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Recovery of soil organic matter, organic matter turnover and nitrogen cycling in a post-mining forest rehabilitation chronosequence

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ABSTRACT

Recovery of soil organic matter, organic matter turnover and mineral nutrient cycling is critical to the success of rehabilitation schemes following major ecosystem disturbance. We investigated successional changes in soil nutrient contents, microbial biomass and activity, C utilisation efficiency and N cycling dynamics in a chronosequence of seven ages (between 0 and 26 years old) of jarrah (*Eucalyptus marginata*) forest rehabilitation that had been previously mined for bauxite. Recovery was assessed by comparison of rehabilitation soils to non-mined jarrah forest references sites. Mining operations resulted in significant losses of soil total C and N, microbial biomass C and microbial quotients. Organic matter quantity recovered within the rehabilitation chronosequence soils to a level comparable to that of non-mined forest soil. Recovery of soil N was faster than soil C and recovery of microbial and soluble organic C and N fractions was faster than total soil C and N. The recovery of soil organic matter and changes to soil pH displayed distinct spatial heterogeneity due to the surface micro-topography (mounds and furrows) created by contour ripping of rehabilitation sites. Decreases in the metabolic quotient with rehabilitation age conformed to conceptual models of ecosystem energetics during succession but may have been more indicative of decreasing C availability than increased metabolic efficiency. Net ammonification and nitrification rates suggested that the low organic C environment in mound soils may favour autotrophic nitrifier populations, but the production of nitrate (NO_3^-) was limited by the low gross N ammonification rates ($\leq 1\ \mu g\ N\ g^{-1}\ d^{-1}$). Gross N transformation rates in furrow soils suggested that the capacity to immobilise N was closely coupled to the capacity to mineralise N, suggesting NO_3^- accumulation *in situ* is unlikely. The C:N ratio of the older rehabilitation soils was significantly lower than that of the non-mined forest soils. However, variation in ammonification rates was best explained by C and N quantity rather than C:N ratios of whole soil or soluble organic matter fractions. We conclude that the rehabilitated ecosystems are developing a conservative N cycle as displayed by non-mined jarrah forests. However, further investigation into the control of nitrification dynamics, particularly in the event of further ecosystem disturbance, is warranted.

1. Introduction

Ecosystem rehabilitation aims to initiate or accelerate recovery of a disturbed ecosystem towards a desired, typically pre-disturbed, state. One of the largest bauxite mining operations in the world takes place in the jarrah forest of Western Australia. The mining company, Alcoa World Alumina Australia, has been operating in the jarrah forest since 1963 and mines and rehabilitates around 550 ha of forest annually (Colquhoun and Hardy, 2000). The current stated objective of rehabilitation is to establish a self-sustaining jarrah forest ecosystem (Grant, 2006). Assessment of the sustainability of post-mining ecosystems requires assessment of vegetation development as well as the development of organic matter quantity, quality and nutrient cycling processes. In jarrah forest rehabilitation ecosystems, successional development of the vegetation has been investigated in a number of studies (Grant and Loneragan, 2003; Grant, 2006; Norman et al., 2006) but relatively little attention has been given to the recovery of microbially driven soil organic matter turnover and mineral nutrient cycling.

Organic matter turnover and nutrient cycling are mediated by the activity of soil microorganisms and measures of soil microbial biomass, the proportion of soil organic carbon (C) present as microbial biomass C (microbial quotient) and the ratio of microbial respiration to microbial biomass C (metabolic quotient) can provide

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useful indices of ecosystem recovery within a rehabilitation context (Harris, 2003). Initial increases in soil microbial and metabolic quotients following ecosystem disturbance, and subsequent declines with increasing age of succession, has been observed previously in both primary and secondary successional ecosystems (Insam and Domsch, 1988; Schipper et al., 2001; Graham and Haynes, 2004). Patterns in microbial quotients in developing ecosystems are thought to reflect changes in organic matter quality and the availability of C to the soil microbial community. The use of soil metabolic quotients has been based conceptually on successional theories of ecosystem energetics (Odum, 1969), where a decline in metabolic quotient is interpreted as an increase in the efficiency of C utilisation with increasing ecosystem maturity (Insam and Haselwandter, 1989; Wardle and Ghani, 1995).

Following mining, or other severe disturbances, there is a potential for a net loss of soil nutrients due to rapid decomposition under conditions of devegetation (Vitousek and Reiners, 1975). In particular, losses of nitrogen (N) are often greater than losses of other nutrients (Vitousek et al., 1982). Odum's theory of succession states that mineral nutrient cycling will become more conservative (i.e. increased capacity to retain nutrients for cycling within the system) with increasing maturity (Odum, 1969). Alternatively, Vitousek and Reiners (1975) suggest that after the initial rapid loss of nutrients, the loss of nutrients that limit or are essential to plant growth will be lower in developing ecosystems, during periods of net biomass increase, than in mature ecosystems. The jarrah forest ecosystem is characterised by conservative biogeochemical nutrient cycling, which is most likely an adaptation to nutrient limitations resulting from the infertile nature of the ancient and highly weathered soils (O'Connell and Grove, 1996). Jarrah forest soil contains particularly low amounts of N in comparison to other Australian eucalypt forests and forests elsewhere (Hingston et al., 1981). Litterfall accounts for the majority of transfer of N to the forest floor, and consequently N mineralisation from organic matter in soil is critical to plant N supply (O'Connell and Grove, 1996). Export of N in stream water from a jarrah forest catchment has been estimated to be low (0.05 $\mathrm{kg\,ha^{-1}\,y^{-1}}$) and mostly in organic forms (Bell and Barry, 1980). Denitrification is unlikely to contribute significantly to N loss in these sandy-textured, well-drained soils (Barton et al., 1999). Thus, to fulfil the aim of returning a self-sustaining jarrah forest ecosystem post-mining it is expected that the rehabilitation ecosystems develop a conservative N cycle with minimal N loss.

Jarrah forest rehabilitation practices, which include seeding an understorey with high densities of native legume species and fertilisation with diammonium phosphate, have been designed to offset expected losses of N and promote rapid vegetation re-establishment (Ward et al., 1996). However, high legume density, relative to non-mined jarrah forest, persists in rehabilitation for at least 14 years (Norman et al., 2006) and total N concentrations in 15-year-old rehabilitation have been found to exceed that of the non-mined forest (Ward and Koch, 1996).

Increased N input into rehabilitation forest soil has the potential to decouple microbial C and N mineralisation processes which are linked through the C:N ratios of the actively mineralising fractions of organic matter. Of particular concern is that a greater accumulation of N, relative to C, within rehabilitation forests may favour nitrification activity (Schimel and Bennett, 2004). If increased losses of soil N through NO_3^- leaching are not balanced by future inputs of N, this has the potential to affect the long-term sustainability of a rehabilitated jarrah forest. It has also been demonstrated that contour ripping practices during site preparation, which create distinct undulations (mounds and furrows), result in significant spatial heterogeneity in organic matter accumulation and that this affects the distribution of soil NO_3^- (Todd et al., 2000). Thus, N cycling dynamics within rehabilitation forests may develop differently to that of a non-mined jarrah forest ecosystem.

The objectives of this study were to assess the recovery of soil organic matter, organic matter turnover and efficiency of C utilisation using biological indicators, and the recovery of N cycling in jarrah forest post-bauxite mining. Recovery was assessed by comparison of a chronosequence of forest rehabilitation to non-mined jarrah forest reference sites. Specifically, we hypothesised that soil microbial and metabolic quotients would decline with rehabilitation age, as observed in other successional ecosystems. We also hypothesised, with respect to N cycling, that (i) gross N transformation rates would increase with rehabilitation age; (ii) net nitrification in rehabilitation forest older than 10 years would exceed that of the non-mined forest, as a consequence of the faster accumulation of N derived from symbiotic N_2 fixation, relative to accumulation of C, and (iii) spatial distribution of organic matter in rehabilitation sites (as a consequence of contour ripping practices) would influence net nitrification rates.

2. Methods

2.1. Site description and soil sampling

The study sites were located in the northern jarrah (*Eucalyptus marginata*) forest region of Western Australia, approximately 110 km SSE of Perth (32°38′S, 116°06′E). The climate is of Mediterranean-type with a mean annual rainfall of 1200 mm, which mainly falls during the winter months and a mean daily minimum temperature range of 11 °C and a mean daily maximum of 23 °C. Fifty sites were selected which encompassed five replicates of seven ages of rehabilitation post-bauxite mining (0-, 3-, 6-, 10-, 14-, 18- and 26-year-old) and the three dominant site-vegetation types of non-mined jarrah forest in the region (SP, S and TS), classified according to the system described by Havel (1975). These three site-vegetation types are all dominated by an overstorey of jarrah and marri (*Corymbia calophylla*) but differ in understorey species composition. A list of indicator species used to classify site-types can be found in Havel (1975). Floristic differences are related to environmental factors including topography, soil moisture, soil leaching, acidity and soil fertility. Soils of P-type sites generally have sandier texture and lower nutrient content than S-type sites, while T-type sites are commonly found on loamier soils in the higher rainfall areas of the forest (Bell and Heddle, 1989). Each site was at least 5 ha in area and where feasible, replicate sites were geographically spread within the approximately 200 $\mathrm{km^2}$ study region (Fig. 1). Rehabilitation forest sites had not been exposed to fire and non-mined forest sites had not been burnt for at least 13 years prior to sampling.

Detailed descriptions of Alcoa's mining and rehabilitation practices have been published elsewhere (Colquhoun and Hardy, 2000; Grant, 2006). In brief, bauxite mining involves the complete removal of vegetation, topsoil (0–10 cm) and the underlying gravel layer (about 40 cm thick). After the removal of bauxite ore, soil is replaced from other mining areas either directly from a freshly cleared site or from stockpiled soil. The topsoil is contour ripped with the aim of relieving compaction, controlling surface water movement and improving plant root access to deeper layers. Ripping produces a distinct surface micro-topography (regular mounds and furrows separated by approximately 50 cm with an average mound height and furrow depth of 30 cm). Post-1988 rehabilitation sites were seeded with a jarrah and marri overstorey and a mix of 60–80 native understorey species and fertilised. Prior to 1988, non-indigenous tree species were used in rehabilitation. The overstorey species present within the study sites and site history details are shown in Table 1.

Composite soil samples were collected in May 2005 from three plots per site positioned to encompass topographical variation. Within rehabilitation, soil from the highest and lowest point of the