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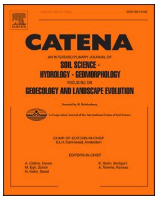

Revegetation as a driver of chemical and physical soil property changes in a post-mining landscape of East Kalimantan: A chronosequence study

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ABSTRACT

As a result of mixing soil materials from various natural soil horizons, mine soils generally have low organic C and total N content. In wet tropical climates where the vegetation is evergreen, we hypothesize that with the start of revegetation, the organic C and total N levels of the mine soils will recover rapidly and increase as the time since revegetation increases. The increase in organic C and total N content will have implications for changes in other soil chemical and physical properties. The development of mine soils in wet tropical climate conditions is so far rarely considered only. This study aims to determine changes in the physical and chemical properties of mine soils in the initial stages of formation triggered by the increasing time since revegetation. Soils from permanent observation plots in ex-coal mined sites divided by time since revegetation (0–12 years) were sampled together with an adjacent site with natural forest. Decisive soil physical and chemical properties were determined for the soils from 0 to 30 cm depth. With the increasing time since revegetation, there was a decrease in bulk density, and an increase in total soil porosity following a logarithmic equation. Linear changes with increasing time since revegetation were found for organic C, total N, and available P levels. The linear increase in organic C, total N, and available P levels, the logarithmic decrease in bulk density and the increase in total porosity with increasing time since revegetation suggest that these parameters are controlled by vegetation in the initial stages of mine soil development, while the polynomial changes in extractable P and K (25% HCl), CEC, exchangeable bases, base saturation percentage, and exchangeable Al over time suggest that these parameters can be assigned to processes independent of vegetation and are highly dependent on the composition of the original substrate.

1. Introduction

The reclamation of ex-coal mine sites begins by rearranging waste rock materials at predetermined locations with the shape, thickness, and slope as planned. The presence of sulphide minerals in waste rocks poses the risk of acid mine drainage. To avoid this, this type of rock is placed at the bottom of the reclamation area and then covered with non-acid forming waste rocks in a layer with a sufficient thickness (Sobek et al., 2000; Iskandar and Gautama, 2011; Pozo-Antonio et al., 2014). The waste rock is compacted during deposition. Unlike soils, waste rock is unstructured and generally has a high clay content and very low permeability. These properties make waste rock unsuitable for functioning as a plant growing medium. Hence, for revegetation purposes, the waste rock is covered with soil material that was previously peeled, collected and salvaged from the initial soil at the beginning of mining activities. Thus, the soil material, which is the growing medium for revegetation plants at the reclamation site of these former coal mines, is a mixture of soil materials derived from the A and B and sometimes also the C horizons of the original soils (Pratiwi et al., 2021). Depending on the availability, the thickness of the soil material distributed as a planting medium above the waste rocks generally varies from 50 to 125 cm. This planting medium is known as mine soil (Sencindiver and

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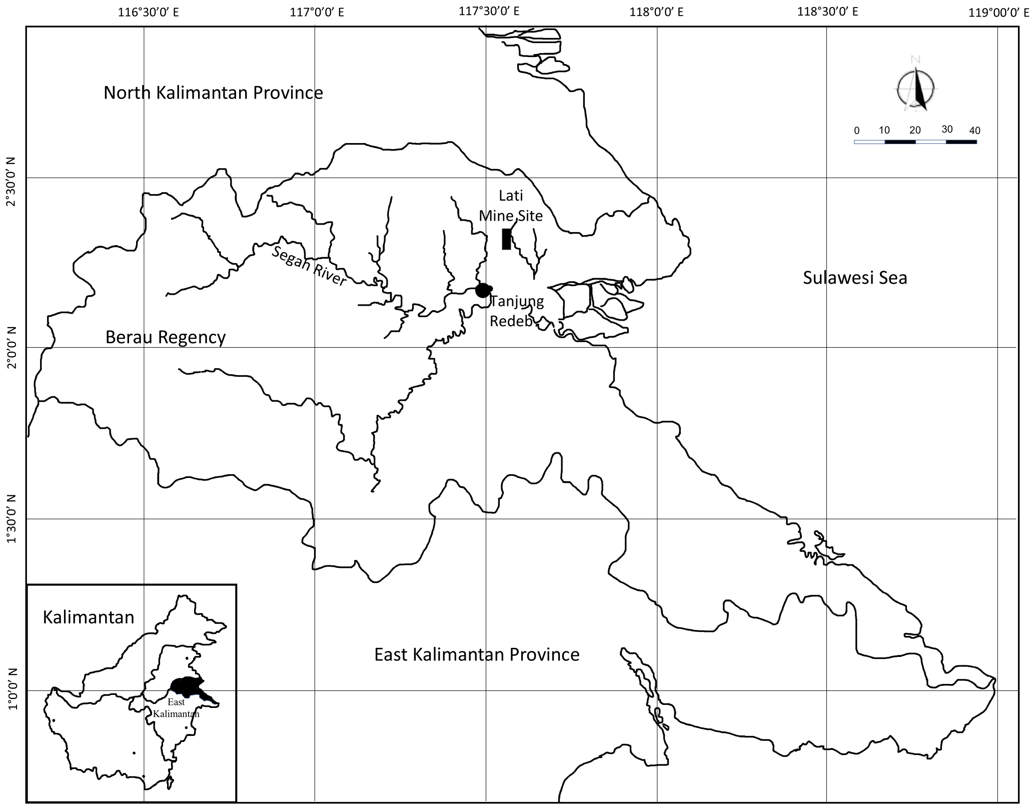

Fig. 1. Lati coal mine location in Berau Regency, East Kalimantan Province, Indonesia.

Ammons, 2000; Daniels et al., 2004; Zipper et al., 2013; Liu and Lal, 2014; Mukhopadhyay et al., 2014). The zero time for the mine soil development process is when the soil material is ready for use as a planting medium. The initial stages of pedogenesis of the mine soils are mainly related to the cover consisting of materials from former soil horizons and not to the waste rock underneath because the waste rock present at depths >50–125 cm is not affected much. The properties of the mine soil are directly controlled by the soil type and the physical and geochemical properties of the rock layers from which they originate (Sencindiver and Ammons, 2000; Mukhopadhyay et al., 2014; Iskandar et al., 2022). The technique of soil material collection and its backfill (Vicklund et al., 1996) implies that mine soils are often, to some extent, inhomogeneous, which makes investigations on soil formation challenging. Various studies have shown that revegetation generally has a positive effect on the improvement of the physical, chemical, and biological properties of mine soils. Thomas et al. (2000), Reynolds and Reddy (2012), and Mukhopadhyay et al. (2014) reported improvements in soil physical properties in the form of a decrease in bulk density and increases in porosity and infiltration, while Šourková et al. (2005), Pietrzykowski (2008) and Fu et al. (2010) reported increases in the C and N levels in mine soils after revegetation. Improvements can also occur for (micro)biological properties such as soil microbial biomass C, N, and P, as well as for fatty acid methyl ester (FAME) biomarkers for total biomass, bacteria, and fungi (Mummey et al., 2002; Dutta and Agrawal, 2002; Li et al., 2014). Vegetation type and litter quality were found to be more important that soil properties for the development of microbiological activity (Šourková et al., 2005). Revegetation in mine soil will increase root biomass and litter accumulation, which subsequently decompose to form soil organic matter (SOM). Increased levels of SOM will trigger changes in the soil structure and the physical chemistry of soils. SOM plays an important role in determining the water holding capacity, macropore formation, nutrient sequestration/adsorption, and (micro)biological diversity (Fu et al., 2010).

The effect of revegetation on the development of mine soils was studied for different climate regions, typically following an approach using the analysis of time sequences with chronological order for the study sites. Whereas Pietrzykowski (2008) and Asensio et al. (2013) conducted their studies under marine west coast climate conditions in Poland and Spain, respectively, Jitesh Kumar and Amiya Kumar (2013) and Mukhopadhyay et al. (2014) conducted research in the dry tropic climate of India. The results showed that, in general, increasing the age of the revegetation plants not only improved the overall quality of mine soils (Pietrzykowski, 2008; Asensio et al., 2013; Jitesh Kumar and Amiya Kumar, 2013; Mukhopadhyay et al., 2014; Noviyanto et al., 2017) but also improved the quality of the microclimate, i.e., reduced the temperature and increased the relative air humidity (Procházka et al., 2011; Zhao et al., 2015; Iskandar et al., 2019).

For the humid tropical climate of Indonesia, it can be assumed that the progress of pedogenesis is faster than that in any other climate. Despite the fact that the reclamation of mined areas is carried out extensively in Indonesia, studies on revegetation as a driver of chemical and physical soil property changes in post-mine landscapes and evaluations of the progress of soil formation in the initial stages are missing thus far. Under conditions where the addition of organic matter from plant debris takes place throughout the year, we hypothesize that plants and ground cover crops planted during revegetation produce a fairly high amount of organic matter, which is transferred through different pathways into the soil. The decomposition of high shares of organic matter introduced in the soil will take place over a relatively short time, and it can be assumed that several physical and chemical soil properties will be significantly affected. Here, the high temporal resolution determination of mine soil formation under the special conditions of the humid tropic climate rendering a relatively high input of organic matter into the soil is of particular interest.

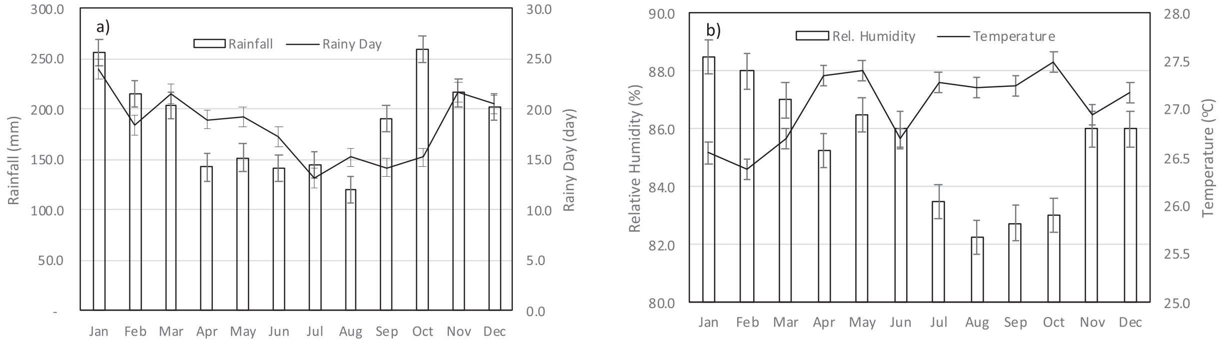

Fig. 2. Average rainfall and number of rainy days (a) and relative humidity and temperature (b) in Berau Regency in the 2014–2017 observation period.

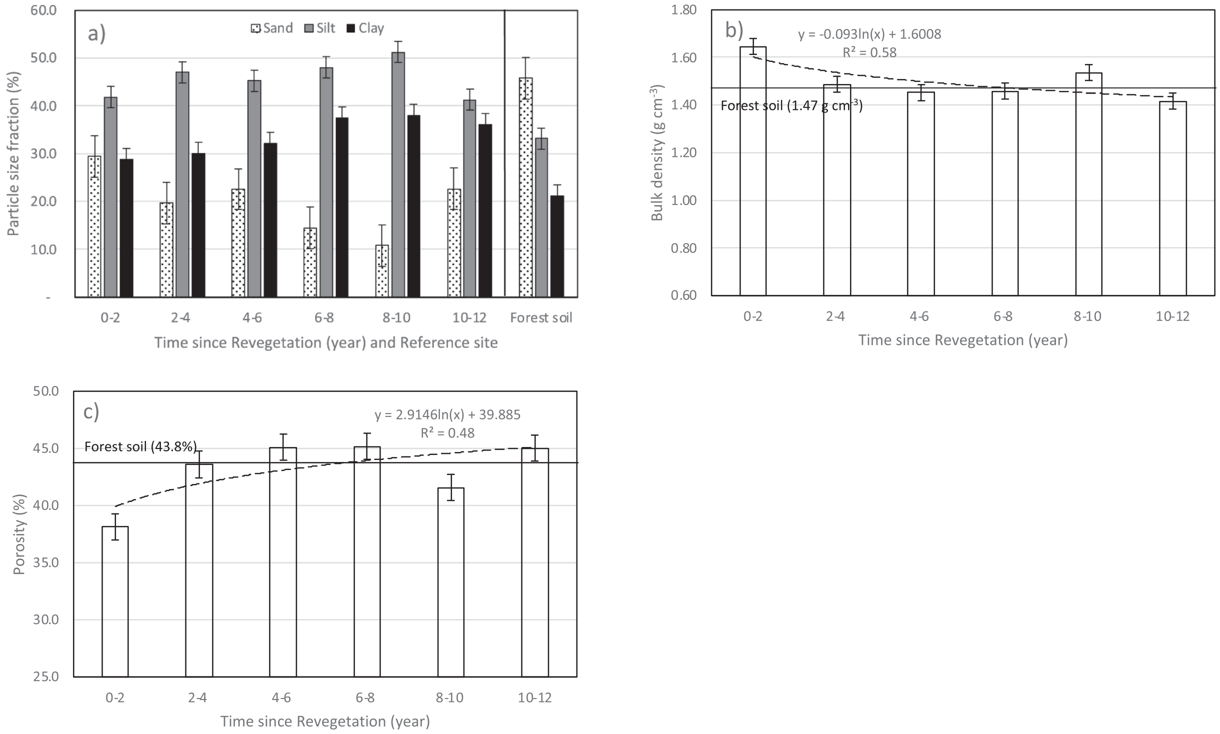

Fig. 3. Texture (a), bulk density (b), and total porosity (c) of mine soils at 0–30 cm depth in the Lati revegetated sites divided by time since revegetation. For comparison, data from an adjacent forest soil are shown.

2. Materials and methods

2.1. *Description of the study area*

The study was conducted at the Lati coal mine, Tanjung Redeb, Berau Regency, East Kalimantan (Fig. 1). This location was chosen because it has a systematically varied time for the reclamation of ex-mining areas, allowing chronosequence approaches to be used.

Geologically, the location is included in the Latih Formation, which is composed of sandstone rich in quartz, claystone, siltstone and coal in the upper part and the intercalation of sandy shale and limestone in the lower part (Situmorang and Burhan, 1995). The sandstone has a marked porosity and is poor in lithification. Under moisture conditions, a softening of the surface of the sandstone was observed indicating a low degree of cementation and a relatively high susceptibility for weathering.

According to the semi-detailed soil map of Berau Regency with a scale of 1:50,000 (IAARD, 2016), the initial soil type in this mine area is Typic Dystrudepts, characterized by an acidic pH, a moderate CEC, a low base saturation, a deep solum, and good drainage correlated with its sandstone parent material. Based on the 2014–2017 data, the average monthly rainfall in this region ranges from 120.3 to 259.6 mm, with the number of rainy days ranging from 13.3 to 24.0 days. During that period, the average air temperature ranged from 26.4 to 27.5 °C, while the humidity was approximately 82.3–88.5% (Fig. 2).

Soil materials, as a plant growth medium, are transported from the stockpile location using heavy trucks and distributed evenly on waste rock materials using bulldozers. Therefore, mine soil is compacted by the pressure from the use of heavy machinery. Types of vegetation introduced in the reclamation area include *Falcataria moluccana*, *Entorolobium cyclocarpum*, *Cassia siamea*, *Shorea balangeran*, *Acacia mangium*, *Macaranga* sp., and others. The population density of these pioneer plants, as the main revegetation tree species, is 625 trees/ha. The stand structure of plants in the group of 0–2 and 2–4 years since revegetation was still dominated by vegetation with seedling and sapling growth rates. The composition of the structure of the stand began to change in the group of >4 years after revegetation; for example, the growth rate of trees is more dominant in the areas with older vegetation than in the areas with saplings and poles (see images in Appendix 1). This indicates that the older the plant age since

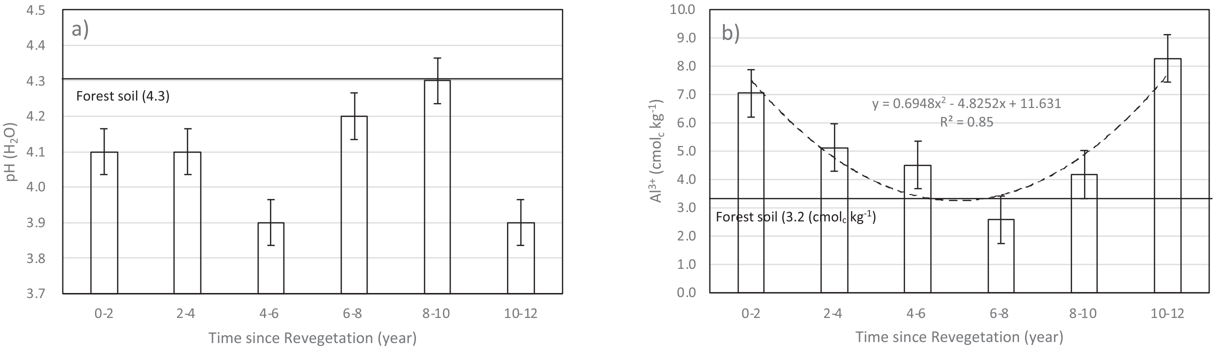

Fig. 4. Soil pH (a) and Al^{3+} in the soil sorption complex (b) at 0–30 cm depth in the Lati revegetated sites with time since revegetation of 0–12 years.

revegetation, the greater the amount of biomass produced by the plant. In all the observation plots, legumes such as *Centrosema pubescens*, *Calopogonium mucunoides*, *Pueraria javanica*, *Axonopus compressus*, *Chrysopogon aciculata* and grass were intentionally maintained as ground plants (see images in Appendix 2).

2.2. Soil sampling and analysis

Soil sampling was conducted periodically every year in August-October from 2014 to 2017 in permanent observation plots in ex-mining areas that were reclaimed and revegetated. Reclamation involved an arrangement of waste rock materials and their coverage with soil material of approximately 125 cm thickness. The permanent observation plots were grouped into the following categories: 0–2, 2–4, 4–6, 6–8, 8–10, and 10–12 years since revegetation. The soil on the 0–2 year observation plot is considered as a control representing the initial stage in mine soil development. For comparison, soil sampling was also carried out at undisturbed sites in adjacent natural forest areas. Selected photos from the soil profiles are presented in Appendix 3.

For the analysis of soil chemical properties, bulk soil samples were taken from the 0–30 cm soil depth, whereas for physical properties, undisturbed soil samples were taken approximately 5 cm below the soil surface using a sampling ring with a diameter of 7.5 cm and a depth of 4 cm.

Some parameters of the chemical and physical soil properties were measured as described by van Reeuwijk (2002): soil pH was measured at a soil: water ratio of 1:5 (w/v); exchangeable Al was determined using 1 N KCl extraction; soil organic C was measured using the Black and Walkey method; total N was measured according to the Kjeldahl method; available P was measured by the Bray-1 method; and the CEC and exchangeable cations of K, Na, Ca, and Mg were determined using the 1 N NH_4OAc extraction method at pH 7. The base saturation percentage was calculated from the CEC and exchangeable bases. Another parameter measured the potential reserves of P and K using extraction with 25% HCl according to Eviati and Sulaeman (2009). Particle size analysis for sand (0.05–2.0 mm), silt (0.002–0.05 mm) and clay (<0.002 mm) was determined using the combined sieve and pipette method as described by van Reeuwijk (2002). Bulk density was quantified using a ring sampler and the gravimetry method. Total porosity was calculated from bulk density (Wilke, 2005).

Each parameter of the physical and chemical soil properties was associated with each revegetation age group and correlated using a simple statistical equation to obtain the best R^2 value. Using linear and logarithmic or polynomially correlations between soil properties and revegetation age groups, it was tested whether soil properties were influenced by the time since revegetation.

3. Results and discussion

3.1. Change in physical properties of mine soil

Texture analysis of the top 30 cm of the soil revealed that at the natural forest site, a higher share of the sand fraction was contained than that in mine soils in the reclamation area, where the silt fraction was most common (Fig. 3a). Most likely, this difference in particle size distribution was not inherited from an inhomogeneity of the source rock. It was more likely that the mine soil contained different shares of soil materials derived from the A, B, and possibly C horizons, whereas the natural forest soil sample contained material from only the upper 30 cm layer.

With increasing time since revegetation, the soil bulk density decreased, and the total porosity increased (Fig. 3b, c). The bulk density of mine soils decreased from 1.64 ± 0.10 g cm^{-3} in the area of 0–2 years since revegetation to 1.42 ± 0.14 g cm^{-3} in the area of 10–12 years since revegetation. In comparison, the bulk density of the reference soil in the natural forest area was 1.47 ± 0.13 g cm^{-3}. This decreasing tendency of bulk density followed a logarithmic equation.

In a similar study, Mukhopadhyay et al. (2014) found that bulk density decreased from 1.56 g cm^{-3} in recently reclaimed mine soils to 1.39 g cm^{-3} in 17-year-old mine soil compared to 1.24 g cm^{-3} in the forest soil. The decrease in bulk density appeared to be closely related to the formation of aggregates in the mine soil, which was triggered by the growth of revegetation plants, in the form of both root development and the addition of organic matter. Kumar et al. (2013), Šimanský and Bajčan (2014), and Mukhopadhyay et al. (2014) also reported that an increase in SOM in mine soil increased aggregate stability. Angers and Caron (1998) explained that root penetration into the soil creates macropores, which will further facilitate fluid transport. Along with wetting and drying processes, root penetration creates a zone of failure that contributes to aggregate formation. Aggregate formation is also carried out by the entanglement by roots and the resulting exudate and by microflora and fauna that live using plant and root residues as a food source. Moreover, Lucas et al. (2019) showed that the formation of structures by plant roots in topsoil (0–20 cm) could be observed from the formation of a stable and connected biopore system that reached equilibrium within 6 years after reclamation. Ghezzehei (2012) explained that aggregate formation and stabilization occurred not only by biotic but also by abiotic factors, such as the presence of inorganic binding agents and wetting and drying cycles. In line with the decrease in bulk density, the total soil porosity of mine soil increased from 38.1 ± 4.7% in the reclamation areas of 0–2 years since revegetation to 45.0 ± 5.3% in the reclamation areas of 10–12 years since revegetation. The reference forest soil had a total porosity of 43.8 ± 5.8%. The tendency of increasing total soil porosity followed a logarithmic equation (Fig. 3c).

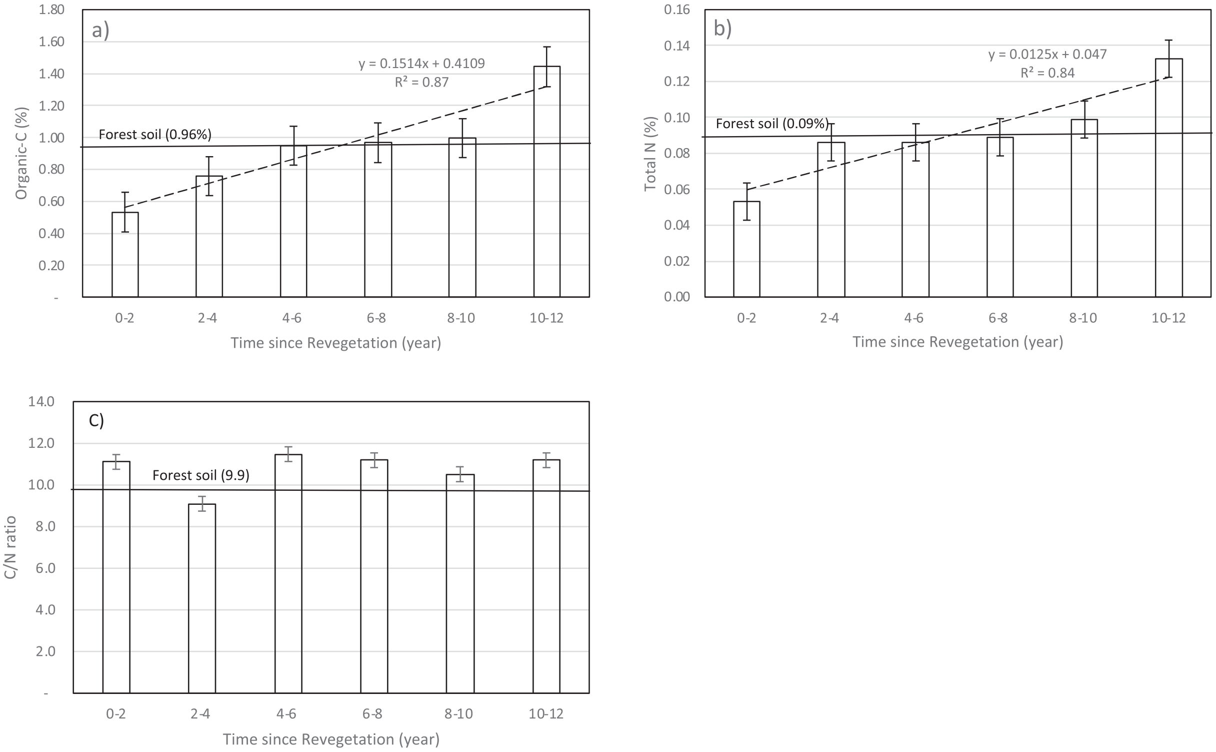

Fig. 5. Organic C (a), total N (b), and C/N ratio (c) levels of mine soil at a 0–30 cm depth in the Lati revegetated sites with time since revegetation of 0–12 years.

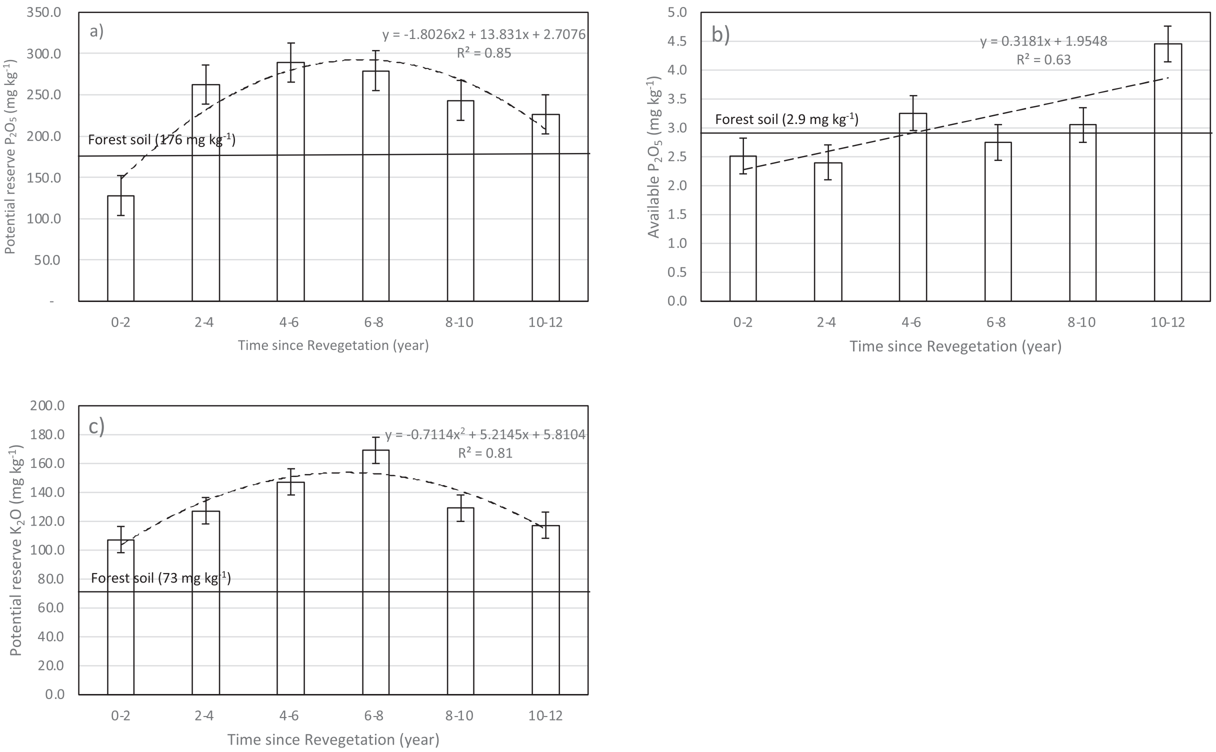

Fig. 6. Potential reserve of P (a) and available P (b), and potential reserve of K (c) levels of mine soils at 0–30 cm depth in the Lati revegetated sites with time since revegetation of 0–12 years.

3.2. Change in chemical properties of mine soil

Fig. 4a shows that the mine soils in the reclamation area had a pH of 3.9 ± 0.3 to 4.3 ± 0.1, which was slightly lower than the pH of the top 30 cm of the natural forest soils, which had a pH of 4.3 ± 0.4. This result showed that the mine soil used as a planting medium in the reclamation area had a marked variation in acidification. The low pH of mine soil was caused by the high Al^{3+} content in the soil sorption complex, as shown in Fig. 4b. The distribution of Al^{3+} followed the polynomial equations, which showed that the distribution of Al^{3+} was not in line

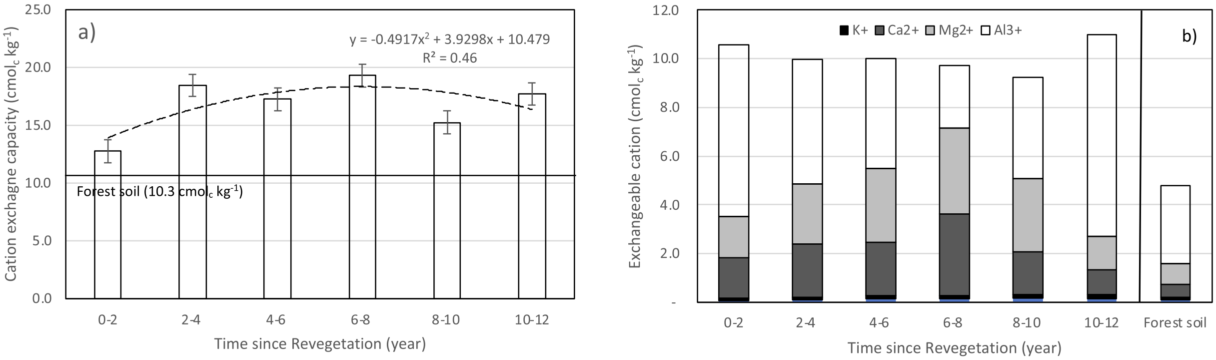

Fig. 7. CEC of mine soils at 0–30 cm depth (a) and content of the exchangeable cations K^+, Ca^{2+}, Mg^{2+} and Al^{3+} (b) in the Lati revegetated sites with time since revegetation of 0–12 years.

Table 1
Polynomial equations describing the distribution of the exchangeable cations of mine soils with time since revegetation of 0–12 years in the Lati sites.

No.	Type of exchangeable cation	Equation	R^2
1.	K^+	$y = -0.0045x^2 + 0.0461x + 0.0343$	0.93
2.	Ca^{2+}	$y = -0.2248x^2 + 1.4772x + 0.2753$	0.68
3.	Mg^{2+}	$y = -0.2901x^2 + 2.0488x - 0.2714$	0.91
4.	Al^{3+}	$y = 0.6948x^2 - 4.8252x + 11.631$	0.85

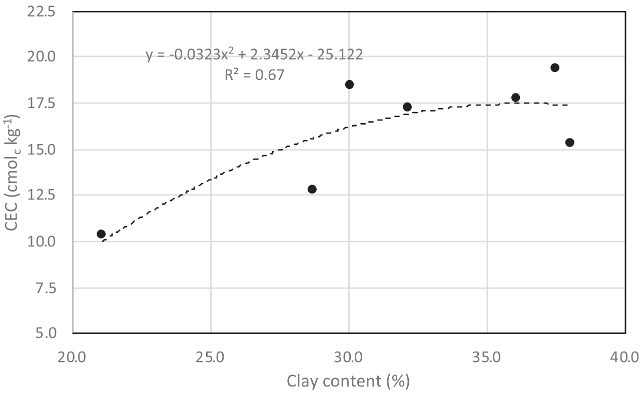

Fig. 8. Relationship between clay content and CEC values of the mine soils under investigation in the Lati revegetated sites.

Table 2
Relationship of clay content with some soil chemical properties in the Lati revegetated sites.

No.	Relation of clay content with	Equation	R^2
1.	Exchangeable Ca^{2+}	$y = 0.2027e^{0.0646x}$	0.42
2.	Exchangeable Mg^{2+}	$y = 0.2686e^{0.0635x}$	0.54
3.	Exchangeable K^+	$y = 0.0004x^2 - 0.0184x + 0.327$	0.69
4.	Base saturation	$y = -0.0879x^2 + 6.316x - 77.304$	0.38
5.	Potential reserve K_2O	$y = 3.7549e^{0.0365x}$	0.69
6.	Potential reserve P_2O_5	$y = -0.0065x^2 + 0.9414x - 0.3963$	0.33

with the increase in the revegetation plant age. The low pH of mine soils in the area of 4–6 years and 10–12 years since revegetation was suspected because the mine soil was accidentally sporadically mixed with pyrite-containing waste rocks. In areas that are highly contaminated by pyrite-containing waste rocks even grass as ground cover crops are difficult to grow (see image in Appendix 4).

As time since revegetation increased, the levels of organic C and total N in the mine soil increased from 0.53 ± 0.27% for organic C and 0.05 ± 0.03% for total N in 0–2-year-since revegetation to 1.44 ± 0.68% for organic C and 0.13 ± 0.06% for total N in the reclamation area of 10–12 years since revegetation. The organic C and total N contents of the top 30 cm of the natural forest soils were 0.96 ± 0.60% and 0.09 ± 0.05%, respectively. The increase in the organic C and total N contents in the mine soil followed linear equations (Fig. 5a and 5b). The strongly increasing levels of organic C and total N in mine soils originated not only from the litter and roots of pioneering plants but also from the legume cover crop and grass. Tambunan et al. (2017) found that legume cover crops, such as *Pueraria phaseloides*, *Centrosema pubescens*, and *Calopogonium mucunoides*, significantly increased the C and N levels of mine soil. Observations of species within the revegetation plants revealed that these plants were dominated by legumes (Fabaceae), which have the ability to fix N_2. Here, in turn, the decomposition of organic matter could contribute to the N stocks in the mine soil. For mine soils from the group of 8–10 years since revegetation and older, the C and N stocks exceeded those from the forest soil. The C/N ratio values in mine soils ranged from 9.1 ± 2.9 to 11.5 ± 1.9 in the reclamation area with an revegetation plants of 0–12 years since revegetation, while in the top 30 cm of the natural forest soils, it was 9.9 ± 1.2 (Fig. 5c). The value of the C/N ratio which was almost evenly distributed in all observation plots indicated that the organic matter decomposition took place rapidly since the beginning of revegetation in the 0–2 year group.

The organic C content in Lati mine soil increased in the top 30 cm of the soil from 0.53 ± 0.27% to 1.44 ± 0.68% within 12 years. A marked increase in organic C in mine soils within a few years of cultivation has also been reported in previous studies. In the temperate climate of Poland, the organic C content in sandy mine soils for Ai horizons (2.5–3.5 cm thickness) was 0.67% in the 17-year-old areas and 0.78% in the case of the oldest 25-year-old sites, while in the AC horizon (12.4–20.0 cm thickness), the organic C content was 0.12–0.16% (Pietrzykowski, 2008). Here, it must be considered that this sand mine cast was revegetated with Scots pine (*Pinus sylvestris* L.) and common birch (*Betula verrucose* Erhr.) and an initial 2-year cycle of cultivation of legume plants (mostly *Lupinus* sp.). For conditions in India with a dry tropical climate, Jitesh Kumar and Amiya Kumar (2013) found an increase in organic C levels in the 0–15 cm layer of sandy mine soils of 0.2% over a period of 10 years, whereas Mukhopadhyay et al. (2014) obtained organic C levels of 0.021% in 0–10 cm loamy sand mine soil with a tropical climate at the age of reclamation of 2 years, 1.15% at the age of 5 years and 2.25% at the age of 17 years. Both of these coal mine sites in India were revegetated with deciduous tree species, such as *Dalbergia sissoo*, *Cassia siamea* and *Acacia auriculiformis*.

The different organic C content levels in mine soils in these areas appeared to be closely related to climate, vegetation type, and soil texture. The types of trees planted in the respective reclamation areas were adapted to the local climate conditions. Unlike in temperate and dry tropical climates, trees in the wet tropics were always green throughout the year and contributed to the accumulation of litter and roots at any time, which then turned into soil organic matter. Litter and

Fig. 1. Reclamation area at various time since revegetation (years): (a) 0–2, (b) 2–4, (c) 4–6, (d) 6–8, (e) 8–10, (f) 10–12.

root contributions originated not only from trees but also from grasses and legumes as herbaceous ground cover. Herbaceous ground cover is stable for many years (see images in Appendix 2). The C content is also closely related to the soil texture. Mine soils containing a high amount of clay and silt will accumulate higher amounts of organic C than mine soils with a high share of sand fraction. Clay and silt particles have large specific surface areas and reactive sites capable of binding SOM (Ding et al., 2014; Yang et al., 2016). The interaction of clay and silt particles with these organic compounds will stabilize soil aggregates and C compounds within the aggregates (Oades, 1988).

The potential reserve of P levels in mine soils at the 0–30 cm soil depth ranged from 128 ± 57 to 289 ± 100 mg P_2O_5 kg^{-1} with a distribution following a polynomial pattern equation (Fig. 6a). The distribution obtained for a potential reserve of P content was in contrast to that of available P, which increased linearly from 2.5 ± 1.5 mg P_2O_5 kg^{-1} in the area of 0–2 years since revegetation to 4.4 ± 1.1 mg P_2O_5 kg^{-1} in the area of 10–12 years since revegetation (Fig. 6b). The potential reserve of the P level in the top 30 cm of the natural forest soil was 176 ± 75 mg P_2O_5 kg^{-1}, while the available P level was 2.9 ± 0.7 mg P_2O_5 kg^{-1}.

Obviously, increased levels of organic C and total N subsequently had a positive effect on the amounts of available P in the soil. Desorption of P, inducing availability to plants, can be influenced by pH, affecting the surface charge of soil constituents and DOM by ion competition (Negassa et al., 2008). Because the soil in this location is very acidic due to the dominance of Al^{3+} ions at adsorption sites (Fig. 4a and b), the P desorption, which increases with the increasing time since revegetation, was certainly due to the increase in SOM levels. Yang et al. (2019) showed in a study on the effects of organic matter on phosphorus adsorption and desorption in black soil that increasing levels of organic matter could efficiently increase the levels of available P by reducing the strength of P adsorption and the maximum buffering capacity of phosphates. According to Ch'ng et al. (2014), organic matter can effectively bind dissolved Al and Fe on acidic soils, releasing P from Al-P and Fe-P bonds. Unlike the C and N levels in mine soils that followed a linear equation with revegetation plant age, the distribution of the potential reserve of P levels followed a polynomial equation (Fig. 6a). This result showed that the potential reserve of the P level was not related to the time since revegetation but rather followed the P level in the "original" soil material from the natural forest.

The levels of K extracted with 25% HCl in the mine soil ranged from 107 ± 40 to 169 ± 90 mg K_2O kg^{-1} (Fig. 6c). In contrast, the top 30 cm of the natural forest soil contained 73 ± 20 mg kg^{-1} potential reserve K_2O, which was markedly lower than that in the mine soils of all

Fig. 2. Legume cover crops and grass as ground plants to prevent soil erosion at various time since revegetation (years): (a) 0–2, (b) 2–4, (c) 4–6, (d) 8–10.

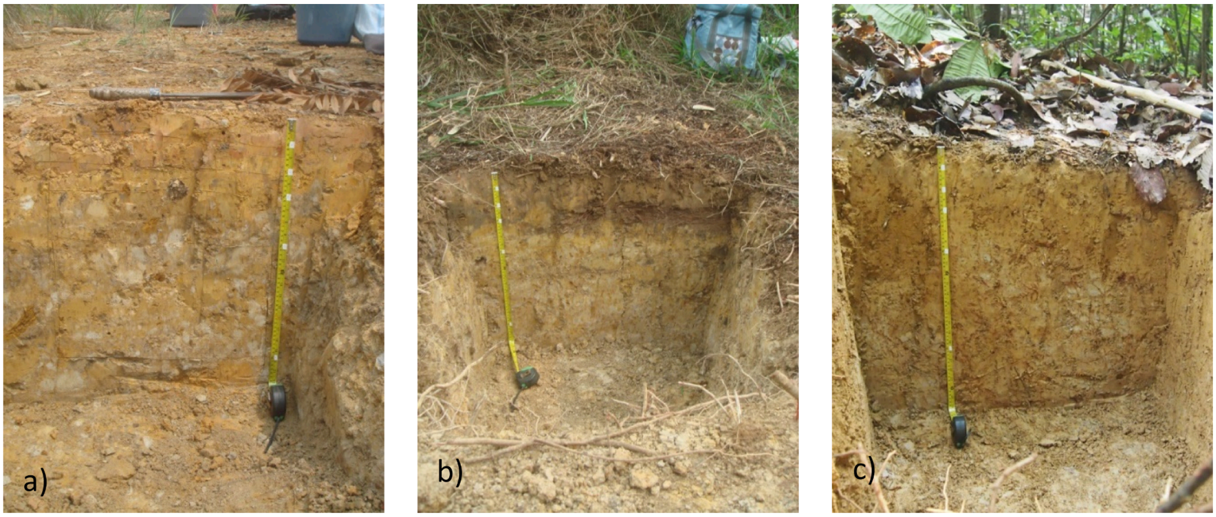

Fig. 3. Soil profiles at 0–2 years (a) and 4–6 years (b) since revegetation compared to the soil profile in the original forest (c).

different time since revegetation. This finding for potential reserve K_2O was similar to that for potential reserve P_2O_5 and might indicate a strong depletion of the macronutrients P and K in the topsoil under forest vegetation at the reference site. For mine soils, it must be considered that stocks of potential reserve P and K are replenished by the admixture of soil material from the B- and C-horizons. The increase and decrease in the potential reserves of K_2O and P_2O_5 in mine soils do not correlate with the increase in time since revegetation but show the nature of mine soils at each revegetated site. The distribution of K in the soil can also be affected by plant growth because plants take up large amounts of K nutrients and return them to the soil when the plants die. The main source of K in the soil is derived from mineral weathering (Brady, 1984; Manning, 2010). According to Sparks (2001), the total K content in the soil varies from 3000 to 100,000 kg ha^{-1} in the upper 0.2 m of the soil profile. From this amount, the weathering of fine litterfall in moist tropical forests in soils with medium fertility contributed only 41 ± 18 kg ha^{-1} of K (Vitousek and Sanford, 1986). In dry tropical forests, Raherison and Grouzis (2005) found that the K contribution from the dead aboveground organic matter fraction was 24.2 kg ha^{-1}. With such a small contribution, the amount of K in mine soils associated with plant growth was difficult to detect by the analytical method developed in this study.

The CEC of mine soils at the 0–30 cm soil depth in the reclamation area ranged from 12.8 ± 6.9 to 19.3 ± 10.6 cmol$_c$ kg^{-1} and spread

Fig. 4. Revegetation area contaminated with pyrit-containing waste rocks (arrow).

following a polynomial pattern (Fig. 7a). The top 30 cm in the natural forest soil used as a comparison in this study had a lower CEC, which was 10.3 ± 3.2 $\mathrm{cmol_c\,kg^{-1}}$. The CEC of the top 30 cm of this forest soil was lower than the CEC of the mine soils at various time since revegetation, which was in line with its low clay content (Fig. 3a). The particle size distribution could explain the observed polynomial pattern for the CEC to some extent, as in the top 30 cm of the 0–2 and 10–12 year since revegetation sites, and the sand content was highest in comparison (Fig. 3a).

The exchangeable cations were dominated by Al^{3+}, followed by Mg^{2+} and Ca^{2+}, and finally K^+ (Fig. 7b). The amount of exchangeable K^+ in the top 30 cm of the reclaimed soils varied from 0.08 ± 0.05 to 0.16 ± 0.07 $\mathrm{cmol_c\,kg^{-1}}$, from 1.04 ± 0.49 to 3.36 ± 1.91 $\mathrm{cmol_c\,kg^{-1}}$ for Ca^{2+}, from 1.38 ± 0.62 to 3.50 ± 0.48 $\mathrm{cmol_c\,kg^{-1}}$ for Mg^{2+} and from 2.58 ± 1.26 to 8.27 ± 0.90 $\mathrm{cmol_c\,kg^{-1}}$ for Al^{3+}. In comparison with the top 30 cm of the natural forest soil, the amount of exchangeable K^+ in mine soils was closest to the values from the reference site (0.11 ± 0.05 $\mathrm{cmol_c\,kg^{-1}}$), whereas exchangeable the levels of Ca^{2+} and Mg^{2+} were much lower (0.54 ± 0.20 $\mathrm{cmol_c\,kg^{-1}}$ and 0.84 ± 0.41 $\mathrm{cmol_c\,kg^{-1}}$, respectively) and the level of exchangeable Al^{3+} was 3.22 ± 0.43 $\mathrm{cmol_c\,kg^{-1}}$. The distribution of exchangeable cations in the Lati reclamation area followed the polynomial equations (Table 1), which showed that the distribution of cations was not in line with the increase in the time since revegetation. Such distribution patterns are thought to be inherited from the properties of the soil material introduced, i.e., soil texture and types and quantities of minerals in the soil materials.

3.3. General discussion

In contrast to the organic C levels, total N, and available P, which increased with increasing time since revegetation, some of the chemical soil properties described above, such as potential reserves of P_2O_5 and K_2O levels (Fig. 6a and 6c), the CEC (Fig. 7a) and the exchangeable Al^{3+}, Ca^{2+}, Mg^{2+}, and K^+ (Table 1), were spread following polynomial equation patterns and obviously not influenced by the time since revegetation. The principal course of these properties with time since revegetation appeared to be more strongly inherited from the inhomogeneous properties of the original soil material used in the time period of reclamation; in this study, it was mainly related to clay content. This result can be clearly derived from the relation between the clay content and CEC, where the CEC values of mine soils increased with increasing clay content (Fig. 8) following a polynomial equation with a strong correlation ($R^2 = 0.67$). Other soil properties, such as exchangeable Ca^{2+}, Mg^{2+}, K^+, the resulting base saturation and the potential reserve content of P_2O_5 and K_2O, correlated with the clay content, with R^2 values varying from 0.37 to 0.67 (Table 2).

4. Conclusions

Mine soil, which functions as a substrate for revegetation plants, was composed at the beginning of soil formation of materials derived from the A, B and sometimes C horizons. Often, it was a heterogeneous mixture, rendering varying pH values and different particle size distributions within the chronosequence of mine soils in comparison to the original topsoil material from the adjacent natural forest. Revegetation in the area of the former Lati coal mine site played a major role in the initial soil formation processes. In the early stages of soil development, the chemical properties of the mine soil controlled by vegetation were organic C, total N, and available P, where the parameters increased linearly with the increasing time since revegetation in a relatively short time. Vegetation also controls the physical properties of the soil, especially the decrease in bulk density and the increase in total porosity, which increased logarithmically with the increasing time since revegetation. Other soil chemical characteristics, such as the CEC, exchangeable bases, and levels of potential reserve P and K, changed following polynomial equations, which showed that these properties were more controlled by the nature of the original soil material and not by pedogenetic processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

See Fig. 1.

Appendix 2

See Fig. 2.

Appendix 3

See Fig. 3.

Appendix 4

See Fig. 4.

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