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# The sensitivity of the high mountain ecosystems of New Guinea to climatic change and anthropogenic impact

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## Abstract

The New Guinea alpine-subalpine zone is the highest, largest, and wettest such region on any tropical island and it preserves great variations in biodiversity between the individual mountain areas. Relatively few plant species are confined to the alpine zone and this may reflect a limited time for adaptation by herbaceous species arriving in the formerly extensive alpine-subalpine biome. In the Pleistocene a zone above 3400 m was affected by glaciation while open subalpine habitat was greatly expanded by cooler climates and low levels of CO<sub>2</sub> which hindered the formation of subalpine forest. With post-glacial warming, the subalpine contracted and open areas were invaded by shrublands and forest. Early to late Holocene opening out of the subalpine forest and shrublands is associated with fire that was a result of hunting by humans. This process starts early in some areas but is late or absent on more remote areas.

The alpine is threatened by increased warming and potential invasion by emergent shrubs but is likely to prove resilient to extinction provided that wet conditions continue to prevail. Changing cultural use of high altitudes suggests that the subalpine shrublands are recovering in some areas. However, some mammals and bird species seem to have been lost or become restricted on mountains that are accessible from population centers at lower altitude. With few exceptions, management consists of benign neglect although widespread fires in 1997–1998 point to continuing human impacts linked to drought events. The large mine on Mount Jaya influences subalpine usage over a large area. Tourism is very minor and unlikely to expand while political problems affect both Papua New Guinea and Papua province and logistics remain a severe difficulty. However, locally managed tourism on Mount Wilhelm provides a good model for future development.

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## Introduction

A number of high tropical mountains occur on the islands lying between the continents of Asia and Australia, including the Indonesian archipelago, the island of New Guinea (including both the eastern part [Papua New Guinea] and the Indonesian western part [Papua or Irian Jaya]), and the Malaysian portion of the island of Borneo. The highest point is Puncak Jaya (4954 m) in Papua (Irian Jaya, Indonesia), the highest mountain on any island in the world. Significant peaks on other islands include the granitic Mount Kinabalu (4101 m) on Borneo and eighteen volcanic peaks in Sumatra, Java, Bali, and Lombok, which exceed 3000 m. However, the most extensive island mountain habitats in the tropics lie just south of the equator and extend for 1200 km along the island of New Guinea (Prentice et al., 2011). The New Guinea high mountains cover a latitudinal range from about 3°S to 8°S, with lower outliers to the west in the Bird's Head peninsula and to the east in New Britain.

New Guinea is a composite terrane incorporating Australian and possibly Asian fragments that formed from the mid-Tertiary (Baldwin et al., 2012; Polhemus, 2007). It is connected to Australia by shallow seas and tropical lowlands with seasonal rainfall. The very high altitudes were probably formed in the Plio-Pleistocene as a result of plate collision. Hence the high-altitude flora is quite young and has developed in isolation from temperate mountain areas (Smith, 1977a). The flora incorporates elements from the Himalayan (e.g., *Rhododendron*, *Gentiana*, *Potentilla*) and southern temperate (*Styphelia*, *Astelia*, *Podocarpus*, *Stellaria*) floras. It

has also recruited from tropical (*Eurya*, *Rapanea*, *Schefflera*) and cosmopolitan taxa (Poaceae, *Olearia*, *Plantago*, *Ranunculus*). Regional or micro-endemism in rapidly radiating genera is paralleled by some keystone species found along the cordillera such as *Dacrycarpus compactus*, *Rhododendron culminicolum*, *Rapanea vaccinioides*, *Styphelia suaveolens*, *Deschampsia klossii*, *Carex gaudichaudiana*, and *Gleichenia vulcanica*. This vascular flora of about 2100 species in 84 families (2 gymnosperm, 11 monocot, and 71 dicot) has been collated by van Royen (1979, 1982, 1983). No island-wide enumeration of the ferns has been made, but Johns et al. (2006) noted 4 families of fern allies and 17 families of ferns on Mount Jaya. Of the 710 vascular species in 228 genera noted on this mountain, fern species make up 20% of the mountain's flora, while there are 23% monocot species in 8 families and 56% dicots in 58 families (Utteridge and Edwards, 2009).

The alpine zone in New Guinea has been defined as “a treeless zone bordering a transitional subalpine zone and along its higher altitudinal border limited by the last vascular plants” (van Royen, 1979: p. 22). However, plants occur up to the highest points available and it is unlikely that a true limit to growth is reached. The treeline varies, being highest on limestone at up to 4050 m and lower on the shaded and waterlogged parts of volcanic and metamorphic mountains at 3650 m a.s.l. In most areas, however, the natural treeline has been greatly disturbed, and open grasslands are extensive to below 3000 m a.s.l. Some of these lower grasslands are regarded as subalpine as they support shrubs and tree ferns that are absent from the alpine. The subalpine forest is low (10–15 m) and variable, transitioning from taller complex forest (upper mon-

tane forest) around 2800–3000 m a.s.l. On some mountains it is reduced to small stands surrounded by grassland.

The New Guinea alpine is an example of islands within an island—numerous young isolated and fluctuating habitats with island-like characteristics of habitat, local endemism, and active species radiations. As such, it is a remarkable laboratory for studying evolution and differential adaptation to climate change in conditions of relatively low past human impact. This paper outlines the major features of the alpine flora and vegetation, but in doing so it emphasizes the paucity of knowledge currently available.

#### ALPINE ENVIRONMENTS

The Malesian mountains are probably the most humid on earth, surrounded by warm seas that are a major source of latent heat. Only the Amazonian slopes of the eastern Andes can match the humidity, and there is a substantial surplus of precipitation over evaporation in the summit areas, in contrast to African mountains such as Mount Kenya or those farther from the equator such as Mauna Kea, Hawai'i. Because the central cordillera runs NE-SW it intercepts the southeast trade winds as well as monsoonal (Intertropical Convergence Zone) moisture from the north. The high rainfall convergence zone is more than 1200 km north-south in the western Pacific and it usually overlies at least northern New Guinea throughout the year. Thus, there are no extreme aspect differences in precipitation in contrast to the rain shadow effects seen in the equatorial Andes or Hawai'i. In New Guinea, there is a pronounced precipitation maximum at midaltitudes (Prentice and Hope, 2007). However, rainfall totals there are so high (6000–12,000 mm per annum), and diurnal convective activity so intense, that any reduction in rainfall with altitude does not lead to moisture deficits longer than a few days at the summits in most years (Prentice and Hope, 2007). Summit rainfall is estimated at ca. 2500–4000 mm pa for the main cordillera but is possibly less along the Owen Stanley Range (around 8°S). Cloud-lie from midmorning is a feature of most summit areas. There are a variety of seasonal precipitation maxima, but seasonality is less in the west and increases eastward, where a distinctly drier season of two to three months, June–September, can be found.

The very wet conditions reduce the diurnal temperature range by comparison with less humid areas of the Andes and Africa. Hence there is no analogue to the “Afro-alpine” or Páramo zone with plant adaptations to severe frost. Temperatures below –5 °C are rarely encountered. Surface temperatures in the intense sunlight can often exceed 30 °C, but soil temperatures indicate that the treeline lies at about the 7.1 °C mean for all tropical sites (Körner, 2012). Between-year variability can be more extreme than within-year variation, which for Mount Wilhelm is the lowest so far reported of any of the tropical mountains (Körner, 2012: p. 45). El Niño events can lead to drought periods of several weeks duration every few decades, as occurred in 1972, 1984, and 1997–1998 (Ballard, 2000). Heavy frosts cause tree deaths in the upper montane forest and crop losses down to 1500 m.

Upland New Guinea is peopled by agricultural specialists who traditionally farmed frost-sensitive crops at or below 2500 m altitude. Pigs and dogs were domesticated by 4500 yr B.P. and some feral populations have spread into unsettled areas. The mountains are used for hunting birds, giant echidna, possums, rats, and wallabies but seem not to have provided any reliable plant foods above the montane forest (Fairbairn et al., 2006). Accordingly, there has been no long-term settlement in the subalpine, in contrast to major utilization of the subalpine for grazing or crops elsewhere in the

tropics. However, fires lit by hunters have been a major factor in vegetation distribution. During rare drought periods, fires can be extensive and subalpine forest will burn. In normal years, fires lit in grasslands fail to penetrate beyond the forest edges but influence grassland composition.

### Alpine and Subalpine Vegetation

Due to disturbance, the alpine vegetation of New Guinea extends below 3800 m altitude and merges in many areas with subalpine shrublands and grasslands (Hope, 1980). The best surveyed vegetation is on Mount Wilhelm (Wade and McVean, 1969; Smith, 1977b), Mount Jaya (Carstensz) (Hope et al., 1976; Johns et al., 2006), and Mount Trikora (Brass, 1941; Lam, 1945; Mangan, 1993). These studies, and expedition reports from other mountains (e.g., Costin et al., 1977; Kalkman, 1963; Paijmans and Löffler, 1972; Stevens and Veldkamp, 1980), show that the similarities in the flora and structural communities conceal a wealth of variation at species and community levels. Each mountain area, and even different peaks on the same range, will support endemic species. The same structural community may have similar floristics but different dominants, as shown in a comparison of forest stands on Mount Kerigomna with those nearby on Mount Wilhelm (Grubb and Stevens, 1985). It is even apparent that the same species may have different ecological responses in different areas. This can reflect variation in the climatic or edaphic conditions. However, there has probably been selection of ecotypes due the major fluctuations in range and dominance caused by glacial cycles in the Pleistocene.

The alpine vegetation is dominated by grasslands but has extensive areas of mires. Shrublands are found but are generally restricted in extent. Rather few species are obligate to the alpine zone, as many alpine species extend into subalpine grasslands down to 3400 m or lower.

Characteristic communities found on most mountains are as follows:

*Treeline forests and shrublands.* The treeline consists of small nanophyll and leptophyll trees and shrubs of *Dacrycarpus compactus*, *Rapanea vaccinioides*, *Eurya brassii*, *Tasmannia* sp. and various *Schefflera*, *Olearia*, *Pittosporum*, *Rhododendron*, and *Vaccinium* species. Heavy epiphytic cushions of moss, hepatics, and lichens with orchids cling to the trunks and branches. On Mount Trikora an unusual forest of the cedar *Papuacedrus papuana* forms a common subalpine forest type up to 3750 m (Mangan, 1993). Elsewhere, *Papuacedrus* is usually absent above 3200 m and is occasional in mixed upper montane forest. Near treeline, individual larger trees of *Dacrycarpus compactus* become scattered so the canopy is open above grass- or shrublands, but it is unknown whether the remnant trees reflect former denser cover. Burning of the treeline has often removed these transitional shrublands allowing alpine grasslands to extend lower. Discrete patches of subalpine forest form “islands” in grasslands on many mountains. At its lower limit, subalpine forest merges with taller montane forest around 3100 m. Again, there is great variety in the transitions, with dominant stands of *Nothofagus pullei* giving way to subalpine mixed conifer forest on Mount Trikora, whereas in other areas a mixed forest gradually loses species such as *Pandanus* and *Cunoniaceae* while *Pittosporum*, *Rapanea*, and *Dacrycarpus* increase.

*Alpine tussock grassland.* This grassland is found on peaty soils as dense stands of *Poa*, *Deschampsia*, *Anthoxanthum*, and *Danthonia* species forming robust tussocks generally 30–50 cm in height. Small shrubs of *Styphelia suaveolens* and *Tetramolopium* species may occur within the canopy and there is a rich herb flora

including composites, *Potentilla*, *Plantago*, *Parahebe*, and *Epilobium*. The community may represent stable vegetation on mature peat soils. At least one species (*Deschampsia klossii*) has a viviparous form that is found on fresh till, suggesting adaptation to disturbance. While structurally similar, the floras of these grasslands vary widely between mountains, with some intriguing disjunctions. Examples include *Detzneria tubata* (Scroph) restricted to the Saruwaged Range and Mount Wilhelm, and two species of thorny *Lepidium* (Brassic) with *L. laeteviridis* currently known from the Saruwaged Ra and *L. minutiflora* from Mount Giluwe to Mount Jaya.

**Short alpine grassland.** This grassland is dominated by tuft, sward, and small tussock grasses, including *Danthonia vestita*, *Deeyuxia brassii*, *Poa callosa*, and *Danthonia oreoboloides*. Small shrubs such as *Tetramolopium* species, *Eurya brassii*, *Coprosma* spp., and *Styphelia suaveolans* are scattered throughout. *Poa* species vary between mountains, *P. nivicola* being important on Mount Wilhelm and Mount Jaya, *P. wisselli* on Mount Jaya and Mount Trikora. On the Owen Stanley ranges, the grassland type dominates but the 25-cm-high canopy is formed by *Poa erectifolia* with *P. saruwagetica*. It occupies mineral soils and is adapted to periodic dry conditions (Fig. 1).

**Alpine mosslands** (termed tundra by Wade and McVean, 1969). Carpets of mosses, liverworts, and lichens form incomplete cover on fresh till and scree in the summit areas. Small tuft-grasses and herbs such as *Epilobium* spp. and *Ranunculus* spp. are scattered about, their frequency determined by the degree of waterlogging. They are restricted to areas affected by neoglacial ice retreat and are probably successional.

**Alpine and subalpine fens and bogs.** These are widespread and floristically less variable than other communities, perhaps due to seed dispersal by waterbirds. Communities include *Carpha alpina* fen, *Carex gaudichaudiana* fen, *Gleichenia vulcanica* fen, *Astelia papuana* cushion bog, hard cushion bog, and short grass bog. The cushion bogs are better developed in the west (Hope, 2007c) where they support bolsters of *Rhododendron saxifragoides*, a cushion-forming species that only occurs west from Mount Giluwe. An unusual fern ally, *Isoetes hopeii*, seems to be restricted to cushion bog on calcareous substrates but is only known from

Mount Jaya and Mount Trikora. It appears to have a similar role to *Stylites andicola* in Andean cushion bogs, though strictly subalpine and never dominant. A mat-forming fern, *Gleichenia vulcanica*, is widespread across New Guinea but forms extensive blanket bogs on mountains with poor drainage, such as volcanic Mount Giluwe or granitic Mount Scorpio.

**Dwarf shrub heath.** The heath consists of 15–30 cm high dwarf shrubs of *Styphelia suaveolens*, *Vaccinium*, and *Gaultheria*, which can form larger bushes at lower altitude, together with *Drapetes ericoides*, *Tetramolopium* spp., and other small shrubs. The community occupies well-drained stony soils such as moraine crests and stream edges. The heath is common on Mount Albert Edward but rare on wet mountains with peaty substrates. It is possibly a successional community, being replaced as mineral soils become buried by peat.

Subalpine tussock grasslands of *Deschampsia klossii* and *Poa* species often occur with 3- to 6-m-high tree ferns (*Cyathea muelleri*, *C. atrox*, *C. macgregorii*) and tall shrubs of *Coprosma*, *Rhododendron*, *Vaccinium*, *Gaultheria*, *Styphelia*, and *Eurya* species. Some grasslands, such as those dominated by *Cortaderia archboldii* on Mount Albert Edward and Mount Giluwe, are peat-forming and follow drainage lines. The subalpine grasslands have invaded formerly forested areas down to 2800 m. At the lower end of their range (e.g., the Neum Basin; Fig. 2) they also recruit montane species such as *Imperata cylindrica* and *Dodonaea viscosa*.

## Historical Influences

### CLIMATE CHANGE

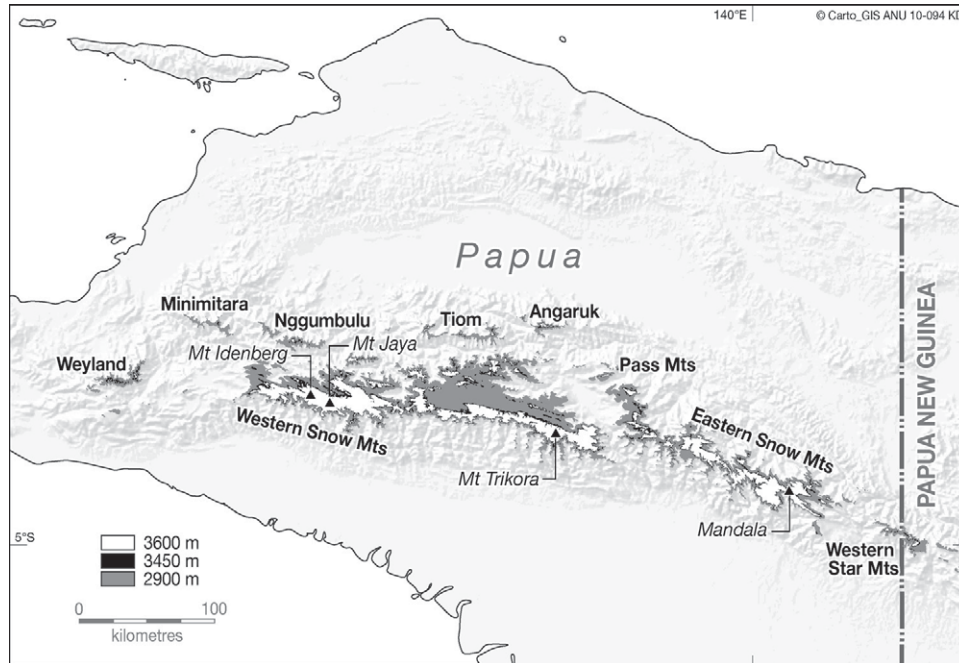
In common with other tropical areas, the alpine of New Guinea has been exposed to large climatic shifts that were more extreme than those of lower altitudes and included widespread glaciation. Prentice et al. (2011) used the SRTM 90m DEM to update the areas of the subalpine and alpine elevational zones in New Guinea (Table 1). The area above 3450 m that was glaciated at maximum ice extent is estimated at about 3770 km<sup>2</sup> (West Papua, ~3270 km<sup>2</sup>; Papua New Guinea, 500 km<sup>2</sup>), a considerable increase on older measurements derived from maps (e.g., Hope and Peterson, 1975). Past



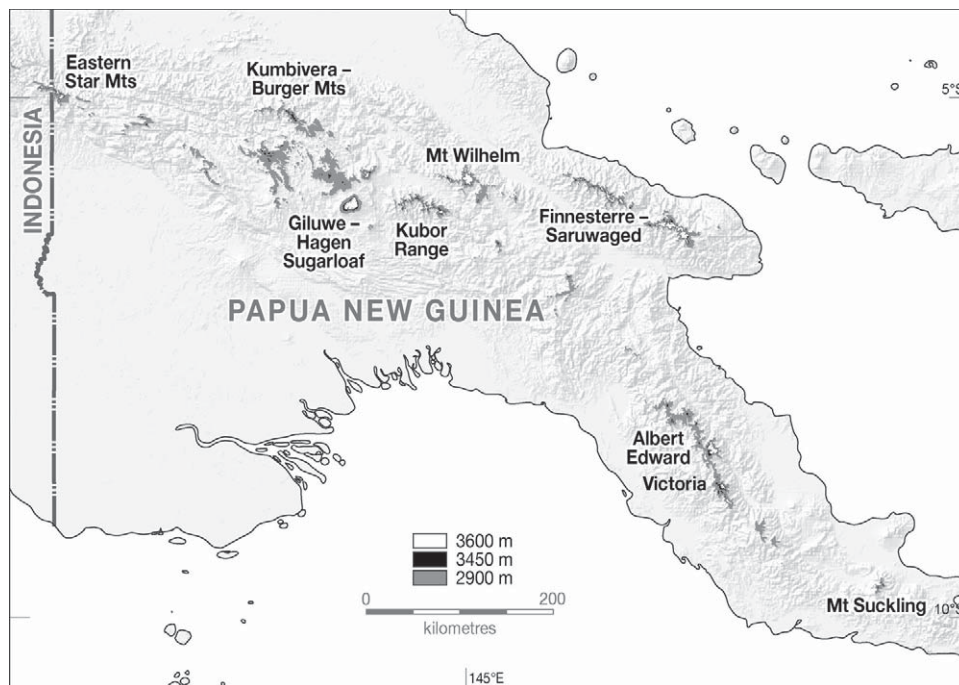
**FIGURE 1.** Short alpine grassland at 3800 m on Mount Albert Edward, with remnant patches of subalpine forest.



(a)



(b)



**FIGURE 2.** Extent of subalpine and alpine habitats in (a) Papua province and (b) Papua New Guinea.

glacial limits seem to have been higher in the west, with a snowline at 3850 m a.s.l. around Mount Jaya, than to the east where the snowline was about 3450–3550 m a.s.l. with glacial termini as low as 3100 m. If this difference resulted from a precipitation gradient, there may have been an ice-free nival or periglacial zone in the western Maoke Ranges at times (Fig. 2)

Multiple glaciations are assumed to have affected the high mountains, based on evidence from dating old moraines and palaeontological breccias on Mount Giluwe, a shield volcano in Papua New Guinea (PNG). Löffler (1972) dated the earliest ice cap at around

800 ka, when the volcano was active and building. Barrows et al. (2011) found evidence for four distinct glacial periods between 293 and 306 ka (Gogon Glaciation), 136–158 ka (Mengane Glaciation), centered at 62 ka (Komia Glaciation), and from >20.3 to 11.5 ka (Tongo Glaciation).

During the glacial phases of the mid-late Pleistocene, the treeline seems to have stood at only 2200–2400 m a.s.l., giving a treeless area of about 50,000 km<sup>2</sup> (Hope and Haberle, 2005). Thus, in at least the last period of maximum ice in MIS 2 (28–17 ka) a subalpine shrub-rich grassland with abundant tree ferns (*Cyathea*)

TABLE 1

Extent of nival, alpine, and nonforest subalpine environments at the present and Last Glacial Maximum (LGM). PNG = Papua New Guinea.

Zone	Alt (m a.s.l.)	Western Papua (km <sup>2</sup> )	Central Papua and PNG (km <sup>2</sup> )	PNG Highlands (km <sup>2</sup> )	Eastern Ranges (km <sup>2</sup> )	Total (km <sup>2</sup> )
<b>Mapped present extent of alpine and subalpine</b>						
Nival	>4650	2	<1	0	0	2
Alpine	>3600	2179.1	916	180.9	78.5	3350
Subalpine	>2900	3254.9	1421.8	339.6	402.8	5420
Extended subalpine (Est.)	>2700	5500	1850	1600	1600	10550
<b>Estimated extent at 19,000 cal years BP (LGM)</b>						
Nival	>3600	1870	1420	340	140	3770
Alpine	>2900	9240	3605	2335	2360	17540
Subalpine (Est.)	>2350	18515	13290	6990	7620	46410

formed a zone above a treeline of mixed montane forest that is 1600 m lower than the present subalpine forest limit (Fig. 3). Because the maximum depression of ice limits is only 800–1000 m below their level at the present day, relatively wet conditions prevailed. Lower CO<sub>2</sub> concentrations seem likely to be an underlying cause for the relative absence of trees in this expanded subalpine zone, although more extreme frost may have contributed. Temperatures are estimated to have been 5–8 °C lower than present (Prentice et al., 2005, 2011).

The altitudinal position of the alpine/subalpine boundary is not well known because the highest pollen site spanning the Last Glacial Maximum is Komanimbuno on Mount Wilhelm at 2740 m (Hope, 1976). This currently forested site was then treefern and shrub-rich subalpine grassland but the transition to the alpine may have occurred only a little higher at 2800–3000 m.

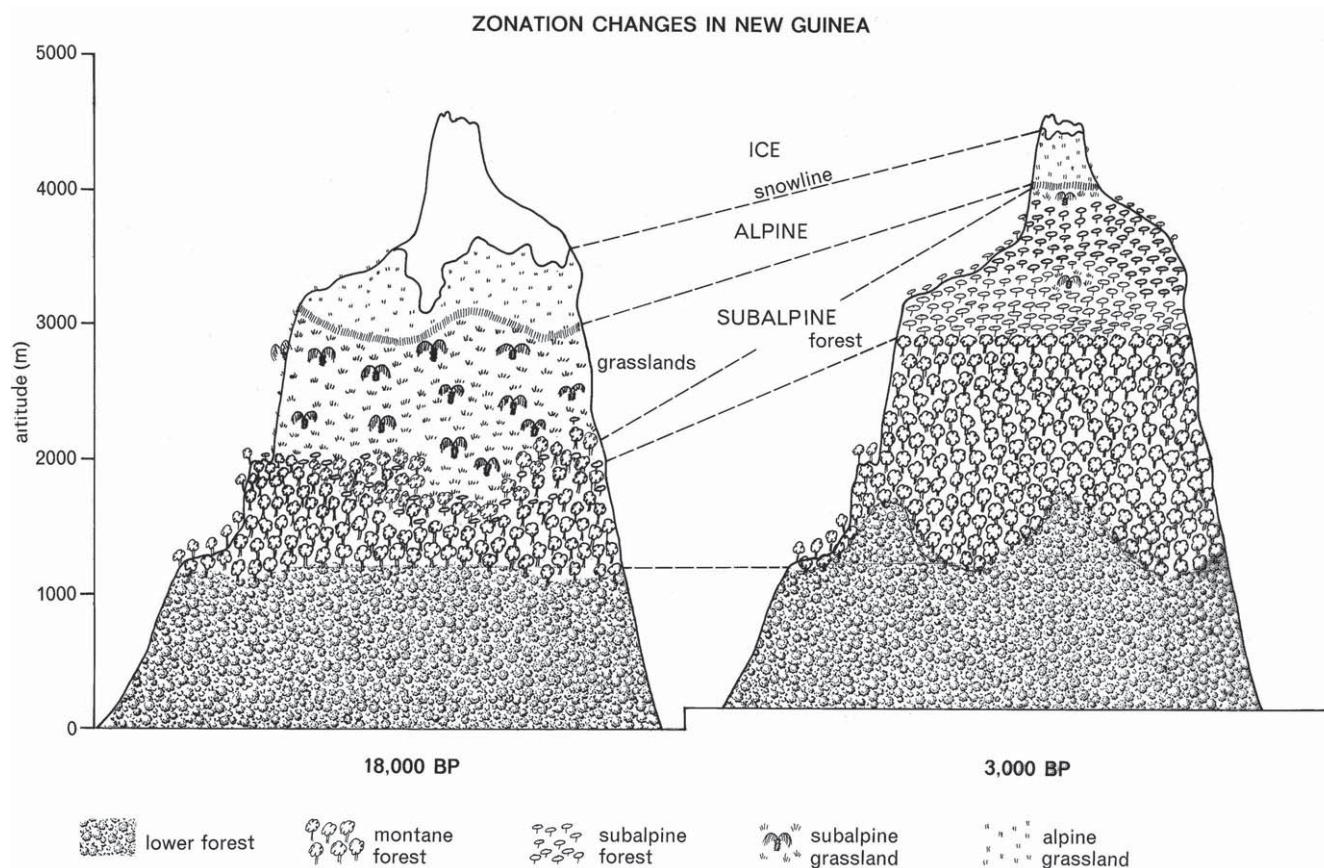
Pollen analyses from several mountains indicate that a subalpine scrub of *Rapanea* and Ericaceae expanded after 14 ka and that the subalpine forest formed later with the invasion by podocarps and other taxa after 10.5 ka (Hope, 2009). This invasion may have reduced the total treeless alpine area in New Guinea to ~3200 km<sup>2</sup> by 8.5 ka (Fig. 4). The extent of treeless subalpine in the absence of fire would have been quite small, consisting of frost hollows and swampy valley floors.

The role of Holocene climatic fluctuations in expanding the subalpine and influencing the alpine-subalpine boundary is not well known. This is mainly because human disturbance has been widespread, but also because volcanic tephra falls create vegetational responses in eastern PNG. Neoglaciation spanning at least the past 3000 years has been established on Mount Jaya (Prentice and Hope, in press), and temperature changes of 1–2 °C are thought



**FIGURE 3.** *Cyathea muelleri* grasslands at the Neum Basin, Mount Albert Edward at 2950 m are replacing forest but resemble widespread Pleistocene subalpine habitats. Photo by G. Hope.





**FIGURE 4.** Zonation changes with post-glacial warming in New Guinea. The subalpine biome changes from open tree fern shrublands to low closed forest.

to be responsible (Prentice and Hope, 2007). However, little vegetational response can be discerned in the low-temporal resolution pollen data. A reduction in tree pollen about 4800 yr B.P. may indicate a lowered treeline at 3960 m on Mount Wilhelm, although this coincides with local fire. There is a reduction in *Castanopsis* pollen around this time, which may suggest an adjustment in the montane forests to greater diversity (Hope, 1976).

#### ANTHROPOGENIC CHANGE

The role of humans in the high mountains prior to the last deglaciation lacks direct evidence, although Kosipe, in the Ivani valley, an area adjacent to the high mountains of the Owen Stanley Range at 2000 m, was settled by 45,000 years ago (Summerhayes et al., 2010). The Ivani valley floor was extensively burnt and subalpine taxa were present in a swampy plain (Hope, 2009). Humans may have contributed to modifying the fauna because at least three marsupial species that adapted to grazing in the subalpine have become extinct in the late Pleistocene to mid-Holocene (Hope et al., 1993). Fairbairn et al. (2006) speculate that the subalpine zone may have been visited for hunting over the last glacial period.

The modern treeless subalpine includes large areas of grassland and tree fern shrubland down to 2700 m on areas that were actually or potentially forested in the early Holocene. The areas are roughly estimated as extended subalpine in Table 1, based on the analysis of satellite cover of grasslands and mires in many areas across the island. Pollen analyses from several mountains

show individual histories of this opening out (Fairbairn et al., 2006). At Lake Habbema, near Mount Trikora, Lake Hogayaku near Mount Jaya (Prentice et al., 2005), and the Neum Basin on Mount Albert Edward (Hope, 2009), the subalpine forest is subject to fire throughout the Holocene and forest contraction seems to have occurred over a long time scale. Other sites such as Laravita Tarn on Mount Albert Edward, sites on Mount Giluwe and possibly Lake Gwam, Saruwaged Range have forest contraction from the mid-Holocene that may relate to the spread of agriculture and population increases at lower altitudes. On Mount Wilhelm, forest clearance occurs around 1000 years ago and could reflect rapid expansion as populations colonized the upper Chimbu Valley (Corlett, 1984). By contrast, at Yakas Tarn, a remote and very high rainfall site in the Star Mountains, no human disturbance is discernible. However, without human disturbance (or the tephras found farther east) the *Papuacedrus-Dacrycarpus* forest gradually becomes more open and stunted as blanket peat traps the available mineral nutrition (Hope, 1980) (Fig. 5).

In a few instances the gradual loss of forest has been reversed. At Ijomba on Mount Jaya, the vegetation is becoming more shrubby and overgrown while stone pavements indicate a former destructive fire regime that destroyed the soil cover. This reduction in human impact is supported by pollen data, which show increasing shrub cover after 2500 years ago when hunting may have lessened (Hope and Haberle, 2005). However, on other mountains such as Mount Trikora and Mount Giluwe, subalpine forest is still being destroyed by fires lit by hunting parties.



**FIGURE 5.** Mount Scorpio at 3720 m. Unaffected by human burning on deep wet peats, the forest of *Rapanea* and *Dacrycarpus* has become stunted and open above a groundcover of the fern *Gleichenia vulcanica*. Photo by G. Hope.

## Possible Impacts of Climate Change

### DIRECT IMPACTS

Warming trends have been evidenced in three ways: reductions in ice cover, increases in plant altitudinal limits, and direct observations. The rise in the snowline is shown by a dramatic retreat by ice over the past century with only one ice area remaining from four known prior to 1940 (Prentice et al., 2011). This loss of nival habitat is exposing fresh rock and till surfaces to a rapid succession by fungi, algae, lichens, bryophytes, and vascular plants. Specialized snow algae communities (Hope et al., 1976) are being lost in the process.

In the next few centuries, there will be a loss of rocky open habitats in the face of generalized warming that may result in increasing shrub cover and changes in subalpine tree composition as frost-sensitive taxa migrate upward. Raised CO<sub>2</sub> levels will encourage woody plants to invade grasslands. The evidence for this can be seen by comparing old photos with more recent ones in areas of little human impact. However, the effect is not marked and in many cases fire is maintaining or reducing shrub cover.

Phenological changes have been noted in species in the alpine zone, including flowering at higher altitudes. Asteraceae shrubs such as *Papuacalia versteegii* are growing in newly exposed till, and other readily dispersed taxa will follow. However, there are no systematic observations and many changes, such as increasing shrubbiness, may be responding to changing disturbance regimes and not climate change. At lower altitudes, Bourke (2011) has identified significant changes in the ranges of economic plants over the past 30 years that point to temperature increases of 1 °C and lower frequencies of limiting conditions, such as frost.

Few direct observations have been made. Two dataloggers were buried to 10 cm at treeline on Mount Wilhelm from 2007 to 2010, but they fail to show any warming trend and have the least seasonal changes known for the tropics (C. Körner and K. Green, personal communication, 2013). A good reference climate station exists at the mine site on Mount Jaya (Prentice and Hope, 2007). The rainfall data identified the large impact of the 97–98 El Niño on the snowline at that time, which rose 100 m but has since stabilized. This highlights that a possible future climate impact might



be increased and more severe drought events. These events include high levels of ultraviolet radiation linked to low cloud cover.

## Fires and Human Impacts

While treelines rose generally after 15 ka, variable human burning has expanded the available habitat for treeless subalpine vegetation in the past 9000 years. If major drought events increase in frequency, then human ignited, and possibly natural, fires will alter the balance further. Large blanket peat areas (Hope, 2007c) may dry out in droughts and are at risk of burning. Some composite weed species such as thistles and other weeds such as *Anagallis arvensis* invaded the subalpine after the 1998 fires and were still persisting in burnt grasslands on Mount Giluwe in 2001. Hence these disturbances provide a route for invaders. European bulbs such as *Lilium* and grasses such as *Poa annua* are following track lines upward on Mount Wilhelm. Other introduced grasses, composites, and *Lantana* are potential threats. Mount Albert Edward supports a large pig population causing disturbance of large areas to overturn, leading to local erosion. Potential problems could arise from other mammals such as rabbits.

### MANAGEMENT AND KNOWLEDGE GAPS

The present status of both management and research on the subalpine and alpine is one of benign neglect. Isolated areas have never been studied and are rarely visited. In many cases traditional use of the grasslands is declining as the population becomes better educated and more oriented to town life. Over the past 40 years, I have found it harder to find knowledgeable guides with the skills to work in the high regions, and many areas seem less visited, despite generally increasing highland populations. Agriculture is not practiced above 2800 m, so the main purposes for visiting are for hunting and to traverse the area to settlements across the ranges. In some cases, alternative transport has reduced the use of tracks in the high country. Tourism is very minor and has probably diminished as the logistic difficulties and security problems in both

Papua and PNG are perceived to have increased. Some summits host radio telephone equipment serviced by helicopter, but some of these (Mounts Ialabu and Wilhelm) have been abandoned as mobile phone technology expands.

Exceptions to this relatively low human impact include the area near the Ertsberg and Grasberg mines west of Mount Jaya where a large open cut is depositing waste rock up to 4100 m altitude on formerly glacierized terrain. Mine workers from villages to the north now walk several days to and from the mine across the Kemabu Plateau. Mine workers also visit the ice area, with consequent litter problems (Utteridge and Edwards, 2009). This area is part of the Lorentz National Park, a 25,056 km<sup>2</sup> reserve that extends 150 km from Mount Jaya to Mount Trikora across the largest high altitude area on the island. A road, built for military purposes, connects the town of Wamena with the subalpine area north of Mount Trikora and this has led to greater visitation, including exploitation of wildlife and forest products (Fig. 6). The park is not managed to any great extent at present and traditional uses are continuing. Numerous tracks cross the range from north to south and burning is common along these routes. This area was affected by widespread fire during the 1997–1998 El Niño event.

A second exception to the absence of tourism is Mount Wilhelm, the highest mountain in PNG, where local groups are developing ecotourism along the Pindaunde valley, the most popular route to the summit at 4510 m from the road head at 2850 m. Lodges have been built with locally collected funds, and official guides are employed. Tracks have been improved, funded from guide fees. Fuel for cooking is brought up to the subalpine and cutting the subalpine forest is discouraged. The area above 2900 m is national land but managed by the agreement of the local landowners. Visitor numbers are still relatively low, at a few hundred per year, but the enterprise provides a possible model for the management of other mountain areas. Gaining an income then provides incentives to maintain the vegetation and wildlife. The concentration on a single valley allows other valleys to remain unvisited because access is much more difficult. Visits are of short duration so far.

However, the concentration of benefits to one clan can create conflict. In a study of alpine tourism on Mount Kenya and the



**FIGURE 6.** A road built in 1998 extends into the subalpine north of Mount Trikora at 3200 m. Built without consultation about conservation objectives it will drain peatlands and provide a nucleus for hunting and fires. Photo by P. Hiscock.

Ruwenzori, Neuburger and Steinicke (2012) concluded that some benefits accrue to the local population from the 25,000 visits a year (30% Kenyan nationals) on Mount Kenya due to cooperation between a guides and porters cooperative and National Park management. The ~1500 visitors per year all visit one valley in the Ruwenzori, which has concentrated the benefits but created local disparities. Benefits (and incentives for conservation) largely evaporate if centralized tourism companies based in towns take over the activities and tourism management. This has been the tendency in ecotourism on Mount Trikora where the web largely promotes Jakarta-based firms and local attempts to provide services lose out to better organized and resourced firms.

Knowledge gaps are large, particularly in Papua and remote PNG. Even the biological census is incomplete, particularly for invertebrates and cryptogams. Substantial ecological studies on alpine plants and animals have been very few since those at Mount Wilhelm 30–40 years ago. However, the Freeport McMoran company has provided major encouragement for studies on Mount Jaya, such as on its flora (Shea et al., 1998; Johns et al., 2006). Current work on paleoecological records aims to increase the resolution of pollen and charcoal and use isotopic changes to identify the sensitivity of the vegetation to climatic, volcanic, and anthropogenic disruption. Monitoring of environmental change in any systematic way is not occurring. Hence scientific knowledge to support conservation and to guide management at a local scale is lacking. This in turn prevents any realistic assessment of or planning for the effects of climate change.

This situation will hopefully improve in the long term as Indonesia and PNG produce their own researchers with an interest in the high mountains. For example, the Indonesian Academy of Science (LIPI) has offices in Wamena that host Indonesian researchers. Resources to visit isolated sites are often lacking other than as collaborators with episodic foreign research efforts, but such partnerships with local institutions and nongovernmental organizations introduces university graduates to mountain research. Hence the situation should improve as both Papuans and Papua New Guineans learn more about their high mountain environments. People from local groups who have been educated about these issues are in the best position to develop long-term relationships with the local communities. There is an urgent need for baseline studies and new monitoring to be able to assess climate change and its impacts in these most sensitive areas.

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