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Estimates of late Holocene soil production and erosion in the Snowy Mountains, Australia

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ABSTRACT

Soil production in actively uplifting or high precipitation alpine landscapes is potentially rapid. However, these same landscapes are also susceptible to erosion and can be sensitive to changes in climate and anthropogenic activity which can upset the balance between soil production and erosion. The Snowy Mountains, southeastern Australia, are a tectonically stable, low relief, moderate precipitation mountain environment. The alpine area is extensively blanketed by soil that has been subjected to more intensive episodes of erosion during past periods of anthropogenic disturbance and under cold climate conditions of the late Quaternary. In this study, rates of soil development and hillslope erosion were investigated using radiocarbon dating, fallout radionuclides and sediment cores collected from lakes and reservoirs. Estimated Holocene soil development rates were 20–220 t/km^2/y. Erosion rates determined from the radionuclides ^{137}Cs and ^{210}Pb were equivocal, due to the inherent spatial variability of radionuclide inventories relative to apparent erosion rates. Estimated average erosion rates over the past 100 years, determined from ^{210}Pb$_{ex}$ inventories, were 60 t/km^2/y (95% CI: 10, 90). Inventories of ^{137}Cs observed at the same site implied that more recent erosion rates (over the past 60 years) was below the detection limits of the sampling method applied here (i.e. <70 t/km^2/y). The upper estimate of 90 t/km^2/y is comparable to the mean erosion rate estimated using the radionuclide method for uncultivated sites in Australia and is significantly lower than that measured at sites were vegetation cover was disturbed by livestock grazing prior to its exclusion from the alpine area in the 1940s CE. Low erosion and high soil production rates relative to the lowland soils are likely related to extensive vegetation cover, which, in this context, protects soils against erosion and contributes to the formation of organic alpine soils, that rapidly accumulate organic matter by comparison to other soil types.

1. Introduction

On a global scale, alpine landscapes are recognised as regions of relatively high geomorphic activity (Dedkov and Moszherin, 1992; Milliman and Syvitski, 1992). This has been ascribed to their climate, which is typically cold and wet, tectonic activity and corresponding high elevations and steep slopes (high potential energy), which in combination promote rapid physical weathering, erosion and sediment transport (Milliman and Syvitski, 1992; Syvitski and Milliman, 2007; Vanmaercke et al., 2011; Walling and Webb, 1996). For example, rivers draining mountain basins transport a disproportionately large proportion of the global sediment yield, that is, 870 t/km^2/y compared to 115 t/km^2/y for the rest of the World's rivers (Milliman and Farnsworth, 2011). Especially in tectonically active mountain ranges, erosion can be so rapid as to equal or exceed the rate of uplift (Brozović et al., 1997; Koppes and Montgomery, 2009; Mitchell and Montgomery, 2006).

Despite high rates of geomorphic activity, the historical perception was that in cold mountain environments, rates of chemical weathering and, therefore, soil formation were low (e.g. Peltier, 1950). Contrary to this assumption, rapid rates of soil production have been measured in alpine environments, especially in regions experiencing rapid uplift and high precipitation. For example, in the Southern Alps New Zealand, where rainfall may exceed 10 m/y and uplift approximates 10 mm/y, soil production rates may reach 2.5 mm/y (Larsen et al., 2014), an order of magnitude higher than soil production rates measured elsewhere (Larsen et al., 2014). The potential significance of chemical weathering in mountain environments is further evidenced by the existence of extensive soil mantles in a variety of alpine settings worldwide

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(Dixon and Thorn, 2005; Egli et al., 2014; Norton and von Blanckenburg, 2010; Riebe et al., 2004).

Soils in high mountain environments have been shown to be sensitive to changes in climate and human activity, which alter soil production processes and may accelerate the erosion rates by multiple orders of magnitude (Barsch and Caine, 1984). Episodic changes in climate, vegetation cover, fire frequency and human disturbance are therefore likely to be important controls on the balance between soil production and erosion in some mountain environments (Hewawasam et al., 2003; Kirchner et al., 2001; Koppes and Montgomery, 2009; Schmidt et al., 2002).

In tectonically stable, non-glaciated, high to moderate rainfall, i.e. less than 2 m/y, alpine areas, such as the Snowy Mountains in south-eastern Australia, rates of soil production and erosion have received less attention. The Snowy Mountains have traditionally been viewed as distinct from other alpine regions (Costin, 1989; Kirkpatrick, 1994). This is due to their intra-plate setting and resulting tectonic stability and moderate relief (slopes) (Bishop and Goldrick, 2000). In addition, they experienced relatively limited Pleistocene glaciation (Barrows et al., 2001). These characteristics have facilitated the development of a relatively thick soil mantle (0.6 to <1 m) over almost the entire alpine area (Costin, 1989). Nevertheless, the Snowy Mountains are considered to have experienced pulses of intensified sediment transport in response to changing climate during the late Quaternary (Costin, 1972; Kemp and Rhodes, 2010; Ogden et al., 2001; Page et al., 2009) and as a result of livestock grazing between the mid-1800s and 1940s CE (Costin et al., 1960).

The quantification of inherently spatially and temporally variable soil production and erosion rates remains a major challenge within geomorphology. Measurement of hillslope erosion has been undertaken by a variety of methods that can be broadly categorised into: plot and survey approaches (e.g. Costin et al., 1960); measurement of sediment yields by either stream gauging, or by measurement of the mass of sediment accumulated in geomorphic sinks, such as lakes (e.g. Neil, 1991; Tomkins et al., 2007); erosion tracer methods using fallout radionuclides (e.g. ^{137}Cs and ^{210}Pb) (Blake et al., 2009; Loughran et al., 1988; Porto et al., 2009; Ritchie and McHenry, 1990; Walling et al., 2003) and; the application of cosmogenic nuclides (e.g. Dixon and Riebe, 2014; Heimsath et al., 2002). These methods are each limited by the challenges of upscaling point measurements in time and space in relation to the representativeness of reference sites, the spatial heterogeneity of tracer fallout and transport and the issues of sediment storage and delivery (Chappell et al., 2011b; de Vente et al., 2007; Zhang et al., 2015). In addition, these methods provide data over different time periods, e.g. stream gauging typically provides short term data (event to decadal scale), radionuclides provide decadal to centennial scale data, and commonly used cosmogenic nuclides integrate over millennial scales. As a result, different approaches will commonly yield very different results (e.g. Tomkins et al., 2007; Wasson et al., 1996) that are then subject to various interpretations.

The objective of this study is to quantify soil development and erosion rates in a tectonically stable, currently non-glaciated mountain environment and to advance the understanding of the relative controls that changing climate and anthropogenic activities place on landscape stability and sediment budgets. In doing so the likely age of these soils is discussed, which in this setting is likely to be constrained by glaciation and/or periglacial processes to at least <11–16 ka (Barrows et al., 2001, Costin, 1972). This study employs multiple methods to attempt to quantify rates of soil development, hillslope erosion and sediment transport. Hillslope erosion rates are investigated using fallout radionuclides (^{137}Cs and ^{210}Pb$_{ex}$) and by calculating sediment mass accumulation rates in alpine lakes and reservoirs. Soil development rates are examined using geomorphic and paleoclimate evidence combined with radiocarbon analysis. These approaches overlap in time, allowing the balance between soil development and erosion rates to be investigated. Results are placed within the context of past climate variability and athropogenic impact in the Snowy Mountains.

2. Regional setting

The Snowy Mountains are a high' elevation plateau of moderate (undulating) relief. Despite being the highest region of Australia, they reach an elevation of only 2228 m at their highest point (Mt Kosciusko) and local relief of the alpine area is usually <200 m. The Snowy Mountains are the erosional remnants of uplift associated with the Cretacous breakup of Gondawana, beginning at 100 ma with most intense tectonic activity centered around 55 ma (Bishop and Goldrick, 2000). Their intraplate setting results in low denudation rates (2–5 m/Ma) over geological timescales (Young and McDougall, 1993). The basement rocks of the mountains are Silurian and Devonian aged granites with Ordovician meta-sediments and occasional Tertiary basalts. The Snowy Mountains contain the only peaks above 2000 m in Australia and form part of mainland Australia's limited subalpine and alpine area, which covers only 2500 km^2.

Aligned perpendicular to the prevailing westerly moisture bearing winds, the Snowy Mountains experience a cool montane climate, with mean temperature varying from 18 °C in summer to −7 °C in winter and annual precipitation ~2000 mm (BOM, 2014). In the alpine tract, continuous snow cover is present for up to 4 months of the year with isolated snow patches sometimes persisting through the year (Green and Pickering, 2009). Interannual variability of snow-depth and snow persistence is high and is related to the frequency of occurrence of snow bearing synoptic weather systems (Nicholls, 2005; Theobald et al., 2015; Whetton et al., 1996). Minor periglacial activity (needle ice formation and frost heave) is currently confined to the alpine zone, with gelifluction and frost shattering most significant above 2000 m (Barrows et al., 2001; Galloway, 1965).

In the montane zone (900–1500 m), vegetation comprises wet-sclerophyll forests dominated by alpine ash (*Eucalyptus delgatensis*) and mountain gum (*Eucalyptus dalrympleana*). Subalpine (above 1500 m) vegetation consists largely of snowgum (*Eucalyptus pauciflora*) woodlands with a grassy (*Poa ceaspitossa*) understory. Above 1850 m are alpine herbfields (dominated by *Celmisia and Poa* spp.) with areas of heath, sod tussock grassland and fen-bog communities (*Carex-Sphagnum*). Vegetation cover is almost complete, extending to the highest peaks.

From the mid 1800s to the mid 1900s CE the Snowy Mountains were exploited for summer grazing of sheep and cattle (Green et al., 2006). By the late 1920s CE, deliberate burning by graziers and trampling of vegetation by stock had resulted in the initiation of soil erosion over a substantial area of the alpine zone (Bryant, 1971). Surveys undertaken at this time implied that sheet erosion was the predominant erosion process (Bryant, 1971), however, gully erosion also occurred particularly around the summits of the highest peaks (Irwin and Rogers, 1986). Since 1944 CE, when it was declared a National Park, the entire alpine area of the Snowy Mountains has been protected from grazing and resource extraction.

Soils in the alpine and subalpine zone of the Snowy Mountains are classed as humose chernic tenosols (Australian Soil Classification) (McKenzie et al., 2004). At the study location, they are characterised by a humose A horizon of approximately 30 cm depth with an abrupt to distinct transition to a relatively shallow, stony BC horizon. The BC horizon grades to the granite substrate at approximately 60 cm depth. The soils are considered polygenetic (Brewer and Haldane, 1972). The A horizon has been assumed to be Holocene in age and is dominated by high organic inputs from the covering snowgrass accompanied by slow decomposition due cold temperatures, frequently waterlogged soils and high aluminium content (McKenzie et al., 2004). The soils are augmented by significant dust accretion (Costin et al., 1952; Johnston, 2001; Marx et al., 2011). Together this suggests that the A horizon undergoes pedogenisis by upbuilding. This differs markedly from the underlying poorly developed B/C horizon which has been considered to represent a truncated Pleistocene palaeosol developed during a period of greater chemical weathering (these were originally termed