Quantifying the soil- and ecosystem-rejuvenating effects of loess in a high leaching environment, West Coast, New Zealand

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Abstract
Ecosystem succession through pioneer, seral, climax and finally retrogressive communities is usually strongly associated with biogeochemical accession of soil nutrients. In leaching-driven, humid environments, retrogression is known to coincide with soil nutrient decline, particularly soil P. Counteracting this tendency are rejuvenating processes, included within what has been referred to as regressive pedogenesis, which replenish soil nutrients. Despite large areas of old landsurfaces, ecosystem retrogression seems to be rare, indicating that rejuvenation processes are effective in avoiding ecosystem decline. Regressive pedogenesis, however, has received little attention despite its importance for ecosystem evolution.
In this paper we quantify the regressive effect of loess on soil and ecosystem properties in a superhumid, high leaching environment on the west coast of the South Island, New Zealand. A dune sequence downwind of a riverbed loess source provides a gradient of loess flux, and away from loess deposition, an age gradient (chronosequence). Coincidence of property values between the soils of the loess gradient on the oldest (6500 y old) dune and the chronosequence allow an 'apparent soil age' for a given loess flux to be estimated. A regression index calculated from dune age and apparent age quantifies the regressive effect of the loess flux. Early results show the regressive effect of loess is retarding podsol formation and increases foliar nutrient content. This effect seems to reach no further than to 1000 m from the source of the loess. Soil pH does not show any relation to loess accretion. Further work is currently underway to determine more soil and ecosystem properties in order to quantify the regressive effect of loess on these properties. These results will be available at the time of the conference.

Key Words
Regressive pedogenesis, atmospheric deposition, loess, ecosystem retrogression, soil chronosequence

Introduction
Soil chronosequence studies under unmodified vegetation have demonstrated a co-evolution of soils and ecosystems. In humid environments where leaching drives ongoing nutrient loss, some soil chronosequence studies show that after initial successional phases with increasing biomass, diversity and soil fertility, ecosystems can go into a state of decline (Chadwick *et al.* 1999; Wardle *et al.* 2008). This retrogressive phase has been shown to occur once thresholds of nutrient availability, particularly soil P, are crossed (Richardson *et al.* 2004; Walker and Syers 1976). Despite the large area of humid zones on Earth, including land surfaces of great antiquity, ecosystems in a state of retrogression are rare, suggesting that processes of soil rejuvenation are effective at replenishing nutrients. This tendency for rejuvenation of the soil system is captured in Johnson and Watson-Stegner's (1987) soil evolution model. A progressive vector, which is viewed as resulting in soil deepening, horizonation and chemical depletion, is counteracted by a regressive vector which includes soil mixing, shallowing or incorporation of new mineral material that homogenises the soil or increases its chemical reactivity and fertility. Johnson and Hole (1994) argue that while there has been a lot of research driven by a focus on the soil forming factor model of soil development, there has been little attention on regressive processes, which is equally true for ecosystem decline (Wardle *et al.* 2004). Yet, these processes are clearly important for understanding trajectories of soil and ecosystem evolution.
On the superhumid west coast of the South Island of New Zealand, soil chronosequence studies on sequences of glacial moraines have documented a moss/lichen-shrub-angiosperm/conifer forest succession culminating in ecosystem retrogression on landsurfaces > 100,000 y old. The retrogressive phase is characterised by shrub, stunted conifers and heath vegetation (Richardson *et al.* 2004; Wardle *et al.* 2004). The parallel soil evolution is from Entisols to Inceptisols to Spodosols (Sowden 1986; Stevens 1968). As elsewhere, despite the presence of significant areas of landsurfaces > 100,000 y old (GNS Science 2008), ecosystems in a state of retrogression are relatively rare. In this paper we examine the role of loess as a vector of regressive pedogenesis and a mitigator of ecosystem nutrient depletion in this superhumid environment. We develop a new conceptual framework and an index to quantify the regressive effects of loess.

Study area

The study area is a sequence of shore-parallel coastal dunes on the prograding coastal plain west of the Southern Alps, north of the mouth of Haast River, South Island, New Zealand (MAT 11.3°C, precipitation 3455 mm/a; Hessel 1982). The dune ridges are densely forested with unmodified temperate rainforest consisting of conifers (*Dacrydium cupressinum*, *Prumnopitys ferruginea*) and angiosperms (*Weinmannia racemosa*, *Metrosideros umbellata*).

The oldest dune is ca 6500 years old, forming soon after the culmination of the post-glacial sea level rise (Gibb 1986). Younger dunes represent phases of coastal progradation and dune building associated with pulses of sediment brought down the Haast River. At least for the youngest six dunes, these sediment pulses correspond to periods immediately after large earthquakes generated on the range-bounding Alpine Fault (Wells and Goff 2006). The dune ridges have relief which varies from ca 2 to 15 m and are generally continuous or semi-continuous for up to 8 km. A uniform quartzo-feldspathic sand parent material, low variation in the Holocene climate and an undisturbed native vegetation cover (Eger and Almond in prep.) offer good conditions for soil and ecosystem chronosequence studies (Dickinson and Mark 1994; Palmer *et al.* 1986). A previously unpublished report by Palmer *et al.* (1986) presents four soil profiles of 360, 1000, 3000 and 6500 years of age. The sequence progresses from a typic udipsamment (acid brown soil) to several stages of placorthods (podsols).

Throughout the Holocene the braided Haast River has extended seaward and its bed has provided a source of silt which has been deflated by the dominant south-westerly winds (Marx and McGowan 2005), and now drapes the dunes. The loess mantle is limited to within 2 km down-wind of the river. The dune sequence thus provides two soil gradients: first, a gradient of soil age from youngest to oldest dune which we assume is only minimally affected by the regressive effect of loess, and second, a gradient of loess accession which decreases from close to the river to distant from the river (Figure 1).

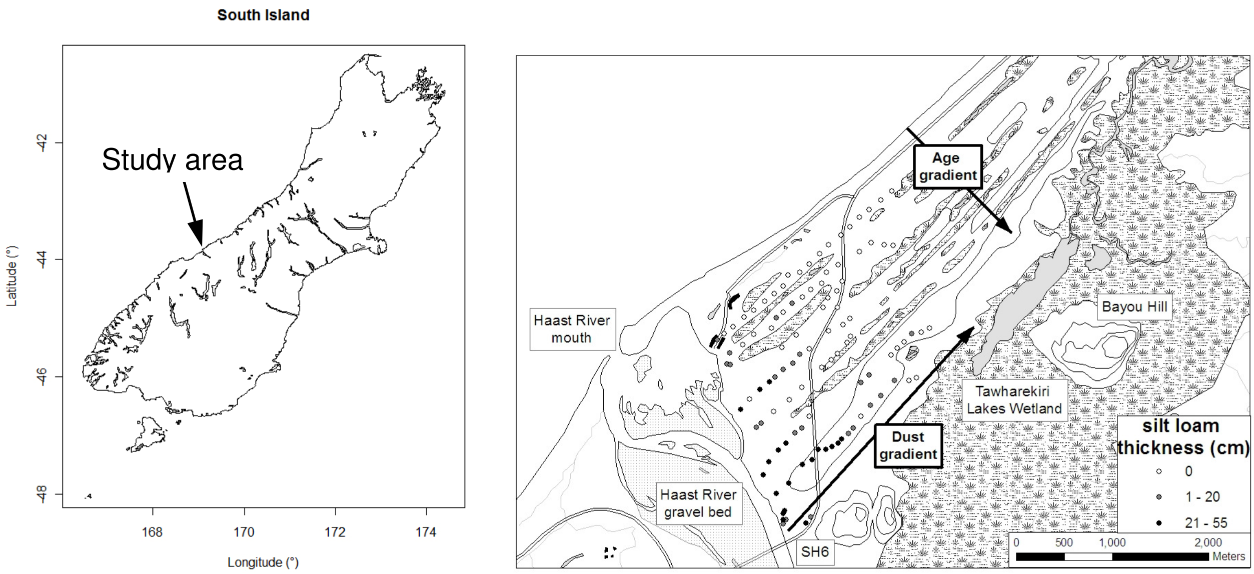

Figure 1. Location of the study area, the dune sequence NE of Haast River, with age and loess gradient.

Conceptual Framework and Methods

Our approach to quantifying regressive pedogenesis is based on the principle that addition of loess, if regressive, will result in a soil of a given age having properties consistent with those of a younger soil. How much younger quantifies the strength of the regressive effect. We calibrate the regressive effects of the loess by comparing soil chemistry and vegetation nutrient status along the loess gradient with chronofunctions of the same properties derived from the chronosequence. This concept is shown in Figure 2 where the red line shows a hypothetical chronofunction, and the blue line represents variation of the same soil or ecosystem property along the gradient of loess accumulation on the oldest (6500 y old) dune. A Regression Index (RI) is calculated from the ratio of apparent age of the soil ($S_{(age)}$), as adjudged by comparing soil/ecosystem properties with those of the chronosequence, to the age of the underlying dune ($P_{(age)}$ = 6500 y), as $RI = 1 - S_{(age)}/P_{(age)}$. Where there is no loess flux we expect $S_{(age)} \approx P_{(age)}$, and therefore RI ≈ 0; where the loess flux has had some regressive effect, $S_{(age)} < P_{(age)}$ and therefore RI > 0.

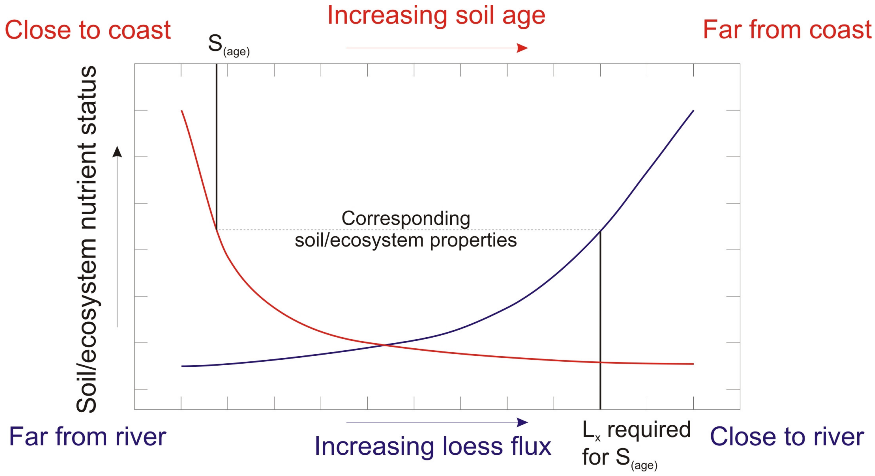

Figure 2. A hypothetical chronofunction for a soil/ecosystem property (red) and variation of the same property along the loess flux gradient on the 6500 y dune (blue). The apparent age $S_{(age)}$ of the soil affected by loess flux L_x is equal to the age at which a soil on the chronosequence would have the same value of that property.

Spatial variability of the loess flux was determined by an auger survey of the dune ridges, comprising ~100 sites drilled at 100-150 m intervals to a depth of 50 cm. So far, seven soil pits have been dug along the oldest dune to a depth of at least 130 cm, and sampled by corer according to soil horizons in 7.5 cm increments or less in the upper 50 cm, and 15 cm increments below 50 cm depth. Soil samples were dried, sieved to < 2 mm and analysed for pH (Blakemore *et al.* 1987), total element content by XRF (van Reeuwijk 2002), oxalate, pyrophosphate and dithionite extractable Al and Fe (Blakemore *et al.* 1987), different P fractions (Chen *et al.* 2000) and carbon/nitrogen by dry combustion (Burt 2004). Particle size distribution was determined according to the pipette method, after removal of organic matter and iron oxides from samples (Burt 2004), bulk density was determined from core samples and the compliant cavity method (Burt 2004).
A reconnaissance sampling of tree foliage from *Prumnopitys ferruginea*, *Dacrydium cupressinum* and *Weinmannia racemosa* was done at each soil pit site, using a shotgun to collect fully expanded, fresh leaves of sunlit branches. The leaves were stored in the dark and kept cool until processing in the laboratory. Sampling time was late February to early March when leaves are fully developed. Samples were dried, ground and digested in HNO_3 and analysed by ICP (Richardson *et al.* 2004).

Preliminary results

Along the chronosequence, increased horizonation is illustrated both morphologically and chemically by development of eluvial (E) and illuvial horizons (Bfm, Bh, Bs) over 1000 years of pedogenesis. Losses of soil nutrients are especially strong during the first 1000 years. At the oldest site, the amounts of P, Ca, K and Na are severely depleted to only 25%, 48%, 38% and 46% of the original parent material values, respectively. Initial profile dilation (+58%) mostly as a result of organic matter accumulation after 360 years becomes collapse (-36%) at the oldest site. The spatial variation of loess flux is reflected in the variation of thickness of a surface silt loam mantle over dune sand, which is thickest on the oldest dune and thins with increasing distance from the river bed (Figure 1). Reflecting their age, the younger dunes have received much less eolian material confined to locations very close to the river bed. Along the loess gradient, the decrease of the soil silt content (kg/m² for the upper 50 cm) in six selected soils on the oldest dune is statistically significant (e.g. for a log model: silt = a * log(distance) + z; $R^2 = 0.90$, $p < 0.01$).
The loess flux has a regressive effect on soil morphology. Closest to the river where silt loam thickness is 34 cm, the soil has the most weakly expressed podsol features, and loess accretion appears to be contributing to formation of an upbuilding Bw horizon (Almond and Tonkin 1999). Further away from the river, typical podsol characteristics become increasingly distinct. Well expressed eluvial/illuvial horizons and broken iron pans develop from 500 m away from the river under a thinner silt loam mantle of between 18 and 27 cm thickness. At a distance of >1800 m, silt loam textures are absent and the soils show continuous cemented iron pans. In contrast, there is no apparent regressive effect of the loess flux with respect to soil pH. The depth relationship is very similar in all studied profiles with very low values (<4) in the H horizons, values between 4 and 5 in eluvial/Bw horizons and an increase to around 5 in Bs horizons. This pattern is similar to the placorthods (≥ 1000 y old) in the chronosequence (Palmer *et al.* 1986). Results from our reconnaissance foliage sampling shows distinctly elevated concentrations of some nutrients for some species close to the river where the loess flux is greatest for example, for *Prumnopitys ferruginea* leaves have 1600 mg/kg P within 200 m of the river but decline to 800 mg/kg at a distance of > 600 m.

Conclusions

The highest loess flux rate (~0.05 mm/y) has a regressive effect on pedogenesis, limiting development of podsol features and maintaining a high foliar nutrient status. At 200 m downwind where loess flux rates decrease to 0.04 mm/y, this effect seems to become weaker as podsol features become more evident. A further decrease of the loess flux rate to 0.03-0.02 mm/y at 1000 m distance coincides with the first iron pans developing. Fertilisation effects as indicated by foliage nutrient status seem to reach no further than 600 m from the river. No regressive effect on soil pH was observed, suggesting rapid and strong acidification exceeding the buffer abilities of the deposited loess. Further work is currently under way to validate the rejuvenating effects of loess for additional soil and ecosystem parameters. Empirical functions relating the regressive effectiveness to loess flux rates for different soil and ecosystem parameters will be provided.

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