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Tropical plant communities modify soil aggregate stability along a successional vegetation gradient on a Ferralsol

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ABSTRACT

Soil aggregate stability is viewed as a promising indicator of the restoration status in eroded ecosystems, where the change in plant community composition through successional dynamics is a key driver of ecosystem restoration. In many tropical regions, ecological restoration is an important issue, but the relationship between different types of plant communities and soil aggregate stability is poorly understood. We examined how tropical plant communities modified soil aggregate stability along a successional vegetation gradient on a Ferralsol in New Caledonia. We identified five plant communities, ranging from an early (sedge dominated ecosystems) to a late successional stage (well-established, dense, mixed rainforest). Aggregate stability, total soil organic carbon (SOC) and iron and aluminium sesquioxides were measured in soil originating from each community. Results showed that aggregate stability of the Ferralsol was very high, even on eroded sites, likely due to the high levels of iron and aluminium sesquioxides. The levels of iron sesquioxides were particularly high ($> 10\%$), due partly to the frequency of wildfires in the region. Total SOC increased from sedge-dominated communities ($< 1\%$) to mixed rainforest ($> 3.5\%$). Aggregate stability was modified by plant cover and community composition and increased from sparse, early successional vegetation to late successional dense, mixed rainforest. Our study showed that certain plant species have a positive impact on soil aggregate stability and should be considered for ecological restoration on Ferralsols. e.g., *Costularia arundinacea*, *Garcinia amplexicaulis* and *Myodocarpus fraxinifolius*. In conclusion, we suggest that vegetation dynamics should be taken into account when investigating changes in aggregate stability in a context of ecosystem restoration.

1. Introduction

Soil aggregates are naturally occurring clusters or group of soil particles in which the forces holding the particles together are much stronger than the forces between the adjacent aggregates (Martin et al., 1955). Clustering and stabilization of soil particles in aggregates are complex processes (Six et al., 2004), influenced by soil characteristics (e.g. abiotic and biotic factors), vegetation (e.g. plant cover, fine root density), land management and climate (Bronick and Lal, 2005; Six et al., 2004). Aggregate stability is a measure of the erodibility of a soil and is defined as the extent to which soil aggregates resist falling apart when hit and wetted by rain drops (Le Bissonnais, 1996). Aggregate stability is seen as a key ecosystem process influencing carbon storage (Jastrow et al., 1998), nutrient availability (Wang et al., 2001) and resistance to erosion (Barthès and Roose, 2002). Among the numerous biotic factors, plant fine root density and mycorrhizal activity play crucial roles in aggregate stability (Graf and Frei 2013; Leifheit et al., 2014; Rillig and Mummey 2006; Tisdall and Oades, 1982). Thus, aggregate stability is viewed as a promising indicator of the restoration status of the site in eroded ecosystems (Burri et al., 2009).

In eroded ecosystems, the change in plant community composition through successional dynamics is a key driver of their restoration (Walker and del Moral, 2009). Several recent studies in sub-arid, Mediterranean or continental climates showed that aggregate stability increased along a successional gradient of vegetation (Cheng et al., 2015; Erktan et al., 2016; Lin et al., 2014; Qiu et al., 2015). In many tropical regions, such as New Caledonia, an archipelago in the south west Pacific ocean, ecological restoration is a major issue, especially on heavily eroded sites (Losfeld et al., 2015). Yet despite the increasing number of studies focusing on ecosystem restoration, soil aggregate stability remains a poorly understood process, and it is not known how stability is modified by tropical plant community composition.

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The New Caledonia archipelago is currently the fifth producer of nickel in the world (US Geological Survey, 2016), and nickel mining is one of the main causes of soil erosion (Dugain, 1953). Nickel mining will remain a major component of the island's economy in the coming decades, therefore programs aim at identifying suitable techniques for ecological restoration, as well as key indicators of success. In areas denuded by deforestation and forest fires, soils in the region are also prone to water erosion. Water erosion is the most significant cause of the degradation of lagoon ecosystems and fringing reefs, in particular during cyclonic floods (Dumas et al., 2010). A better quantification and mapping of potential erosion hotspots would improve management strategies, and soil aggregate stability could be used as an indicator of erodibility. However, to our knowledge, no studies exist providing evidence that aggregate stability could be used as a proxy for erodibility of tropical ultramafic soils such as those found in New Caledonia.

Apart from providing major nickel reserves, ultramafic substrates in New Caledonia also host a unique terrestrial biodiversity. A total of 1160 plant species, 95% of which are endemic to New Caledonia, are strictly restricted to ultramafic areas (L'Huillier et al., 2010), highlighting the necessity to preserve and manage soils hosting this unique flora (Isnard et al., 2016). Soils derived from ultramafic substrates in New Caledonia are found mainly in the south of the main island (Schmid, 1982) and are characterized by high contents of iron oxides and low concentrations of calcium (Ca), two abiotic parameters known to influence aggregate stability (Amézketa, 1999). Vegetation is represented by sclerophyllous shrubland formations (called maquis), and to a lesser extent by patches of rainforest (L'Huillier et al., 2010). The shrublands are floristically diverse and can be dominated by a single or several species, e.g. Tristaniopsis spp. (L'Huillier et al., 2010). These communities represent mostly secondary vegetation resulting from the degradation of the initial rainforests (Isnard et al., 2016). As successional phases progress, shrubland develops into rainforest, e.g. mixed rainforests or ectomycorrhizal monodominant rainforests (i.e. a forest where ≥ 50% of the canopy trees' cover, or basal area, or stems, or biomass, belongs to a single species (Connell and Lowman, 1989)). Nothofagus aequilateralis (Nothofagaceae) and Arillastrum gummiferum (Myrtaceae), two endemic tree species, commonly form monodominant rainforests on this part of the main island (Read and Jaffré, 2013). Their monodominance is related to competitive advantages due to disturbances (e.g., wildfires and cyclones) (Demenois et al., 2017) and not to differences in soil characteristics with adjacent mixed rainforest (Read et al., 2006).

In this study, we examined how tropical plant communities modified soil aggregate stability along a successional vegetation gradient on a Ferralsol in New Caledonia. We investigated five plant communities, representing five phases of vegetation succession. Communities ranged from sedge dominated ecosystems to well-established mixed rainforest. Results allowed us to identify potentially suitable plant species for restoring eroded soils, to determine if aggregate stability is a valid proxy for soil erodibility in New Caledonia. We also examined our results within the context of erosion mapping, and in particular the use of the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) on Ferralsols. USLE is an empirical model that calculates soil erosion, and which has not yet been tested in New Caledonia.

2. Materials and methods

2.1. Field sites

Studies were performed on two field sites located in the Massif du Grand Sud in New Caledonia (Fig. 1). The first site, called La Rivière Blanche (22°9′S – 166°41′E), is part of the Rivière Bleue Provincial Park. At the beginning of the 20th century, chromium mining and forestry were the main economic activities in the area, but have since been stopped. The second site, called Bois du Sud (22°10′S – 166°46′E), is part of a botanical reserve created in 2009. From the 1940s until late 1980s, logging of *Arillastrum gummiferum* occurred in the area. The two sites are only eight kilometres apart and are located at an altitude between 300 and 500 m. Mean annual precipitation is 3000 mm and the minimal and maximal mean annual temperatures are 20.5 °C and 26.6 °C (Météo France, 2016b). Both sites were selected according to three main criteria: (i) ultramafic substrates characteristic of the Massif du Grand Sud, (ii) sites comprised a Ferralsol with a slope < 30° and (iii) plant communities were typical of the ultramafic landscape and represented different successional vegetation stages.

2.2. Successional stages of vegetation

Five types of plant communities were examined:

(i) Sedge dominated communities with dominance of *Costularia nervosa* and *C. arundinacea* (Cyperaceae). These communities arise largely as a result of repeated shrubland fires. In these communities, sedges make up 20% of ground cover and are considered as an early successional stage (Fig. 2a).

(ii) *Tristaniopsis glauca* (Myrtaceae) (Fig. 2b) growing in open sclerophyllous shrubland with a maximum height of less than 2–3 m (Jaffré, 1970). *Tristaniopsis glauca* is ubiquitous in shrublands of the Massif du Grand Sud and is associated with ectomycorrhizal fungi (Amir and Ducousso, 2010).

(iii) Monodominant *Arillastrum gummiferum* rainforest which succeeds the sclerophyllous shrubland stage (Fig. 2c) Demenois et al. (2017). *Arillastrum gummiferum* usually occurs in extensive, monodominant stands (Sebert, 1874; Virot, 1956). The monodominance seems to persist because of frequent disturbance by wildfires (Demenois et al., 2017). *Arillastrum gummiferum* is monotypic, endemic to New Caledonia and is the sister taxon to the Australian genera of eucalypts (Ladiges and Cantrill, 2007). *A. gummiferum* grows exclusively on ultramafic substrates and is associated with ectomycorrhizal fungi (Papineau, 1989).

(iv) Monodominant *Nothofagus aequilateralis* rainforest, which is an early successional forest (Fig. 2d) (Read and Jaffré, 2013), forming monodominant stands (Read and Hope, 1996). Cyclone disturbances may be involved in the establishment and persistence of *Nothofagus* rainforests, at least at low or mid-elevations (Read and Jaffré, 2013). *Nothofagus aequilateralis* is endemic to New Caledonia, occurs on ultramafic substrates and is associated with ectomycorrhizal fungi (McCoy, 1991).

(v) Mixed rainforest, which is defined as a forest that is not dominated at its canopy by a single tree species (Fig. 2e). Nevertheless, plant species known to typically form monodominant stands can also be present, but as isolated trees.

2.3. Plant community composition

For each plant community, four plots of 20 m x 20 m were established as part of a permanent experimental research site (Gourmelon et al., 2016). All plots were separated from each other by at least 100 m. For each plot, plant coverage was assessed using the Braün-Blanquet abundance index (Braun-Blanquet et al., 1932). This method measures the percentage of plant coverage by using coefficients ranking from + (representing less than 1% of coverage) to 5 (between 75 and 100% of coverage). Plants were identified mostly at the species level with the support of the IRD Herbarium (Nouméa, New Caledonia). Plant names follow FLORICAL nomenclature (Morat et al., 2012). Non-metric multidimensional scaling (NMDS) (Kruskal, 1964a), conducted on the botanical inventory of each plot, indicated that all four plots from a same plant community were clustered together, allowing us to consider them as replicates for each community type.