

## **Plant Invasions in Mountains: Global Lessons for Better Management**

Authors: Keith L. McDougall, Anzar A. Khuroo, Lloyd L. Loope, Catherine G. Parks, Aníbal Pauchard, et. al.

Source: Mountain Research and Development, 31(4) : 380-387

Published By: International Mountain Society

URL: <https://doi.org/10.1659/MRD-JOURNAL-D-11-00082.1>

---

BioOne Complete ([complete.BioOne.org](https://complete.BioOne.org)) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at [www.bioone.org/terms-o-use](https://www.bioone.org/terms-o-use).

Usage of BioOne Complete content is strictly limited to personal, educational, and non - commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

---

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

# Plant Invasions in Mountains: Global Lessons for Better Management

Keith L. McDougall<sup>1\*</sup>, Anzar A. Khuroo<sup>2</sup>, Lloyd L. Loope<sup>3</sup>, Catherine G. Parks<sup>4</sup>, Aníbal Pauchard<sup>5</sup>, Zafar A. Reshi<sup>2</sup>, Ian Rushworth<sup>6</sup>, and Christoph Kueffer<sup>7</sup>

\* Corresponding author: keith.mcdougall@environment.nsw.gov.au

<sup>1</sup> Office of Environment and Heritage, PO Box 733, Queanbeyan, NSW, 2620, Australia

<sup>2</sup> Department of Botany, Centre for Biodiversity and Taxonomy, University of Kashmir, Srinagar – 190 006, Jammu and Kashmir, India

<sup>3</sup> Pacific Island Ecosystems Research Center, U.S. Geological Survey, Makawao, Hawaii, USA

<sup>4</sup> Pacific Northwest Research Station, US Forest Service, 1401 Gekeler Lane, La Grande, OR 97850, USA

<sup>5</sup> Facultad de Ciencias Forestales, Universidad de Concepción, Casilla 160-C, Concepción, Chile and Institute of Ecology and Biodiversity, Santiago, Chile

<sup>6</sup> Ezemvelo KZN Wildlife, PO Box 13053, Cascades 3202, South Africa

<sup>7</sup> Institute of Integrative Biology – Plant Ecology, ETH Zentrum, Universitätsstrasse 16, CHN, CH-8092 Zurich, Switzerland

Open access article: please credit the authors and the full source.

Mountains are one of few ecosystems little affected by plant invasions. However, the threat of invasion is likely to increase because of climate change, greater anthropogenic land use, and continuing novel introductions. Preventive management, therefore, will be crucial but can be difficult to promote when more pressing problems are unresolved and predictions are uncertain. In this essay, we use management case studies from 7 mountain regions to identify common lessons for effective preventive action. The degree of plant invasion in mountains was variable in the 7 regions as was the response to invasion, which ranged from lack of awareness by land managers of the potential impact in Chile and Kashmir to well-organized programs of prevention and containment in the United States (Hawaii and the Pacific Northwest), including prevention at low altitude. In Australia, awareness of the threat grew only after disruptive invasions. In South Africa, the economic benefits of removing alien plants are well recognized and funded in the form of employment programs. In the European Alps, there is little need for active management because no invasive species pose an immediate threat. From these case studies, we identify lessons for management of plant invasions in mountain ecosystems: (i) prevention is especially important in mountains because of their rugged terrain, where invasions can quickly become unmanageable; (ii) networks at local to global levels can assist with awareness raising and better prioritization of

management actions; (iii) the economic importance of management should be identified and articulated; (iv) public acceptance of management programs will make them more effective; and (v) climate change needs to be considered. We suggest that comparisons of local case studies, such as those we have presented, have a pivotal place in the proactive solution of global change issues.

**Keywords:** Biosecurity; climate change; cross-scale learning; invasive alien plants; prevention.

**Reviewed by the Editors:** September 2011

**Accepted:** September 2011

## Introduction

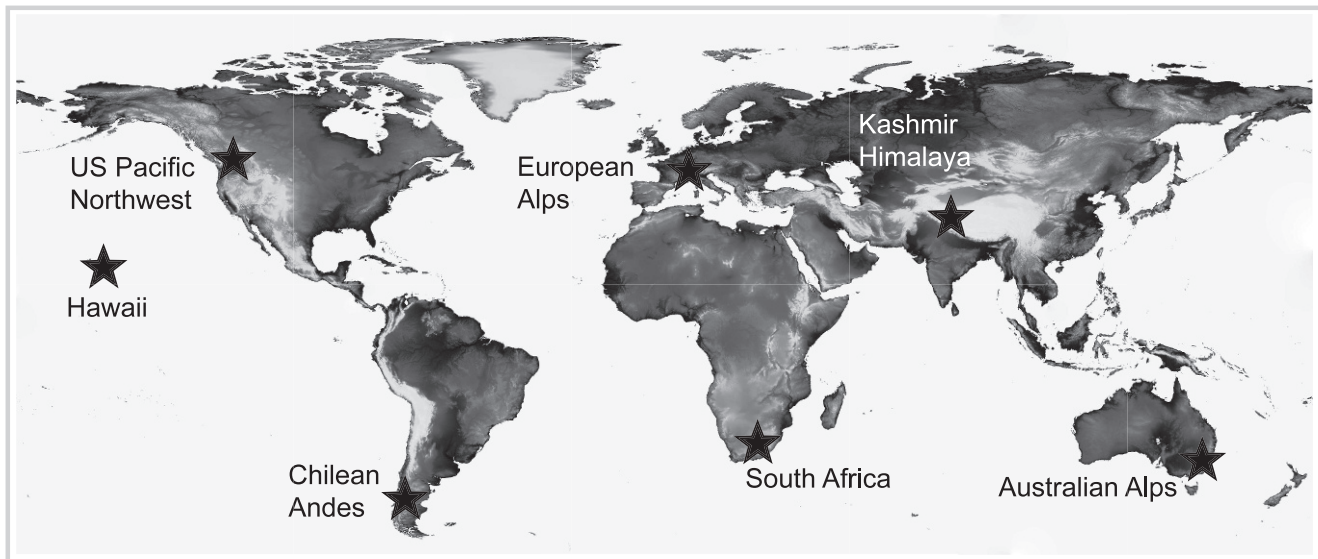
Mountain ecosystems are generally less invaded than surrounding lowland ecosystems, and many mountains have few invasive plant species (McDougall et al 2011). However, mountains may only be less invaded because most past alien plant introductions happened in the lowlands, and few potential invaders of mountain ecosystems managed to spread along steep climate gradients to high elevations (Alexander et al 2011). Indeed, the few alien species that have caused environmental damage in mountains have established relatively recently, and an increased invasion risk and management challenge may be

expected in the near future because of climate change and greater anthropogenic land use (Pauchard et al 2009). The response of land managers to this emerging threat is of great importance because mountains are hotspots for biodiversity, the source of lowland water, and treasured landscapes for tourism and recreation.

Mountains are one of only a few ecosystems where a proactive management strategy may still be possible. However, it can be difficult to convince decision-makers and stakeholders to invest in preventing future but not yet visible problems while current pressing problems are unresolved. In addition, early responses to plant invasion are inherently difficult to implement because they rely on uncertain predictions of future outcomes (Harremoës et al 2002). One way to circumvent these problems is to build on experience elsewhere and learn from comparisons of multiple management case studies. Mountains are especially suitable for such global learning because they are characterized by similar climatic, topographic, geomorphological, and ecological characteristics regardless of their surrounding lowlands, and these similarities enable meaningful comparisons for common learning.

Here, we review the progress and challenges of plant invasion management by using a global scope and a local perspective. We analyze 7

FIGURE 1 Location of the 7 mountain regions. (Map by Karsten Rohweder)



mountain regions, from different climate zones, both developing and developed countries and spread over 6 continents, Australian Alps, Chilean Andes, Kashmir Himalaya, South Africa, European Alps, US Pacific Northwest, and Hawaii (Figure 1), to identify common lessons for effective preventive action in mountain ecosystems. We describe each case study to illustrate the diversity of management situations and then present a number of general conclusions drawn by the authors representing all study regions. Although the focus of this article is the environmental cost of alien plant invasions, we highlight the social benefits of alien plants in some mountain regions and the management conflicts that may arise as a result of competing values. The management of alien species invasions in mountains is a test case for proactive invasive species management in less invaded ecosystems in general.

## Plant invasions and management responses

### No active management

*European Alps:* Although there are almost 500 alien vascular plants in the European Alps (Kueffer 2010a), most are associated with transport

corridors (eg Becker et al 2005), few reach high elevations, and none are currently presumed to threaten biodiversity at these high elevations (Kueffer 2010a). However, the number of recorded alien plants is rapidly increasing in Europe (Pyšek et al 2009) and probably also in the European Alps. Species distribution models for the European Alps predict an upward movement of alien plants into the alpine zone with climate change (Petitpierre et al 2010). There currently is no active management of alien plants in the European Alps and little perceived need for on-ground measures. Awareness is slowly being built in management and policy agencies of this emerging threat in response to calls from researchers, and a list of potential invaders of mountain areas has been compiled by using a global database of mountain invasive species (Kueffer 2010a). Future invasive species management in the European Alps may be guided by policy bodies such as the Alpine Network of Protected Areas (<http://www.alparc.org/>) and scientific projects such as ECONNECT (<http://www.econnectproject.eu/cms/>), which represent the necessary capacity for cross-national and cross-regional collaborations.

### Management focus on species of economic importance

*Chilean Andes:* Chilean mountains harbor many alien species (Pauchard and Alaback 2004), some of which are likely to have an adverse impact on environmental values (eg *Pinus contorta*; Langdon et al 2010). However, there has been minimal management of plant invasions in these mountain ecosystems, possibly because the impacts are not overtly economic. In general, the focus of management of alien plants remains in agricultural systems, where border control, early detection, and rapid response are key strategies. Awareness of the threat from alien species in natural systems is growing, as evidenced by new laws proposed for protection of the Chilean Protected Areas System (Pauchard et al 2011) and the creation of the Laboratory of Biological Invasions, which promotes dialogue between academia, government, and private agencies to better deal with invasive plant species in natural areas.

*Kashmir Himalaya:* Over the last decade, research in the Kashmir Himalaya has highlighted the taxonomic composition of invasive alien flora, invasion pathways and vectors, anthropogenic drivers of

invasions, impacts of already invading plants, and optimal management (eg Khuroo et al 2007; Khuroo et al 2008; Reshi et al 2008). Despite this, management of plant invasions has largely been ad hoc and mostly directed toward costly containment of infestations of agriculture, horticulture, and freshwater lakes. There is no management framework with legal and regulatory measures that relate to plant invasions in natural ecosystems and apparently little awareness that invasive species are a serious threat to the natural environment. Manual and mechanical eradication of aquatic invasive plants (eg *Azolla* sp) in montane freshwater lakes has been ineffective because of poor follow-up action. However, this program has benefits beyond biodiversity because of local community support. For example, mechanical removal of invasive plants in Dal and Wular lakes can benefit tourism and provide fodder to locals, and the manual eradication programs provide daily wage-based employment. Manual eradication of invasive plants (eg *Anthemis cotula*, *Centaurea iberica*) in orchards, recreation areas, and low montane zone grasslands incurs heavy costs for the general public and government agencies. Invasion of *Leucanthemum vulgare* and *Sambucus wightiana* in forest areas and subalpine and alpine meadows is posing a serious threat to these natural ecosystems.

#### Management focus on species of environmental threat

**Australian Alps:** In the 20th century, the threat of plant invasion in Australian high mountain areas was regarded as low because of a climatic barrier (Costin 1954). Therefore, management focused on the control of alien species required under legislation, many of which were species of agricultural importance. Although plans of management provided legislative support for control of alien species in natural

vegetation, few species were deemed to warrant such attention (exceptions being *Cytisus scoparius* and *Rubus* spp).

In the past decade, invasion by 2 *Hieracium* spp (*Hieracium aurantiacum* and *Hieracium praealtum*) has led to a sudden increase in awareness of the threat of alien species to natural mountain values and the realization that mountains are not invulnerable to destructive invasion because of their colder climate. The scale of the threat was largely determined from assessments of threat in other mountain regions, which have proven to be accurate (McDougall et al 2005). Costly eradication programs are underway but have been challenging partly because these species have established in rugged terrain with poor accessibility.

The choice of control measure had to be determined largely by trial and error. The importance of the eradication programs has been promoted in brochures and newspaper articles. This has aided public acceptance of the program cost and minor disruptions to visitor movement because of quarantine closures. It also has led to the early detection of new infestations and increased the likelihood of eradication. The investment in control and eradication has increased dramatically over the past decade, but new incursions continue to be detected. One recent incursion, *Leucanthemum vulgare*, has spread rapidly and will test the capacity of managers to deal with plant invasions in Australian mountains.

**Hawaii:** The high vulnerability of Hawaii to invasions was obvious long ago, and awareness of the severity and importance of preventing invasions has been high since the 1980s. Despite this, the scale of the problem threatens to overwhelm the considerable biodiversity that remains, given that large prevention and response gaps remain (Kueffer and Loope 2009). The greatest weakness is that, in spite of creative and somewhat effective grass-roots

interagency efforts at early detection and rapid response, new alien plant species still are introduced to the Hawaiian Islands at a high rate with little regard for their potential invasiveness (Kraus and Duffy 2010). Nevertheless, Hawaii's 2 large mountain national parks (NP), Hawaii Volcanoes on the island of Hawaii and Haleakala on the island of Maui, are relative strongholds against wholesale invasion of high-elevation areas.

Hawaii Volcanoes NP has demonstrated the effectiveness of early detection and response in high-value areas within the boundaries of the reserve for more than 20 years (Kueffer and Loope 2009). The Maui Invasive Species Committee is an effective interagency mechanism partnering with Haleakala NP with the aim of stopping the spread of alien species to high elevations through early detection, eradication, and containment. The small size of the island of Maui (1894 km<sup>2</sup>) makes this aim more feasible than in most mountain regions.

Three alien species present on Maui but not widespread in Haleakala NP, *Verbascum thapsus*, *Pennisetum setaceum*, and *Cortaderia jubata*, were taken on as targets by Maui Invasive Species Committee in 1999. Eradication efforts for *V. thapsus* and *P. setaceum* are currently ongoing on Maui. Unfortunately, the achievable island-wide level of control for *C. jubata*, after 10 years of effort, is containment. Most of the work on this species is at a relatively high elevation (1500–2000 m) near Haleakala NP. The park has contributed generously to funding Maui Invasive Species Committee's program at a lower elevation outside the park and has continued surveillance and removal of *C. jubata* as needed within the park, given that habitat up to 3000 m is vulnerable. Early detection surveys are being conducted for other potential invaders of upper Haleakala volcano based on their distribution and impact in similar habitat elsewhere.



*South Africa:* The protracted use of South African mountains for agriculture and village development has led to a substantial alien flora at mid-elevations. Management of these invasions has been carefully formulated through economic analysis of the costs and benefits of removal (van Wilgen et al 1997). The benefits of removal of woody species include increased water production for arid lowland areas (Le Maitre et al 2002) and reduced fire risk (Richardson and van Wilgen 2004). Costs of management (eg loss of food, fuel, and building material sources for local populations; Shackleton et al 2007) have been offset by employment programs that provide economic stimulus to mountain communities. Much of the management of alien plants in South Africa, therefore, has its roots in direct economic benefit rather than conservation outcomes, although the two are closely linked.

The focus of management has been largely on mechanical removal of established alien woody species such as *Pinus* spp, *Acacia* spp, and *Hakea* spp. A small proportion of the budget has been allocated to biological control, but there has been resistance to biological control research for species (or those with close relatives) of commercial interest. For instance, despite cost-benefit studies that demonstrate the net advantage of introducing seed-feeding weevils for controlling the spread of Australian *Acacia* spp, the program has encountered resistance from industry, and implementation has been slow. In KwaZulu-Natal Province, a few “emerging weeds” teams have been established to deal with new threats (eg pompom weed *Campuloclinium macrocephalum*) and an emerging aliens database is being developed to raise awareness of new threats and provide management guidance. Ezemvelo KZN Wildlife, the provincial conservation agency for the province of KwaZulu-Natal, has developed and uses a spreadsheet-based prioritization

system that considers multiple criteria for the allocation of resources between protected areas.

*US Pacific Northwest:* High mountains in the US Pacific Northwest have a long history of land use and have experienced plant invasions for more than a century (Parks et al 2005). Until the 1980s, management of invasive plants focused on control of species perceived to be a threat (eg *Cirsium arvense* and *Euphorbia esula* in Rocky Mountains NP; US Department of the Interior 2003). Little attention was paid to prevention, early detection, prioritization, or monitoring until the development of formal management plans (eg Yellowstone NP in 1986 [National Park Service 1986], Rocky Mountains NP in 2003 [US Department of the Interior 2003]). Government agencies that manage land in the Pacific Northwest now use the principles of integrated pest management to deal with their invasive plants. That is, they make decisions about management based on knowledge of invasive species biology, the environment, and cost-effective and minimal-risk techniques. Techniques are applied on a case-by-case basis but include biological control, herbicide application, burning, prescribed grazing, and pulling by hand. Preventive measures include a certified weed-free forage program to prevent people who use stock animals for recreational riding or hunting from bringing invasive plant infested hay into mountain areas.

A partner program strives to reduce invasive plant spread associated with road development and maintenance by using gravel pit inspection standards. A database maintained by the University of Montana (<http://invader.dbs.umt.edu>) provides temporal and spatial data on invasive species to management agencies for proactive decision making about current and future threats. Small programs run by local cooperative weed management

groups offer a monetary reward for public citizens who report a new infestation of a plant of exceptional concern.

## Five lessons for better management of plant invasions in mountains

### 1) Prevention is especially important in mountains

Prevention of invasions is well recognized as more cost effective than later cure (eg Leung et al 2002). The cost-effectiveness of prevention in mountains is far greater than usual because their rugged terrain and remoteness make containment and eradication especially costly and difficult. Despite this, preventive measures were only explicit in 2 regions (Hawaii and the US Pacific Northwest). We suspect that the lack of prevention relates to (1) budgets being stretched by major incursions (eg Australia), (2) lack of awareness of the threat (eg Europe, Chile), and (3) the inherent difficulty of raising awareness for and implementation of proactive measures against future threats. Preventive measures are nonetheless critical and may often be cheap. They include control of potentially invasive plants outside of mountain conservation areas (especially in the adjacent lowlands), prediction by using climate matching, targeting major introduction pathways, staff training, and outreach to visitors. The development of local management strategies and cooperative capacity between land management agencies will be beneficial for creating the structures necessary to prevent invasions and for dealing with them if they penetrate the preventive measures.

A thorough understanding of introduction pathways of alien plants to mountains and how they might change in the future (Kueffer 2010b) is critical for the development of effective preventive measures. In the past, the vast majority of alien species

in mountains entered through a lowland introduction pathway (Alexander et al 2011); that is, they were selected from the pool of alien species that established in surrounding lowland areas and invaded primarily along transport corridors. Unlike lowland areas where transport links are numerous, most mountain areas have few links between lowland and mountain. This means that preventive action can be better focused in mountains.

In developing preventive strategies, managers should first search in the pool of alien species in surrounding lowlands for potential mountain invasive species. Once these potential threats have been identified, they should be treated in the lowlands. A small investment into lowland containment, especially on transport corridors between lowlands and mountains, has the potential to protect mountain areas from future environmental and economic damage. More transport corridors will be created as mountains face increasing pressure from tourism. Managers should be aware that these are corridors for both tourists and invasive plants. Preventive measures to reduce the risk of invasion along new transport corridors include the use of clean fill and vehicle wash-down during construction, vigilance for early detection after construction, and the provision of information to users of mountain areas about hygiene (eg cleaning vehicles and clothing). The invasive species strategy of Haleakala NP in Hawaii, which focuses on prevention of new introductions to the islands and containment and eradication of established alien species at low elevations, is a good example of how a preventive approach for mountain regions can be expanded into the surrounding lowlands (Kueffer and Loope 2009).

In the future, alien plants may increasingly be deliberately introduced to mountains (eg for amenity planting and soil stabilization). These species are not

filtered along climatic gradients and are likely to be well adapted to mountain environments. The few examples of such direct introductions have already proven to be particularly invasive in mountains (McDougall et al 2011). To prevent emerging risks, managers can look to other mountains for potentially invasive species and establish a risk assessment system to prioritize future and current threats (McDougall et al 2011). A global database of mountain alien plants prepared by the Mountain Invasion Research Network (<http://www.miren.ethz.ch/>) will aid the search but should be complemented with risk analysis tools (Gordon et al 2008).

## **2) Connecting mountain managers at local to global scales**

Management of invasive plants in the 7 regions occurred when researchers, managers, and funding bodies recognized the threat that they posed. The lack of awareness of a threat was either because there was no local evidence of a threat (eg Europe), the mountains were thought to be largely invulnerable to invasion (eg Australia), or there was insufficient information about the threat, even though it was present (eg Chile). In the case of Australia, awareness of the scale of the threat did not occur until a disruptive invasion was detected. Management approaches are more advanced in areas with a general high awareness of the invasion threat and established links between lowland and mountain conservation managers through federal programs or institutions (Hawaii, South Africa, US Pacific Northwest) or thanks to a small land area (Hawaii).

The nature of mountains, typically, isolated protrusions in a large, densely populated lowland landscape, has led to the formation of mountain-specific information, research, and advocacy networks at regional levels (eg Alpine Network of Protected Areas in Europe, Australian Alps Liaison Committee

[<http://www.australianalps.environment.gov.au/>], Consorcio para el Desarrollo Sostenible de la Eco-región Andina [<http://www.condesan.org/portal/>]) and global levels (eg Global Mountain Biodiversity Assessment [<http://gmba.unibas.ch/index/index.htm>], International Centre for Integrated Mountain Development [<http://www.icimod.org/>], Mountain Forum [<http://www.mtnforum.org/>], Mountain Research Initiative [<http://mri.scnatweb.ch/>], Mountain Invasion Research Network). If these can be harnessed to promote best practice management of alien plant species, we believe that invasive species will be easier to deal with in mountains than in many other ecosystems. Many of these bodies already function well in areas where management awareness is high. Global bodies might, however, play a pivotal role in prevention of plant invasions in mountains by (1) raising awareness in regions where there is currently little active management, and (2) fostering links between land managers and nongovernment organizations, which will be especially valuable in developing regions (eg McDougall et al 2009).

## **3) The costs and benefits of management should be identified**

In mountain regions of the developing world, management occurred in response to economic expedient. In Kashmir and Chile, species of economic importance are controlled but those causing environmental damage are seldom addressed. In South Africa, there is considerable overlap between species of economic and environmental importance. Here the economic benefits from invasive species management outweigh the societal costs. Although labor is commonly seen as a cost, in South Africa (and other developing countries) payment of salaries has societal benefit. Methods are deliberately labor intensive, and capacity building is integral. As the South African

example shows, environmental benefits can flow from control programs that have economic motives. However, this may not always be the case (eg Kull et al 2007), and there will be pressure in many places for the deliberate introduction of alien plants for economic development (eg Roder et al 2007). In developing countries, therefore, research into the economic costs and impacts on ecosystem services associated with current and future invasions may be more valuable initially than research into other aspects of plant invasion.

Importantly, the South African example shows that there are direct benefits to lowland areas from management of invasive plants in mountains. The benefits, however, are not confined to developing mountain regions. Mountains provide valuable ecosystem services in all regions (eg landscape aesthetics for tourism, water production for lowland agriculture, and protection against natural hazards, such as avalanche and fire). The impacts of invasive species on ecosystem services should be better articulated in developed mountain regions to enable greater societal and financial support for preventive management. In all mountain regions, it will be important to prioritize actions to ensure the most efficient use of limited funds for natural resource management.

#### **4) Public acceptance of management programs will make them more effective**

Management programs related to plant invasions will be most successful when integrated with the livelihood of people who live or work in mountains, or are otherwise dependent on mountain ecosystem services. For example, in South Africa, despite many invasive species having economic value, there has been acceptance of programs because of their benefit in providing employment and water supply. Utility also is important in the

Kashmir Himalaya where invasive plants removed from montane lakes are used as fodder and those removed from forests and meadows help increase timber production, livestock rearing, and tourist use.

Societal support has been important for the removal of potential source populations in ski resorts in Australia (Ben Derrick, Falls Creek Resort Management, pers. comm.), the selection of control procedures in Rocky Mountains NP (US Department of the Interior 2003), and off-reserve containment of invasive species in Hawaii (Loope 1992). Public awareness of the threat of invasion and the cost of management also can aid in the detection of new incursions (as has happened in Australia) and improved hygiene (eg by trail riders in the US Pacific Northwest). The economic and ecological benefits that flow to the lowlands from the mountains need to be shared with mountain dwellers as has happened in South Africa. This will lead to better socioeconomic conditions for people in mountains, who will then have a stake in the management programs that protect mountain ecosystems from plant invasions.

#### **5) Climate change will change the rules of the game in mountains**

Because of their steep environmental and climatic gradients, mountains are recognized as being especially sensitive to climate change (Beniston 2003). The threat from invasive species in mountains is expected to markedly increase because of climate change (eg Pickering et al 2008; Petitpierre et al 2010), making effective preventive management, as recommended in this essay, especially timely. However, species movements will not necessarily be upward. The potential distribution of *Hieracium* spp in Australia, for instance, was modeled to contract under climate change scenarios (Beaumont et al 2009), and, in Hawaii, water availability (precipitation and evapotranspiration) seems to be more

important than temperature in limiting alien species at high elevation (Jakobs et al 2010; Juvik et al 2011).

Climate change may also alter the composition of the invasive flora. For instance, the increase in atmospheric CO<sub>2</sub> is likely to make woody plants more competitive in grassland systems that evolved under low CO<sub>2</sub> levels (eg Kgope et al 2010). Many of the current invaders of montane grasslands in South Africa are woody species, so it is assumed that these will become more invasive in an environment richer in atmospheric carbon. It is essential that climate change scenarios be factored into predictive models so that managers can target alien species of greatest future risk to mountains. A shift in native species distribution because of climate change may also present challenges to land managers. That is, managers will have to decide whether to treat such newcomers as native or alien. Movement of native plant species to higher elevations in mountains has already been noted in Australia, Europe, and South Africa (McDougall and Broome 2007; Lenoir et al 2008; Rushworth pers. obs.), although it is uncertain if only climate change is responsible for the shifts because transport corridors appear to have aided the spread. There is an urgent need for greater discussion of the appropriate management response to native plant expansions into mountain ecosystems.

#### **Conclusions**

Mountains represent a special case in invasive species management. The invasion risk in mountains may be less than in many other ecosystems because of climatic filters, but, once invasions do occur, invasive species quickly become unmanageable because of the rugged terrain and inaccessibility of mountain landscapes. Mountains are especially important for their biodiversity and aesthetic properties, but, as the South African example showed, they typically have immense economic



value as water sources for lowland agricultural systems. Treating alien species invasions in mountains and preventing further invasion, therefore, may result in tangible economic benefits.

In this essay, we have shown that the degree of plant invasion in mountains is variable worldwide, but it is clear that mountain ecosystems are vulnerable to invasion. Managers of mountains with few invasive species, therefore, have a unique opportunity to take cost effective, preventive action. However, the need for prevention is urgent because climate change and increased anthropogenic use of mountains will increase the threat from invasive species. Preventive measures are numerous (as described above) but will be most effective if done with the support of local stakeholders and commenced in the adjoining lowlands. Information sharing at local and global levels can be beneficial to managers in particular to build awareness in regions where there are currently no preventive measures. Advocacy by research institutions and the global conservation community through interlinking invasive species and mountain management networks from regional to global scales can aid in this task. We suggest that comparisons of local case studies, such as those presented here, have a pivotal place in the proactive solution of global change issues.

## ACKNOWLEDGMENTS

The article builds on ideas from and discussion among members of the Mountain Invasion Research Network Consortium (<http://www.miren.ethz.ch/people/index.html>). Karsten Rohweder (ETHZ) kindly produced Figure 1. Aníbal Pauchard received funding from Programa de Fondos Basales, CONICYT, PFB-23, and Iniciativa Científica Milenio, ICM P05-002.

## REFERENCES

- Alexander JM, Kueffer C, Daehler CC, Edwards PJ, Pauchard A, Seipel T, MIREN consortium. 2011. Assembly of non-native floras along elevational gradients explained by directional ecological filtering. *Proceedings of the National Academy of Sciences* 108:656–661.
- Beaumont LJ, Gallagher RV, Thuiller W, Downey PO, Leishman MR, Hughes L. 2009. Different climatic envelopes among invasive populations may lead to underestimations of current and future biological invasions. *Diversity and Distributions* 15: 409–420.
- Becker T, Dietz H, Billeter R, Buschmann H, Edwards PJ. 2005. Altitudinal distribution of alien plant species in the Swiss Alps. *Perspectives in Plant Ecology, Evolution and Systematics* 7:173–183.
- Beniston M. 2003. Climatic change in mountain regions: a review of possible impacts. *Climatic Change* 59:5–31.
- Costin AB. 1954. *A Study of the Ecosystems of the Monaro Region of New South Wales*. Sydney, Australia: Government Printer.
- Gordon DR, Onderdonk DA, Fox AM, Stocker RK. 2008. Consistent accuracy of the Australian weed risk assessment system across varied geographies. *Diversity and Distributions* 14:234–242.
- Harremoës P, Gee D, MacGarvin M, Stirling A, Keys J, Wynne B, Guedes Vaz S. 2002. *Late Lessons From Early Warnings: The Precautionary Principle 1896–2000*. Environmental Issue Report Number 22. Copenhagen, Denmark: European Environment Agency.
- Jakobs G, Kueffer C, Daehler CC. 2010. Introduced weed richness across altitudinal gradients in Hawaii: humps, humans and water-energy dynamics. *Biological Invasions* 12:4019–4031.
- Juvik JO, Rodomsky BT, Price JP, Hansen EW, Kueffer C. 2011. “The upper limits of vegetation on Mauna Loa, Hawaii”: A fiftieth-anniversary reassessment. *Ecology* 92:518–525.
- Kgope BS, Bond WJ, Midgley GF. 2010. Growth responses of African savanna trees implicate atmospheric [CO<sub>2</sub>] as a driver of past and current changes in savanna tree cover. *Austral Ecology* 35: 451–463.
- Khuroo AA, Rashid I, Reshi Z, Dar GH, Wafai BA. 2007. The alien flora of Kashmir Himalaya. *Biological Invasions* 9:269–292.
- Khuroo AA, Reshi Z, Rashid I, Dar GH, Khan ZS. 2008. Operational characterization of alien invasive flora and its management implications. *Biodiversity and Conservation* 17:3181–3194.
- Kraus F, Duffy DC. 2010. A successful model from Hawaii for rapid response to invasive species. *Journal for Nature Conservation* 18:135–141.
- Kueffer C. 2010a. Alien plants in the Alps: Status and future invasion risks. In: Price MF, editor. *Europe’s Ecological Backbone: Recognising the True Value of Our Mountains*. Copenhagen, Denmark: European Environment Agency, pp 153–154.
- Kueffer C. 2010b. Transdisciplinary research is needed to predict plant invasions in an era of global change. *Trends in Ecology and Evolution* 25:619–620.
- Kueffer C, Loope L. 2009. *Prevention, Early Detection and Containment of Invasive, Non-native Plants in the Hawaiian Islands: Current Efforts and Needs: A Report Based on a Symposium and Workshop Held at the 2008 Hawaii Conservation Conference in Honolulu*. Technical Report No. 166. Honolulu, HI: Pacific Cooperative Studies Unit, University of Hawaii at Manoa. [www.botany.hawaii.edu/faculty/duffy/techr/166/](http://www.botany.hawaii.edu/faculty/duffy/techr/166/); accessed on 3 September 2011.
- Kull CA, Tassin J, Rangan H. 2007. Multifunctional, scrubby, and invasive forests? Wattles in the highlands of Madagascar. *Mountain Research and Development* 27:224–231.
- Langdon B, Pauchard A, Aguayo M. 2010. *Pinus contorta* invasion in the Chilean Patagonia: Local patterns in a global context. *Biological Invasions* 12:3961–3971.
- Le Maître DC, van Wilgen BW, Gelderblom CM, Bailey C, Chapman RA, Nel JA. 2002. Invasive alien trees and water resources in South Africa: Case studies of the costs and benefits of management. *Forest Ecology and Management* 160:143–159.
- Lenoir J, Gégout JC, Marquet PA, de Ruffray P, Brisse H. 2008. A significant upward shift in plant species optimum elevation during the 20th century. *Science* 320:1768–1771.
- Leung B, Lodge DM, Finnoff D, Shogren JF, Lewis MA, Lamberti G. 2002. An ounce of prevention or a pound of cure: Bioeconomic risk analysis of invasive species. *Proceedings of the Royal Society of London Series B* 269:2407–2413.
- Loope LL. 1992. An overview of problems with introduced plant species in national parks and biosphere reserves of the United States. In: Stone CP, Smith CW, Tunison JT, editors. *Alien Plant Invasions in Native Ecosystems of Hawai’i: Management and Research*. Manoa, HI: Cooperative National Park Resources Studies Unit, University of Hawaii, pp 3–28.
- McDougall KL, Alexander JM, Haider S, Pauchard A, Walsh NG, Kueffer C. 2011. Alien flora of mountains: Global comparisons for the development of local preventive measures against plant invasions. *Diversity and Distributions* 17: 103–111.
- McDougall KL, Broome LS. 2007. Challenges facing protected area planning in the Australian Alps in a changing climate. In: Taylor M, Figgis P, editors. *Protected Areas: Buffering Nature Against Climate Change*. Proceedings of a WWF Australia and IUCN World Commission on Protected Areas symposium, Canberra 18–19 June 2007. Sydney, Australia: WWF Australia, pp 73–84.
- McDougall KL, Haider S, Seipel T, Kueffer C, MIREN Consortium. 2009. Spread of non-native plant species into mountains: Now is the time to act. *Mountain Forum Bulletin* 9(2):23–25.
- McDougall KL, Morgan JW, Walsh NG, Williams RJ. 2005. Plant invasions in treeless vegetation of the Australian Alps. *Perspectives in Plant Ecology, Evolution and Systematics* 7:159–171.
- National Park Service. 1986. *Exotic Vegetation Management Plan*. Yellowstone National Park, WY: National Park Service.
- Parks CG, Radosevich SR, Endress BA, Anzinger D, Rew LJ, Maxwell BD, Dwire KA, Naylor BJ. 2005. Natural and land use history of northwest mountain ecoregions (USA) in relation to patterns of plant invasion. *Perspectives in Plant Ecology, Evolution and Systematics* 7:137–148.
- Pauchard A, Alaback PB. 2004. Influence of elevation, land use, and landscape context on patterns of alien plant invasions along roadsides in protected areas of south-central Chile. *Conservation Biology* 18:238–248.
- Pauchard A, García RA, Langdon B, Fuentes N. 2011. The invasion of non-native plants in Chile and their impacts on biodiversity: History, current status, and challenges for management. In: Figueroa E, editor. *Successful and Failed Experiences in Biodiversity Conservation: Lessons and Policy Recommendations from the American Continent*. Santiago, Chile: Editorial Universitaria, pp 133–166.
- Pauchard A, Kueffer C, Dietz H, Daehler CC, Alexander J, Edwards PJ, Arévalo JR, Cavieres L, Guisan A, Haider S, Jakobs G, McDougall KL, Millar CI, Naylor BJ, Parks CG, et al. 2009. Ain’t no mountain high enough: Plant invasions reaching high elevations. *Frontiers in Ecology and the Environment* 7:479–486.



- Petitpierre B, Kueffer C, Seipel T, Guisan A.** 2010. Will the risk of plant invasions into the European Alps increase with climate change? *In*: Kollmann J, van Mölken T, Ravn HP, editors. *Biological Invasions in a Changing World—From Science to Management*. Neobiota Book of Abstracts. Copenhagen, Denmark: Department of Agriculture and Ecology, University of Copenhagen, p 7.
- Pickering CP, Hill W, Green K.** 2008. Vascular plant diversity and climate change in the alpine zone of the Snowy Mountains, Australia. *Biodiversity and Conservation* 17:1627–1644.
- Pyšek P, Lambdon PW, Arianoutsou M, Kühn I, Pino J, Winter M.** 2009. Alien vascular plants of Europe. *In*: Hulme PE, Nentwig W, Pyšek P, Vilà M, editors. *Handbook of Alien Species in Europe*. Dordrecht, Netherlands: Springer, pp 43–61.
- Reshi Z, Rashid I, Khuroo AA, Wafai BA.** 2008. Effect of invasion by *Centaurea iberica* on community assembly of a mountain grassland of Kashmir Himalaya, India. *Tropical Ecology* 49:147–156.
- Richardson DM, van Wilgen BW.** 2004. Invasive alien plants in South Africa: How well do we understand the ecological impacts? *South African Journal of Science* 100:45–52.
- Roder W, Dorji K, Wangdi K.** 2007. Implications of white clover introduction in East Himalayan grasslands. *Mountain Research and Development* 27:268–273.
- Shackleton CM, McGarry D, Fourie S, Gambiza J, Shackleton SE, Fabricius C.** 2007. Assessing the effects of invasive alien species on rural livelihoods: case examples and a framework from South Africa. *Human Ecology* 35:113–127.
- US Department of the Interior.** 2003. *Invasive Exotic Plant Management Plan and Environmental Assessment*. Rocky Mountain National Park, CO: US Department of the Interior, National Park Service.
- Van Wilgen BW, Little PM, Chapman RA, Görgens AHM, Willems T, Marais C.** 1997. The sustainable development of water resources: History, financial costs, and benefits of alien plant control programmes. *South African Journal of Science* 93: 404–411.