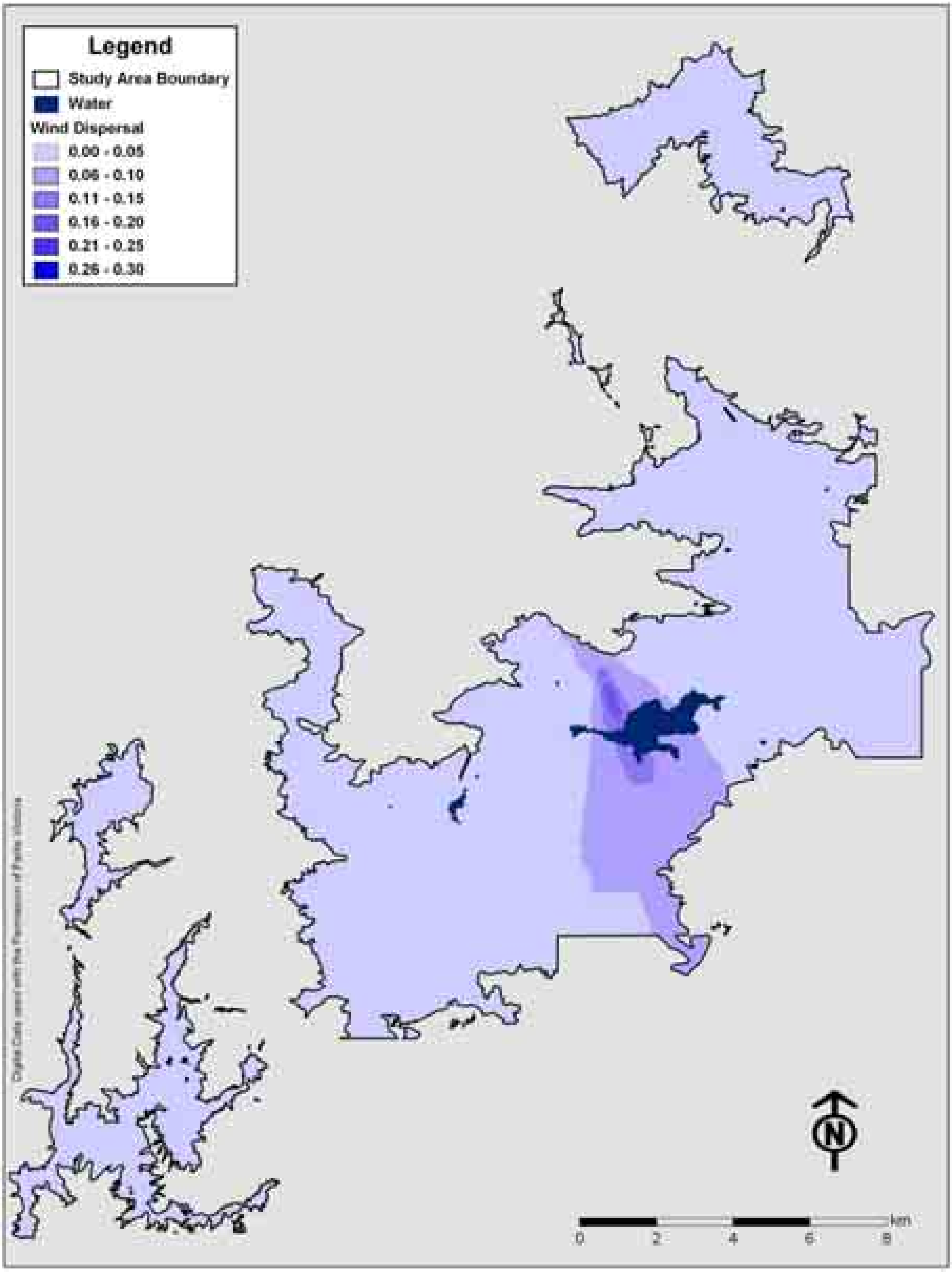


Figure 12. Cumulative dispersal plume of *H. aurantiacum* on the Bogong High Plains, Victoria.

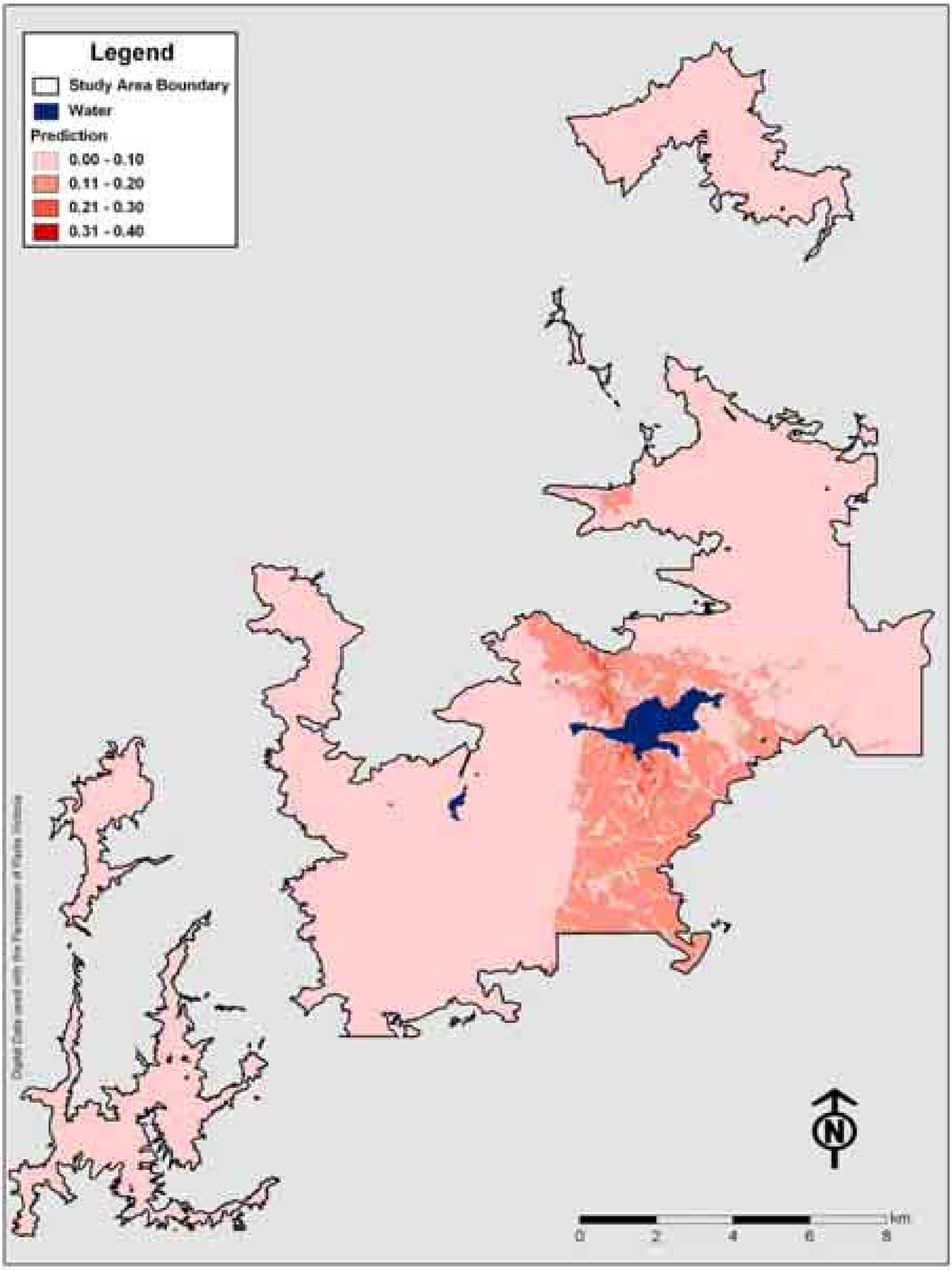


Figure 13. Dispersal constrained HSI for *H. aurantiacum* on the Bogong High Plains, Victoria, illustrating the relative likelihood of *H. aurantiacum* occurring at particular point after February 2006.

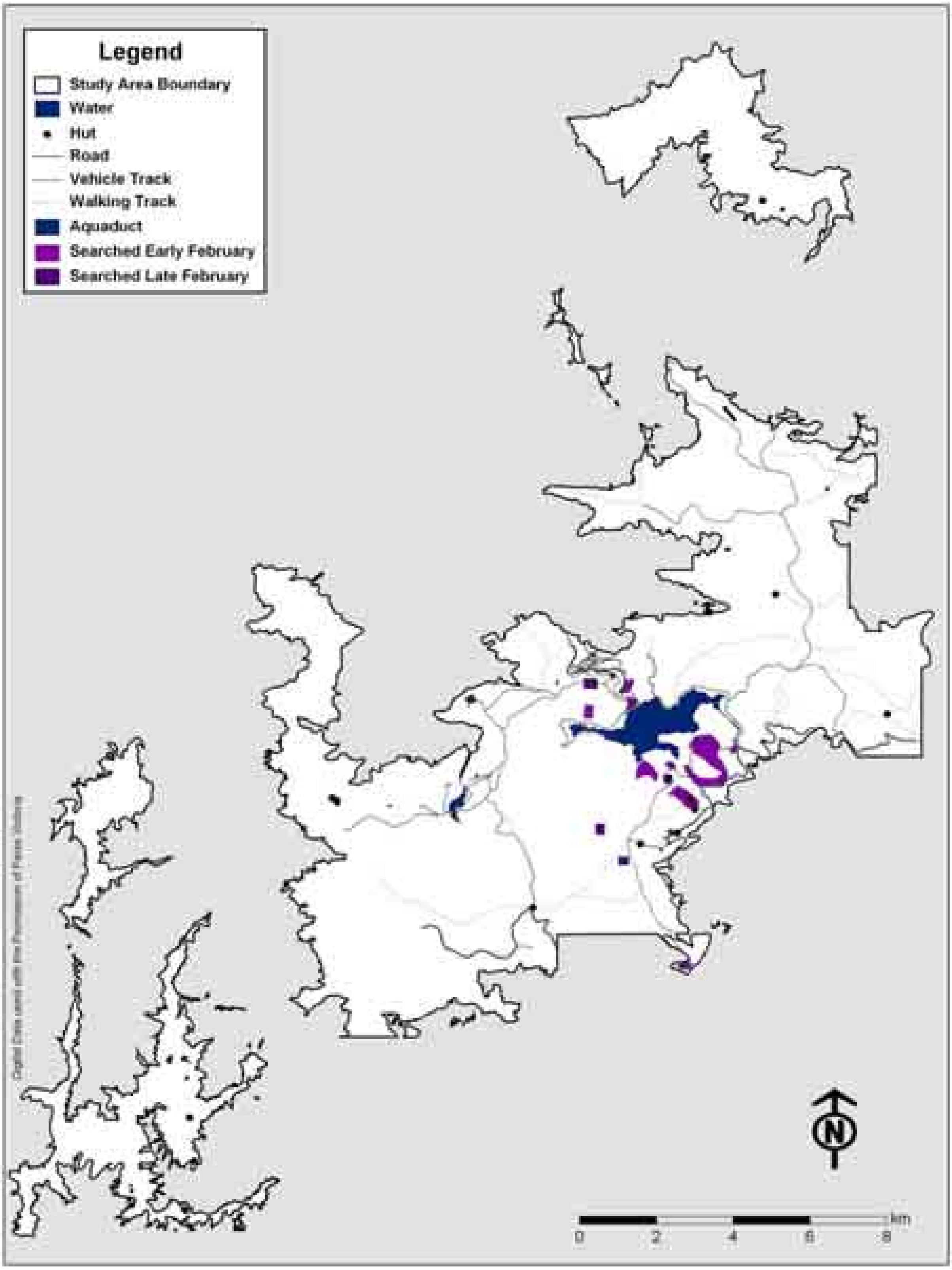


Figure 14. Localities searched for the presence of *H. aurantiacum* by La Trobe University and University of Melbourne students and staff in February 2006.

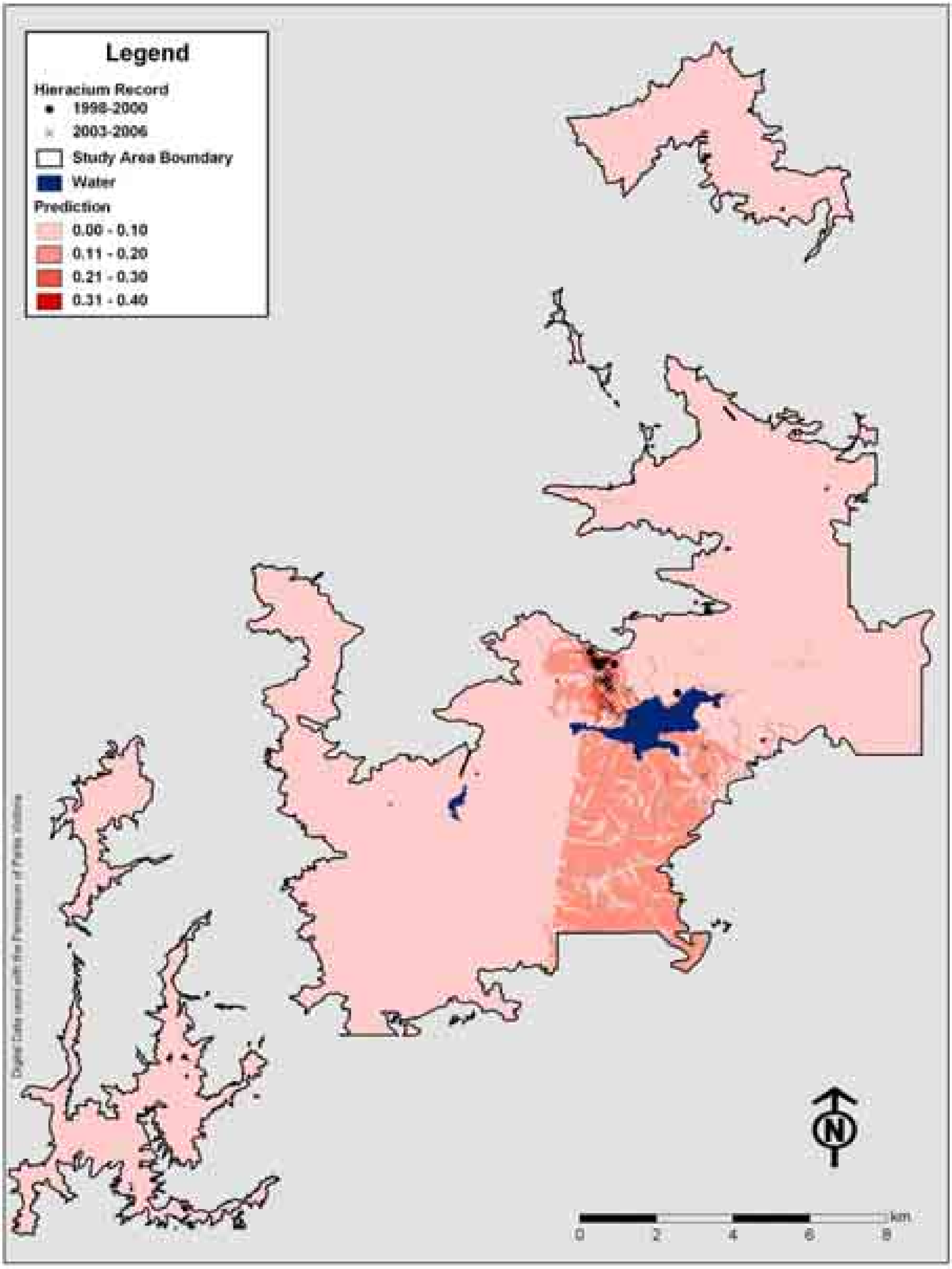


Figure 15. The relative likelihood of *H. aurantiacum* occurring on the Bogong High Plains, Victoria after 2003, and the locations where the species was recorded. The dispersal constrained HSI was modelled using the *H. aurantiacum* localities recorded prior to 2000 and wind data from 1998-2003. The accuracy of the model can be assessed by examining the locations of *H. aurantiacum* populations recorded after 2003 in relation to their predicted occurrence.

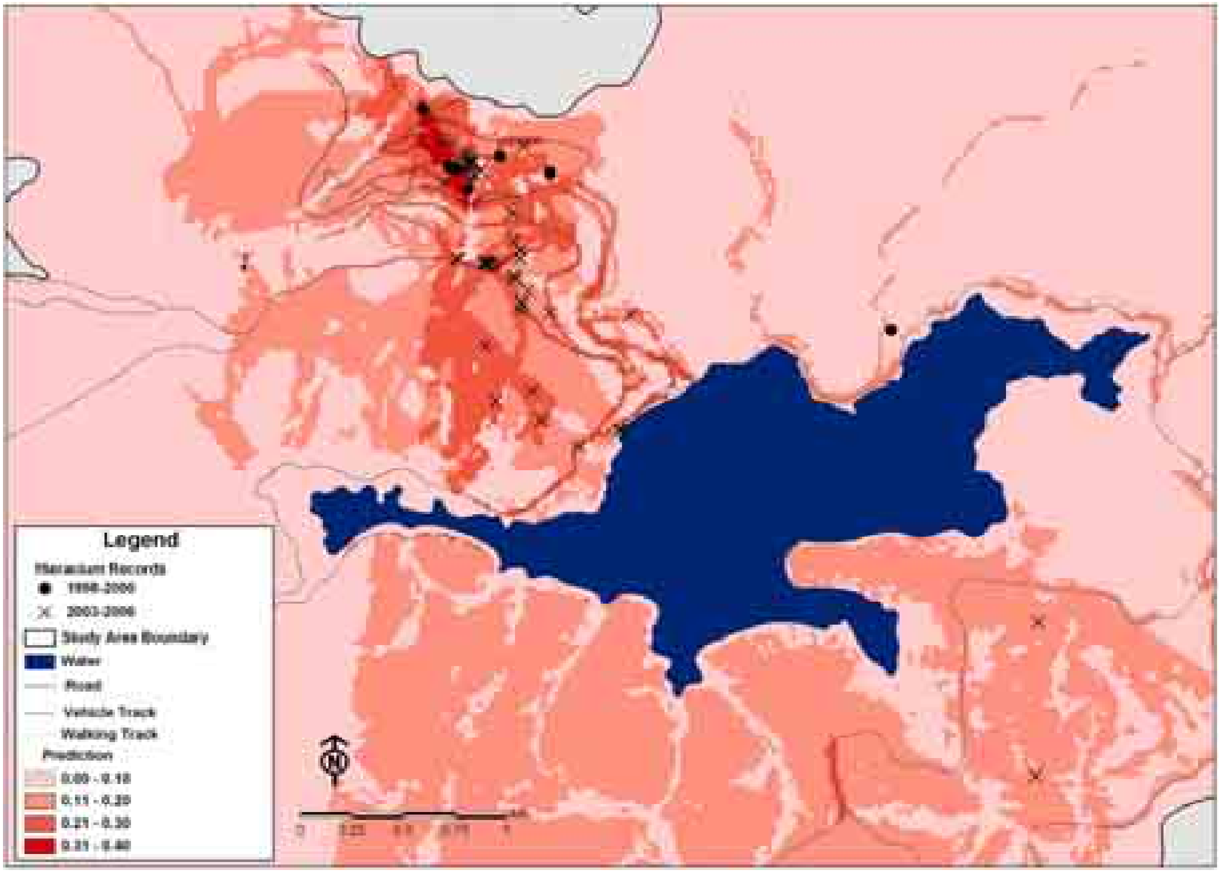


Figure 16. The relative likelihood of *H. aurantiacum* occurring in the Falls Creek-Rocky Valley area of the Bogong High Plains, Victoria after 2003, and the locations where the species was recorded. The dispersal constrained HSI was modelled using the *H. aurantiacum* localities recorded prior to 2000 and wind data from 1998-2003. The accuracy of the model can be assessed by examining the locations of *H. aurantiacum* populations recorded after 2003 in relation to their predicted occurrence.

7 DISCUSSION

7.1 Model Outcomes

We have developed a model that predicts the likelihood of *H. aurantiacum* occurring at any point on the Bogong High Plains of Victoria. The model is GIS based and combines a relatively sophisticated habitat suitability index with a phenomenological dispersal model that incorporates wind direction. We have termed the combined model, a 'dispersal constrained habitat suitability index'. It is a new approach to modelling the potential distribution of invasive species that as far as we can determine has not been used elsewhere.

The model is robust and accurate as it successfully predicted the location of *H. aurantiacum* populations recorded after December 2003 from populations recorded prior to autumn 2000. It is also of sufficient resolution (20 m x 20 m grid cells) to identify small scale variation in the environmental parameters used to construct the HSI, in particular vegetation community and disturbance level.

The habitat suitability index component of the model predicts that large areas of Bogong High Plains are suitable habitat for *H. aurantiacum.* However, the location of known populations and the predicted dispersal pattern from Falls Creek suggests that the species is currently dispersal limited. Areas predicted to have the highest probability of *H. aurantiacum* establishment are ski slopes and tussock grassland on the south side of Rocky Valley Storage in the direction of the prevailing winds. Effective control measures to limit dispersal, such as the identification and destruction of populations before they set seed, are extremely important in preventing the species from expanding its range. This report provides the framework for coordinating future search efforts. Areas predicted to have a high probability of *H. aurantiacum* establishment should be intensely searched. In the absence of control *H. aurantiacum* may colonise large areas of the Bogong High Plains.

The predicted distribution of *H. aurantiacum* highlights the importance of disturbance in the species establishment and the sensitivity of our model to the disturbance component. Ski slopes and areas along roads, tracks and aqueducts have a higher probability of *H. aurantiacum* occurrence than the surrounding landscape. Minimising current and future disturbances and rehabilitating disturbed areas will reduce the risk of *H. aurantiacum* establishment as will the continued recovery of vegetation following the 2003 fire and removal of cattle grazing.

7.2 Model limitations and potential improvements

The habitat suitability index component of the model was constructed using information in the available literature and expert knowledge. Additional or improved data could be used to further refine the model and potentially improve its accuracy. For example we have recently become aware of a GIS layer mapping the intensity of the 2003 wildfire. This could provide more accurate predictions of the distribution of *H. aurantiacum* than the fire boundary layer used, as areas where the understorey was completely removed by fire may be more susceptible to weed invasion than areas that were only scorched. In addition, the effects of fire on *Hieracium* seed and established plants are not well understood and there is the potential for additional research to improve the model.

Dispersal of seeds by wind was modelled using a phenomenological model that was made more realistic by incorporating wind direction. Although adequate for our purposes, simple phenomenological models generally do not fit the shape of observed seed dispersal kernels at all distances and strictly speaking cannot be used for localities other than that for which the model was parameterised (Skarpaas *et al.* 2004). Because wind dispersal distances are context specific and differ with wind speed, updrafts, turbulence and topography, mechanistic models that allow the accurate prediction of dispersal distances at different locations or under varying environmental conditions are increasingly being developed (Skarpaas *et al.* 2004, Nathan *et al.* 2003, Soons *et al.* 2004, Tackenberg *et al.* 2003a). These models are mathematically more complex than phenomenological models because they simulate rare long distance dispersal events by incorporating a stochastic component (Soons *et al.* 2004). Alternatively, they may require vertical wind speed data not commonly recorded by weather stations (Tackenberg 2003). Incorporating a mechanistic wind dispersal model is likely to produce more accurate predictions but was not possible given the resources and data available.

During this study we only considered dispersal of *H. aurantiacum* by wind which is thought to be the most likely and frequent dispersal vector. However, it is known that *H. aurantiacum* is also dispersed by water and by humans via attachment to socks, boots and machinery. It is suspected that the population discovered on the Heathy Spur walking track was dispersed by a bushwalker while the population at Ferntree in Tasmania is thought to mainly disperse by water flowing down slope (National Heritage Trust 2003). Modelling dispersal by water and humans was beyond the scope of this project but could be incorporated into future models if desired. Water dispersal is likely to be over relatively short distances down slope from known populations within the Falls Creek village, but human dispersal is much more difficult to predict.

8 CONCLUSIONS

We have developed a dispersal constrained habitat suitability model that successfully predicts the distribution and spread of *H. aurantiacum* on the Bogong High Plains. It is hoped that the model will enable more efficient, cost-effective management of this highly invasive species and replace current ad hoc search and control activities. The maps included in this report provide a focus for future search efforts that could also be used to further validate and test the model. Variations of this model could be developed to predict the dispersal of *H. aurantiacum* populations at Mt Buller and in Kosciuszko National Park. Similar models could also be parameterised to predict the spread of other wind dispersed weed species in alpine areas such as *Salix cinerea*.

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APPENDIX 1

Spatial data sources used as input for the habitat suitability index and the seed dispersal models

Variable	Code	Database	Source
Alpine Resort Boundary	RES	Plmmt100 AlpineResorts.shp	Parks Victoria
PV Jurisdiction	PV	Parkbound.shp	Parks Victoria
PV conservation area overlays	PVO	Parkbound_overlay.shp	Parks Victoria
Grazing	G	GrazingLicence.shp	Parks Victoria
Fire	F	Final_NE_FireBdy.shp	Parks Victoria
Vegetation	V	Alpine_Floristic_Comm.shp EVC100.shp	Parks Victoria DSE
Hieracium locations	HW	PPInfest_Hawkweed.shp PPAction_Hawkweed.shp HW_locations_Summer_2005-2006.xls Herbarium Records (MEL, and Melb.Uni.) Ecology Australia records (Carr *et al*. 2003)	Parks Victoria Parks Victoria Parks Victoria MEL, MELU Carr et al. (2003)
Wetness Index	W	BIOCLIM (Houlder et al. 2003) output modelled from Vicmap DEM- Vicmap Elevation 1:25,000 (20 m cells)	DSE
Wind profile	WIND	Hourly records from Falls Creek Weather Station (83084)	Bureau of Meteorology
Ski Runs	S	Manually digitised from aerial photograph supplied in the Ecology Australia report (Carr *et al*. 2004)	ARCUE
Urban Settlement	U	Manually digitised from aerial photograph supplied in the Ecology Australia report (Carr *et al*. 2004)	ARCUE
Water Bodies	WATER	Vicmap Hydro 1:25,000 Water Area Poly (HY_WATER_AREA_POLYGON);	DSE
Aqueducts	A	Watercourse Network 1:25,000 - Vicmap Hydro (HY_WATERCOURSE)	DSE
Huts	H	Manually digitised from Hard copy map	(MAP)
Roads	R	Vicmap Roads (ROAD25/ROAD25)	DSE
Walking tracks	T	Vicmap Roads (ROAD25/ROAD25)	DSE
DEM25		Vicmap elevation DEM25	DSE

APPENDIX 2

Buffer distances for features in the landscape associated with disturbances that may facilitate the establishment of *H. aurantiacum*, and the weighting assigned to each type of disturbance

Feature	Buffer Distance	Weighting
Main Roads	20 m	0.70
Vehicle Tracks	10 m	0.70
Walking Tracks	10 m	0.30
Aqueducts	10 m	0.70
Huts	50 m	0.30
Urban areas	50 m	0.99
Ski Runs	10 m	0.99
Grazing	0 m	0.10
Fire	0 m	0.50

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