**NATURAL REGENERATION ON LAND DEGRADED BY COAL MINING IN A TROPICAL CLIMATE: LESSONS FOR ECOLOGICAL RESTORATION FROM INDONESIA**

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# **Abstract**

There are few examples of primary succession from tropical conditions, especially on land degraded by human activity, e.g. mine wastes. Such studies would assist in informing ecological restoration of these degraded sites. Here, a chronosequence approach was used to investigate early-stage primary succession on overburden spoil wastes derived from coal mining in a tropical climate over a 64-month period. Plant species composition and several micro-climatic and spoil physico-chemical and microbial properties were measured, and responses analysed using regression and multivariate (NMDS) analyses. A clear primary successional process was described showing that vegetation cover and species richness generally increased through time with a successional pathway from graminoids and herbs as the early dominants, shrubs in mid-succession and trees in the later-successional stages. Two important differences were noted between our results and primary successions elsewhere; a lower abundance of nitrogen-fixing species and the colonization by some late-successional shrubs and trees at the start. During the succession aggregate stability and organic matter (total C) increased –while electrical conductivity and some potentially toxic elements (Al, B) decreased. The constant high spoil moisture content appears to be an important determinant of vegetation development during primary succession and may be a factor in the rapid pace of succession detected here. The lessons for ecological restoration for coal overburden spoil under tropical conditions are that succession can proceed relatively rapidly.

**Key Words:** coal-mining, ecological restoration, tropical rainforest, species diversity, spoil physico-chemical properties, ecosystem development.

# **INTRODUCTION**

Man-made wastes produced by mining can have devastating effects, producing very degraded environments (Bradshaw, 1997). Indeed, the abiotic and biotic starting conditions often approximate to those of a natural primary succession (Marrs & Bradshaw, 1993; del Moral et al., 2007; del Moral & Walker, 2007). Where this occurs, the mine-spoil is composed largely of minerals with minimal amounts of organic matter and biota (Marrs & Bradshaw, 1993). On mine-wastes, therefore, primary succession often starts after dumping of newly-exposed materials (Walker et al., 2007).

Early successional trajectories are sensitive to site-speciﬁc conditions, founder effects and life-history attributes of the species involved (Walker & del Moral, 2003; del Moral & Titus, 2018), producing different trajectories even when in close proximity (Alday et al., 2011). Therefore, a better understanding of early successional process and the mechanisms that govern them on a greater range of sites is needed urgently to inform restoration operations and management decisions, and to contribute to the generalization of succession theory. To date no general theory of succession has emerged partly because successional trajectories are highly variable and can be very sensitive to site-specific conditions; therefore a large amount of data from many different sites are needed (Walker & del Moral, 2003). This particularly true for tropical areas because information concerning restoration is lacking; most studies of succession on degraded mine spoils come from temperate regions (Marrs & Bradshaw, 1993; Alday et al., 2012; Harantová et al., 2017).

Natural primary succession has been studied under tropical conditions, especially on islands produced by volcanic activity (Whittaker et al., 1989; Sutomo et al., 2011; Marler & del Moral, 2011), However, research on man-made wastes has concentrated on the assessment of the performance of planted species (Sudarmadji & Hartati, 2016) within technical restoration schemes (Prach & Hobbs, 2008). As natural colonization might prove a cost-effective alternative to these technical solutions, information on natural successional processes under tropical conditions on man-made wastes is needed urgently. Here, therefore we report a succession trajectory in an early-stage primary succession on overburden spoil heaps in South Kalimantan, Indonesia.

**1.1 Coal mining in Indonesia**

With reserves of ca. 21.1 x 109 tons (Prasodjo, 2011), coal mining in Indonesia is a major industry that contributes 4% to the country’s GDP (RBA, 2011). Most coal is extracted by opencast mining (Matsui et al., 2001), with approximately 7 x 106 ha of land impacted (Nugroho & Adman, 2011; Anon., 2014; Wijaya & Rahmad, 2014). By its very nature, opencast mining degrades large areas, not just within the mined area, but also through the tipping of large amounts of overburden on to the surrounding area (Alday et al., 2012). If this overburden is not revegetated quickly, there can be large-scale soil erosion with loss of any remaining topsoil (Maryati et al., 2012; Alday et al., 2012), with detrimental impacts on local water resources, sedimentation in rivers leading to increased flooding risks. Moreover, massive land clearance for coal mining in Indonesia is an additional pressure on primary forests, which are already under threat from logging for both timber and conversion to palm oil plantations. Dry-land forests appear most at risk from coal mining (Greenpeace Southeast Asia, 2014).

In order to be permitted to mine, the mining company must develop a reclamation and post-mining plan that includes re-contouring, topsoil soil spreading, installing appropriate drainage and re-vegetation (Maryati et al., 2012). For opencast mining this plan must include not just the area directly affected by mining, but also adjacent areas where large amounts of overburden are stored in external dumps. For an opencast mine, the extraction area and depth will depend on the coal reserves present, the prevailing economic conditions, and mining safety procedures (Anon, 2010), and the stripping ratio is a function of mined volume and amount of overburden present. After the overburden is dumped, rapid vegetation is needed, otherwise there can be large-scale soil erosion, loss of any remaining topsoil (Maryati et al., 2012; Alday et al., 2012), detrimental impacts on local water resources, and sedimentation in rivers leading to increased flooding risks.

In most situations, there is usually insufficient stripped topsoil to cover the overburden heaps, and they usually left to colonize naturally (Audit Board of the Republic of Indonesia, 2008). The spoil is infertile with a low organic matter content, little available N and P, low microbial activity (Rai et al., 2011) and a soil texture formed of loosely-mixed shale, stones, boulders, and cobbles (Gogoi et al., 2007; Maiti, 2007). The spoils may also contain elevated concentrations of trace metals (Al, Fe, Cr, Cu, Cd, Pb, Mo, Hg), which may be toxic to plants (Rai et al., 2011; Maiti, 2007). These conditions, therefore, present an ideal model system to study natural regeneration processes (Prach et al., 2013) under tropical conditions.

**1.2 Studies of succession on Indonesian coal overburden spoils**

Here, we describe the early-stages of natural colonization on coal mine overburden spoils under a tropical rainforest climate. The biodiversity found in most tropical areas is generally high (Brown, 2014), and, therefore, the large species pool in the areas surrounding the mines should provide the potential for a large variety of colonizing plant and animal species (Prach et al., 2017). The information gained from a description of the colonizing species and the factors limiting them, should assist in designing future restoration operations based on the principles of ecological restoration (Alday et al., 2012).

We describe a space-for-time study of the stages of early-succession on six overburden heaps in Kalimantan, Indonesia. Our aims were:

1. To describe the successional processes occurring on coal overburden wastes under tropical climatic conditions to contrast with those of temperate climates (Marrs & Bradshaw, 1993; Prach & del Moral, 2015).
2. To inform active restoration management of these overburden spoils heaps, to see if lessons learned could accelerate this process and increase restoration success (Prach & Hobbs, 2008).

# **METHODS**

# **2.1 Study Site**

The study was conducted at the Satui, coal mine in South Kalimantan, Indonesia (Figure 1, 115°07’51.34”-115°26’50.01”E; 03°46’20.78”-03°34’52.77”S). The overburden heaps are at an elevation of 30-120 m asl with slopes of 30-45o. The climate is a tropical rainforest climate (Af, Köppen classification, Peel et al., 2007) with a mean annual temperature of 27oC, a mean annual rainfall of 1856-3654 mm and a humidity of 73-85%. Temperatures are greatest in September/October and lowest in January. Rainfall is greatest between December and February (>250 mm/month).

# **2.2 Field survey methods**

We selected six mine sites of different ages to produce a successional chronosequence of 7, 10, 11, 42, 59, and 64 months after creation. Spoil-heap age was derived from mining company records for the time of final dumping.

At each site, vegetation was recorded between December 2009 and December 2010 using line transects placed along the long axis of the heap; these were used to ensure the range of variation within each spoil dump was sampled; i.e. the range of micro-topography, e.g. peaks, slopes, and valleys with contrasting moisture conditions (Novianti, 2013). The number of transects sampled on each heap differed (n = 38-101), because of the varying heap widths.

On each transect, the line-intercept method was used (Mueller-Dombois & Ellenberg, 1974); each plant species that was covered by the transect line was recorded as well as plant cover, estimated by measuring the width of each individual from the transect line. This cover measurement can produce a cover > 100% because of overlapping plants. Plant nomenclature follows Anon (2015). Simultaneously, site elevation and slope were measured using an altimeter (Thommen 15000ft, Switzerland) and a clinometer (Suunto PM-5/360 PC, Finland). The distance between the sampling positions and surrounding vegetation was also calculated using GPS (Garmin GPS 60, USA). Measurements were made at the top of the OB to the surrounding vegetation; the distance varied between heaps, ranging from a minimum of 0.006 to 1.080 km at the 59-month and the 42-month old heap respectively.

# **Measurement of environmental factors**

Light intensity (Lux, Extech 407026Heavy Duty Light Meter with PC, USA), air temperature (oC) and relative humidity (%, Elcometer 116C Sling Hygrometer, England), overburden temperature (oC, digital soil thermometer, USA), and moisture (%, soil tester Takemura DM-5, Japan) were measured from three randomly-sampled positions at each site. Monthly rainfall data were obtained from the mining company (Anon., 2010).

Substrates were sampled from three random positions at each site using a 5 cm diameter corer within the available rooting depth (0-30 cm). The sand, silt and clay fractions were determined using the pipette method (Allen, 1989) and aggregate stability was measured with an elutriation test (Kemper & Rosenau, 1986). Spoil pH was measured using a soil tester (Takemura DM-5, Japan) and total soil C and N were estimated using the Walkley and Black and Micro-Kjheldal methods respectively (Allen, 1989). Exchangeable cations, and available concentrations of P and S were measured using 1M ammonium acetate, Bray 1 and the Morgan Venema extraction methods respectively (Nelson & Sommers, 1982). Total concentrations of Al, B, Ca, Cd, Co, Cu, Cr, Fe, Pb, and Mn were estimated after digestion in *aqua regia* (Jackson, 1964). Finally, determination of substrate bacterial and fungal number was determined by agar plate counts (Atlas & Park, 1993) and the dominant bacterial and fungal species estimated by chemical tests (Alexopoulos et al., 1996; Vos et al., 2009).

# **2.4 Data Analysis**

All statistical analyses were performed within the R statistical environment (R Core Team, 2017; R v.3.4.0). First, a range of vegetation indices were calculated for each species at each site: (1) Density, (2) Relative density, (3) Frequency of occurrence, (4) Relative frequency, (5) Cover, (6) Relative cover and (7) Importance Value Index (IVI). In addition, the total vegetation cover and the area of bare ground were calculated. The determination of pioneer and follower plants was based on substrate particle size i.e., unbroken versus broken overburden (Martínez-Ruiz et al., 2001), i.e., pioneer species occurred in coarse materials (cobbles > 256 mm, pebbles 64-256 mm, gravels, 4-64 mm) and followers were found on spoil with a large fraction < 4mm, usually where there was also an undulating surface which caused faster substrate break-down and a greater moisture retention.

Second, a combination of linear regression, generalized linear modelling (glm) and non-linear regression respectively regression approach was used to investigate the relationships between plant community data and environmental variables with time.

Changes in plant community composition (species density) were assessed using Non-metric Multidimensional Scaling (NMDS) using the ‘metaMDS’ function within the ‘vegan’ package (Oksanen et al., 2017); this analysis produced an acceptable stress value of 0.22. The correlation with time since dumping was calculated with the ‘envfit’ function with 1000 permutations and 2-D standard deviational ellipse were fitted for each time period using the ‘ordiellipse’ function’. The cover data provided similar results to those for species density.

### **3. RESULTS**

### **3.1. Changes in plant community structure**

In total, 123 plant species were found (Supplementary material, Table S1). Vegetation cover increased linearly from 14-60% in the early stages (7-11 months) reaching a maximum of 178% after 64 months (y=16.80+2.15x, F1,4 =11.31, P=0.028; Figure 2a). Bare ground decreased linearly from 86% to <25% after 42 months, with the lowest being found in the 59 month old plot (<4%, y=80.88-1.18x, F1,4 =13.56, P=0.021; Figure 2b). There was significant increase in plant species richness with spoil age (y=3.139+0.305x, F1,4 =19.18, P=0.012) and diversity index (Shannon-Weiner, y=0.590 +0.011x, F1,4 =12.83, P=0.023). The rate of increase was greatest for species richness (Figure 2c, d, e).

The dominant species by sample time, i.e. the top ten based on Importance Values (Table 1) showed a successional progression from two annual herbs and a perennial liana at 7 months through a sequence leading to a mixture of annuals and perennial herbs and shrubs.

Eleven species were potential N-fixers, i.e. a member of the Fabaceae, Typhaceae, and Cannabaceae. Very-early colonists (*Typha angustifolia*, *Trema orientalis*, *Trema micrantha,* 7-64 months), *Mimosa pudica* and *Acacia mangium* present from 11 to 64 month, *Centrosema molle* and *Centrosema pubescens* from 59 to 64 months and *Desmodium heterophyllum* only at 64 months.

There was no significant difference between diversity measures and distance from extant vegetation over the measured range (0.006-1.08 km).

**3.2 Changes in plant community composition**

The chronosequence showed a clear pattern along the first NMDS axis with the 7, 10 and 11 year old sites being positioned closely together at the negative end (Figure 3a). The successional time sequence along first axis was highly significant (r2 = 0.61, P<0.001), with a slight positive movement for the 42 month site, but much greater movement towards positive-end for the 59 and 64 month sites (Figure 3a).

The dominant species occurred in four broad groups (Figure 3b) based on position along axis 1 from left to right. Group 1, early-successional species, including Poaceae (*Echinochloa colona*, *Paspalum conjugatum*), Typhaceae (*Typha angustifolia*), Cyperaceae (*Fimbristylis dichotoma* and *Rhynchospora corymbosa*) and the herb (*Alternanthera sessilis*). Group 2, early to-mid seral species, i.e., graminoids (*Paspalum dilatatum*, *Imperata cylindrical*, *Cyperus sulcinux*). Group 3 Late to-mid successional species, graminoids (*Scleria sumatrensis*, *Paspalum scrobiculatum*), ferns(*Pityrogramma calomelanos*, *Pteris vittata*)*,* lianas (*Passiflora foetida, Mimosa pudica*), and shrubs (*Clibadium surinamense*, *Trema orientalis*, *Chromolaena odorata*). Group 4, late-successional species, graminoids (*Neyraudia reynaudiana, Fimbristylis littoralis*, *Cyperus polystachyos*), trees (*Homalanthus populneus*, *Acacia mangium*), forbs(*Cyanthillium cinereum*, *Emilia sonchifolia, Porophyllum ruderale*, *Phyllanthus urinaria*). However, the proportion of potentially N-fixing species was relatively low (2-8.5% of total density and 7-19% of total cover) and showed no obvious pattern of change through time. The term early-, mid-, and later-successional species are used here within the context of early stage primary succession over a 5-year period because the vegetation changes from grass-dominated through to a shrub-forest community.

**3.3 Changes in environmental factors on the coal mine overburden dumps**

There was a large variation in the sampled micro-climatic variables (Figure S1), partly because of the relatively low sample numbers. Nevertheless, some general trends were identified. Spoil and air temperature showed similar modelled responses, increasing from the 7 month stage (25-31oC for both variables) through to 42 months (spoil= 29-45oC, air= 28-36oC) after which there was a decline (spoil= 25-33oC, air= 27-34oC; Figure S1). Air humidity averaged around 80%, although, the 42 month site showed a marked reduction (Figure S1). Importantly, spoil moisture content and showed no significant effects with time since dumping, with values ranging from 60-100%.

Spoil properties showed one of five directional responses during the chronosequence; examples are illustrated in Figure 4, the others along with the statistical properties of the fitted curves are illustrated in the Supplementary Materials (Figure S2, Table S2):

(a) Linear increase. This response was found for aggregate stability, total C (Figure 4a) and C:N ratio. Aggregate stability increased from 5.1% at 7 months to 56.4% at 64 months; corresponding for C were from 1.4% to 23.6% and C:N ratio from 5.2– 24.7.

(b) Linear decrease. This response was found for silt fraction, Al, and exchangeable Ca, Mg, K and Na. The silt fraction decreased from 75.8% at 7 months to 22.5% at 64 months (Figure 4b); corresponding decreases for Al were from 0.08 mg g-1 to 0.014 mg g-1, and all four exchangeable cations (all m-equiv 100g-1); Ca from 1.0 to 0.6, Mg from 8.6 to 0.11, K from 0.51 to 0.45, and Na from 2.65 to 0.64.

(c) Curvilinear response with dip in the middle. Soil pH covered more or less the same range throughout (pH = 3.2 – 6.2) but there was a significant mean reduction at the 42 month site (with a mean of pH = 4.5) (Figure 4c).

(d) Exponential decline. This response was found for B, electrical conductivity and exchangeable Ca; these variables had greatest values in the early stages (B = 0.0091 mg g-1, electrical conductivity = 2.80 mS cm-1), with a relatively rapid decline towards an asymptote (B = 0.0012 mg g-1, electrical conductivity = 0 mS cm-1(Figure 4d), and exchangeable Ca = 0.09 m-equiv 100g-1) at between 10 and 42 months.

(e) No change. This response was found for the sand and clay fractions, soil total N, available P, total Ca, the following metals Ca, Cd, Co, Cr, Cu, Fe, Pb, and Mn, SO4 (Table S3) and both bacterial and fungal counts. Three of these elements (Cu, Fe and SO4) were present in greater concentrations in the chronosequence than published ranges for “normal” soils; Cu = 0.002-0.2 mg g-1 and Fe = 0.03-0.3 mg g-1 (Pickering, 1980) and SO4 = >0.5 mg g-1 (Likus-Cieślik et al., 2017). Bacterial and fungal activities were low with a mean activity (SE) of 1.154±0.577 and 5.60±1.25 colony forming units (CFU); these values are many orders of magnitude lower (< x101 CFU g-1) than typical values for bacteria, actinomycetes and fungi in fertile soils (x109, x104, and x105 CFU g-1 respectively) (Estabrook & Yoder, 1998). The most common species detected (Table S4) showed some differences through the chronosequence. The actinomycete *Streptomyces* sp. was not detected in the 7-month-old site, but ubiquitous thereafter. The common bacterial species showed a sequence of occurrence through the succession with *Bacillus badius* and *Bacillus cereus* in the very early stage (7 months), *Pseudomonas pseudomallei*, and *Flavobacterium odoratum* in the middle stages, *Staphylococcus* sp., *Micrococcus lylae*, and *Bacillus licheniformis* in the late-stages. In contrast, *Micrococcus luteus* was detected at early- and late-stages (7 and 64 months). For the fungi, the successional sequence was less clear: *Penicillium* sp. was ubiquitous and the only species detected at 64 months. In the 7-month stage *Acremonium* sp. and *Cladosporium* sp. were detected, and between 10 and 59 months either *Fusarium* sp. or *Aspergillus* sp. were found.

**4. DISCUSSION**

### **4.1. Change in vegetation during succession**

The key result from this study is that within 64 months after cessation of tipping, primary succession was occurring on these coal overburden spoil heaps. Vegetation was becoming more complex, with increasing vegetation cover and species richness (Jones & del Moral, 2005), conforming to the usual orderly pattern (bare ground > grasses > shrubs > trees) proposed for primary successions (Huston & Smith, 1987; Glenn-Lewin et al., 1992). Here, the succession although dominated by graminoidsin the early stages and then sequentially replaced by forbs, shrubs (*Porophyllum ruderale*, *Clibadium surinamense*) and trees, two crucial differences were noted to the general pattern for primary succession. First, there were few N-fixing species present. The reason for this is unclear but could be because of a combination of at least three factors: (1) low densities of N-fixing species in the surrounding forests, (2) poor seed dispersal, and (3) a lack of *Rhizobium* bacteria in the spoil (Franco & de Fario, 1997). Second there was colonization by shrubs (e.g. *Chromolaena odorata, Trema micrantha, Trema orientalis*), and trees (*Ochroma pyramidale*, *Homalanthus populneus*, and *Mallotus paniculatus*) in the very early phases (within 7 months), act as pioneers and that the tolerance model of Connell and Slatyer (1977) operates in this primary succession from the start. Importantly, these “pioneer” shrubs and trees could be introduced within ecological restoration schemes to “kick-start” the successional process. Moreover, although this general sequence developed quickly, there was considerably heterogeneity with bare patches within each successional stage, almost certainly caused by substrate limitations, reducing the availability of germination safe-sites (del Moral & Wood, 1993; del Moral & Grishin, 1999).

Here, however, and again in contrast to other studies of primary succession (Tsuyuzaki et al., 1997; Lichter, 2000), no significant correlation was found between distance from the surrounding vegetation and either vegetation cover or diversity indices. Our results imply, therefore, that species availability is adequate within tropical climates if the distance between the donor and recipient sites is relatively low (here < 1.1 km). Initially, the species likely to migrate to the site quickly will almost certainly be pioneer species. The dominance of species in the Poaceae and Cyperaceae all with relatively small, wind-dispersed seeds support this view. However, seeds dispersed by bats (e.g. *Ochroma pyramidale*, *Morinda citrifolia*, *Piper aduncum*), birds (e.g. *Melastoma malabathricum*, *Leea indica*, *Lantana camara*, *Solanum torvum, Trema orientalis*)and humans (watermelon, *Citrullus lanatus*, melon *Cucumis melo,* possibly spread by mine workers) were also present.

Within any primary succession, the plant species that arrive will modify and improve substrate conditions for other species (Marrs & Bradshaw, 1993). This could be merely the addition of some organic matter through the turnover of annual species (e.g. *Echinochloa colona*, *Fimbristylis dichotoma, Fimbristylis littoralis*), nitrogen fixation (*Desmodium heterophyllum*, *Mimosa pudica*, *Calopogonium mucunoides, Senna alata*) or substrate reshuffling through root expansion and acid root secretions that break up rocks and gravel (e.g. *Ochroma pyramidale*) (Novianti, 2013).

We also produced a qualitative classification of all 123 species based on observed occurrence and performance during the succession (detailed Table S5). We classified the species into “pioneers”, those arrived and established quickly on very poor substrata and appear to facilitate the subsequent vegetation development and followers which appeared later. Five species were classified as “Pioneers”, the remaining 118 grouped subjectively according to mine spoil conditions. This classification is rudimentary but see it as a first approximation for guiding ecological restoration of mine spoils in Indonesia, and perhaps elsewhere in the tropics.

Whilst, chronosequence studies like this can be criticized because successional change is inferred from a series of sites of different age measured at the same time. Here, such site effects were minimized as the spoil was derived from the same geological substratum by the same company using the same methods. We believe that this is a useful approach to describe successional processes and inform ecological restoration but accept that our results need be tested over the longer period by continuous measurement.

### **4.2 Change in abiotic factors during succession**

During ecological restoration of mine spoils, there is an expectation that there will be improvements in microclimate and soil physical, chemical, and biological conditions (Bradshaw, 1997). This was detected here but these should be viewed with some caution because of the restricted number of replicates taken in this study for logistic reasons. Further investigations are needed to corroborate the.

The temperatures experienced were warm (25-48oC) as would be expected in a near equatorial site, but they peaked in the mid successional site (42 months) followed by a reduction. By contrast the air moisture content were lowest at 42 months. This suggests that temperatures and air moisture content were ameliorated by the vegetation as the succession progressed. Annual rainfall was also high (mean 3750 mm yr-1) resulting in relatively high soil moisture contents (60-100%). This constancy of a high spoil moisture content may be a major factor responsible for the speed of vegetation development found here, as has been suggested (Tsuyuzaki et al., 1997). However, there was also a large variability in the micro-climatic measurements throughout. It might result from differences in spot measurements on different days with slightly different weather conditions, but measurements were done randomly during the day to minimize these effects.

Some of the spoil properties were ameliorated through the succession. Most important was the increased aggregate stability from very unstable (5% at 7 months) to somewhat steady (50-60%) after 64 months (Soil Research Centre, 1983). This improved stability should create improved physical environment conditions for plant root development (Bradshaw, 1997). As the plant canopy cover increases, aggregate stability should increase further, and this will in turn provide a positive feedback improving plant growth (Nimmo & Parkins, 2002).

There was also an increase in soil C but no significant increase in total soil N. It is surprising that N does not change here. One reason might be the relatively low contribution of N-fixing species in the vegetation (< 8 % density, <20 % cover) which usually play a crucial role in ecosystem development in temperate mine spoils (Marrs & Bradshaw, 1993). If there is little N-fixation then the N supply for vegetation growth must come either from the atmosphere or from the breakdown of coal minerals in the overburden (Williams, 1975; Palmer et al., 1985).

The C:N ratio also increased significantly, from 5.2:1 to 24.7:1, and this appears to be driven by the increased C content. This is an important change because decomposition slows as C:N ratios increase above 20:1 (Alexander, 1999). This result is in keeping with the very low microbial activity measured. It is even possible that the low soil N accumulation coupled with the low microbial activity will result in a future N deficiency like that described for “moribund” grassland found on restored wastes in the UK (Marrs & Bradshaw, 1993).

Further changes in soil properties included a reduction in four soil exchangeable cations (Ca, Mg, K and Na) essential for plant growth (Miodrag et al., 2003). This may have been brought about through either leaching or by uptake by the developing plants.

Spoil pH covered a wide range throughout the chronosequence (pH = 3.2-6.2), with a reduced mean in mid succession. The pH would be classified as ultra-acid to slightly acid (US Department of Agriculture-NRCS, 2004).

Of the potentially toxic elements only Cu, Fe and SO4 were greater than the ranges of “normal soils” and there was no reduction in these elements through time. Significant linear or exponential reductions in electrical conductivity and both B and Al concentrations were, however, detected indicating an amelioration of conditions for these properties. The reductions in B and Al could occur either through leaching, adsorption on mineral particles, incorporation in soil organic matter or plant uptake (Marrs, 1993).

### **4.3 Conclusions**

The coal overburden at our study site in this tropical climate had severe nutrient deficiencies and high concentrations of some toxic elements, two common constraints in ecological restoration. The succession described here generally followed those elsewhere in that graminoids were replaced by herbs, shrubs and trees, a typical directional change in species composition and community structure (Huston & Smith, 1987), as well as improvement in some substrate properties. What is remarkable is the speed of succession, in that shrubs and trees colonize very quickly and dominate after only 64 months, probably because of the close proximity to a diverse species pool and the constant high spoil moisture content (Maharana & Patel, 2013). Two differences were found with respect to previously-described primary successions; the relatively low abundance of N-fixing species, keystone species in primary successions elsewhere (Marrs & Bradshaw, 1993; Chapin et al., 1994) and the rapid colonization by shrubs and some trees. This information contributes to our understanding of primary succession as well as providing information to help active restoration management on the coal in overburden spoils in tropical climates, particularly in Indonesia.

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Table 1.Top species with the top 10 importance values on the chronosequence on coal overburden spoils in Indonesia (Ah = annual herb, Ph = perennial herb, Ps = perennial shrub, Pl = perennial liana).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Species** | **Life-form** | **Time (months)** | | | | | |
| **7** | **10** | **11** | **42** | **59** | **64** |
| *Merremia peltata* | Pl | 11.8 |  |  |  |  |  |
| *Cyperus javanicus* | Ah |  | 6.9 |  |  |  |  |
| *Celosia argentea* | Ah |  | 20.1 |  |  |  |  |
| *Paspalum conjugatum* | Ph | 54.9 | 59.8 | 23.5 | 78.9 | 29 | 9.4 |
| *Fimbristylis dichotoma* | Ah | 39.4 | 40.8 | 14.8 | 21 | 16.4 |  |
| *Paspalum dilatatum* | Ph | 37.4 | 38.3 | 13.7 | 11.6 | 16.6 | 26.7 |
| *Rhynchospora corymbosa* | Ph | 27.6 | 14.8 | 29.2 | 21.6 | 13.7 |  |
| *Scleria sumatrensis* | Ah | 14.6 |  |  | 23.3 |  | 17 |
| *Typha angustifolia* | Ph | 14.1 | 29 |  |  | 10.5 |  |
| *Clibadium surinamense* | Ps | 11.2 |  | 21.7 | 30.4 |  | 31.1 |
| *Echinochloa colona* | Ah | 10.8 | 19.7 | 23.7 |  | 11.8 |  |
| *Imperata cylindrica* | Ph | 10.5 |  |  | 12.4 | 10.1 |  |
| *Alternanthera sessilis* | Ph |  | 10.9 | 22.8 |  |  |  |
| *Fimbristylis littoralis* | Ah |  | 23.9 |  |  |  | 13.4 |
| *Eragrostis japonica* | Ah |  |  | 12.4 |  |  |  |
| *Passiflora foetida* | Pl |  |  | 15.6 |  |  |  |
| *Trema orientalis* | Ps |  |  | 17.4 | 14.6 |  |  |
| *Cyperus sulcinux* | Ah |  |  |  |  |  |  |
| *Leptochloa chinensis* | Ah |  |  |  |  |  |  |
| *Ludwigia hyssopifolia* | Ph |  |  |  |  |  |  |
| Bryophyta | - |  |  |  |  |  |  |
| *Paspalum scrobiculatum* | Ph |  |  |  |  |  | 13.4 |
| *Mimosa pudica* | Pl |  |  |  | 12.4 | 13.7 |  |
| *Chromolaena odorata* | Ps |  |  |  | 14.6 | 14.7 | 7.8 |
| *Porophyllum ruderale* | Ah |  |  |  |  | 40.5 | 25.5 |
| *Eragrostis uniloides* | Ah |  |  |  |  |  | 13 |
| *Neyraudia reynaudiana* | Ph |  |  |  |  |  | 22.5 |

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Figure 1. The study area in South Kalimantan, Indonesia illustrating the overburden spoil heaps (From PT. Arutmin Indonesia).

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Figure 2. Change in (a) vegetation cover, (b) bare ground cover, (c) species richness, (d) Shannon-Weiner diversity index, and (e) Simpson’s diversity index. Mean values for each stage are presented (filled circles) along with fitted linear regression lines (±95%CL).

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Figure 3. NMDS biplots of species density in a chronosequence on overburden spoil heaps in Indonesia: (a) quadrats correlated with Time with 2D-SD ellipses for each site age; (b) dominant species. Species codes: Pc = *Paspalum conjugatum*, Fd = *Fimbristylis dichotoma*, Ta = *Typha angustifolia*, Rc = *Rhynchospora corymbosa*, Ec = *Echinochloa colona*, Pd = *Paspalum dilatatum*, Ic = *Imperata cylindrica*, Cs9 = *Cyperus sulcinux*, Ssu = *Scleria sumatrensis*, Ps = *Paspalum scrobiculatum*, To = *Trema orientalis*, Cs = *Clibadium surinamense*, Mpu = *Mimosa pudica*, Pca = *Pityrogramma calomelanos*, Co = *Chromolaena odorata*, Pv = *Pteris vittata*, Pf = *Passiflora foetida*, Hp = *Homalanthus populneus*, Nr = *Neyraudia reynaudiana*, Pru = *Porophyllum ruderale*, Fl = *Fimbristylis littoralis*, Es = *Emilia sonchifolia*, Pu = *Phyllanthus urinaria*, Cc = *Cyanthillium cinereum*, Am = *Acacia mangium*, Cpo = *Cyperus polystachyos*.

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Figure 4. Change in selected soil properties illustrating four temporal responses: (a) linear increase, total C; (b) linear decrease, silt fraction; (c) curvilinear responses dip in middle, spoil pH, and; (d) Exponential decrease, total B. Raw data are presented (filled circles) along with modelled responses. Detailed modelling results are presented in Table S2, along with all other significant relationships (Figure S1).

Table S1.Plant species and life-history classes detected in coal mine overburden (OB) heaps of differing ages in Indonesia (abstracted from Novianti, 2013 and Novianti et al., 2017).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | **Name** | **Family** | **Nature** | **Age of OB heap (month)** | | | | | |
| **7** | **10** | **11** | **42** | **59** | **64** |
| **Herbaceous** | | | | | | | | | |
| 1 | *Ageratum conyzoides* L. | Asteraceae | Annual |  |  |  | + | + | + |
| 2 | *Alternanthera pungens* Kunth. | Amaranthaceae | Perennial | + |  | + |  |  |  |
| 3 | *Alternanthera sessilis* (L.) R.Br. ex DC. | Amaranthaceae | Perennial | + | + | + |  | + | + |
| 4 | *Andropogon chinensis* (Nees) Merr. | Poaceae | Annual |  |  |  |  |  | + |
| 5 | *Axonopus compressus* (Sw.) P.Beauv. | Poaceae | Annual |  | + |  |  |  |  |
| 6 | *Blyxa japonica* Maxim. Ex Asch. & Gürke | Hydrocharitaceae | Annual |  |  | + |  |  |  |
| 7 | *Celosia argentea* L. | Amaranthaceae | Annual |  | + |  |  | + | + |
| 8 | *Centotheca lappacea* Desv. | Poaceae | Perennial |  |  | + |  |  | + |
| 9 | *Chloris barbata* Sw. | Poaceae | Perennial |  |  |  |  | + |  |
| 10 | *Christella dentata* (Forssk.) Brownsey & Jermy | Thelypteridaceae | Perennial |  |  |  | + |  |  |
| 11 | *Chrysopogon aciculatus* (Retz.) Trin. | Poaceae | Annual |  |  |  |  |  | + |
| 12 | *Conyza sumatrensis* (Retz.) E.Walker | Asteraceae | Perennial |  |  |  |  | + | + |
| 13 | *Cyanthillium cinereum* (L.) H.Rob. | Asteraceae | Annual |  |  | + |  | + | + |
| 14 | *Cynodon dactylon* (L.) Pers. | Poaceae | Perennial | + |  | + |  | + | + |
| 15 | *Cyperus babakan* Steud. | Cyperaceae | Annual |  |  | + |  | + |  |
| 16 | *Cyperus compactus* Retz. | Cyperaceae | Annual |  |  | + | + | + | + |
| 17 | *Cyperus compressus* L. | Cyperaceae | Annual |  |  |  |  | + | + |
| 18 | *Cyperus difformis* L. | Cyperaceae | Annual |  |  | + |  | + |  |
| 19 | *Cyperus entrerianus* Boeckeler | Cyperaceae | Annual |  |  |  |  | + | + |
| 20 | *Cyperus haspan* L. | Cyperaceae | Annual |  | + |  |  |  | + |
| 21 | *Cyperus iria* L. | Cyperaceae | Annual |  |  | + |  | + |  |
| 22 | *Cyperus javanicus* Houtt. | Cyperaceae | Annual | + | + | + |  | + | + |
| 23 | *Cyperus michelianus* (L.) Delile | Cyperaceae | Annual |  |  |  |  |  | + |
| 24 | *Cyperus polystachyos* Rottb. | Cyperaceae | Annual |  |  |  |  | + | + |

Table S1 (continued).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | **Name** | **Family** | **Nature** | **Age of OB heap (month)** | | | | | |
| **7** | **10** | **11** | **42** | **59** | **64** |
| 25 | *Cyperus pulcherrimus* Willd. ex Kunth | Cyperaceae | Annual |  |  | + |  |  | + |
| 26 | *Cyperus rotundus* L. | Cyperaceae | Annual | + |  | + | + |  | + |
| 27 | *Cyperus* sp.1 | Cyperaceae | Annual |  |  |  |  | + |  |
| 28 | *Cyperus* sp.2 | Cyperaceae | Annual |  |  |  |  | + |  |
| 29 | *Cyperus* sp.3 | Cyperaceae | Annual |  |  |  |  | + | + |
| 30 | *Cyperus* sp.4 | Cyperaceae | Annual |  |  | + |  | + |  |
| 31 | *Cyperus* sp.5 | Cyperaceae | Annual |  |  | + |  |  |  |
| 32 | *Cyperus* sp.6 | Cyperaceae | Annual |  |  | + |  |  |  |
| 33 | *Cyperus sulcinux* C.B.Clarke | Cyperaceae | Annual | + | + | + | + | + | + |
| 34 | *Dactyloctenium aegyptium* (L.) Willd. | Poaceae | Perennial |  |  |  |  | + |  |
| 35 | *Desmodium heterophyllum* (Willd.) DC. | Fabaceae | Annual |  |  |  |  |  | + |
| 36 | *Digitaria ciliaris* (Retz.) Koeler | Poaceae | Perennial |  |  | + |  |  | + |
| 37 | *Echinochloa colona* (L.) Link | Poaceae | Annual | + | + | + | + | + | + |
| 38 | *Eclipta prostrata* (L.) L. | Asteraceae | Annual |  |  |  |  | + |  |
| 39 | *Elaphoglossum blumeanum* J. Sm. | Lomariopsidaceae | Perennial |  |  |  |  | + | + |
| 40 | *Eleocharis dulcis* Hensch. | Cyperaceae | Perennial |  |  | + | + |  | + |
| 41 | *Eleusine indica* (L.) Gaertn. | Poaceae | Annual | + | + | + |  | + | + |
| 42 | *Emilia sonchifolia* (L.) DC. | Asteraceae | Annual |  |  | + | + | + | + |
| 43 | *Eragrostis amabilis* (L.) Wight & Arn. | Poaceae | Annual | + |  | + | + | + | + |
| 44 | *Eragrostis japonica* (Thunb.) Trin. | Poaceae | Annual |  | + | + | + | + | + |
| 45 | *Eragrostis leptostachya* (R.Br.) Steud. | Poaceae | Annual |  | + |  |  |  |  |
| 46 | *Eragrostis unioloides* Nees ex Steud. | Poaceae | Annual |  |  | + |  | + | + |
| 47 | *Erechtites valerianifolia* (Link ex Wolf) Less. Ex DC. | Asteraceae | Annual |  |  |  |  |  | + |
| 48 | *Eulophia graminea* Lindl. | Orchidaceae | Annual |  |  |  |  |  | + |
| 49 | *Fimbristylis dichotoma* (L.) Vahl | Cyperaceae | Annual | + | + | + | + | + | + |
| 50 | *Fimbristylis littoralis* Gaudich. | Cyperaceae | Annual | + | + | + | + | + | + |

Table S1 (continued).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | **Name** | **Family** | **Nature** | **Age of OB heap (month)** | | | | | |
| **7** | **10** | **11** | **42** | **59** | **64** |
| 51 | *Fimbristylis schoenoides* (Retz.) Vahl | Cyperaceae | Annual |  |  |  |  | + | + |
| 52 | *Fimbristylis* sp.1 | Cyperaceae | Annual |  |  |  |  |  | + |
| 53 | *Fimbristylis* sp.2 | Cyperaceae | Annual |  |  |  |  |  | + |
| 54 | *Hyptis capitata* Jacq. | Lamiaceae | Annual |  |  |  |  | + | + |
| 55 | *Imperata cylindrica*  (L.) P.Beauv. | Poaceae | Perennial | + | + | + | + | + |  |
| 56 | *Ipomoea aquatica* Forssk. | Convolvulaceae | Annual |  |  | + |  |  |  |
| 57 | *Kyllinga brevifolia*Rottb. | Cyperaceae | Annual |  |  |  |  |  | + |
| 58 | *Leersia hexandra* Sw. | Poaceae | Perennial | + | + |  | + | + | + |
| 59 | *Lindernia crustacea* (L.) F.Muell. | Scrophulariaceae | Annual |  |  | + |  | + |  |
| 60 | *Ludwigia hyssopifolia* (G. Don) Exell | Onagraceae | Perennial |  |  | + | + | + | + |
| 61 | *Melochia corchorifolia* L. | Sterculiaceae | Annual | + |  |  |  | + | + |
| 62 | *Mitracarpus hirtus* (Sw.) DC. | Rubiaceae | Annual |  |  | + |  |  |  |
| 63 | *Neyraudia reynaudiana* (Kunth) Keng ex Hitchc. | Poaceae | Perennial | + |  | + | + | + | + |
| 64 | *Panicum repens* L. | Poaceae | Perennial |  |  |  | + |  |  |
| 65 | *Paspalum conjugatum* P.J.Bergius | Poaceae | Perennial | + | + | + | + | + | + |
| 66 | *Paspalum dilatatum* Poir. | Poaceae | Perennial | + | + | + | + | + | + |
| 67 | *Paspalum scrobiculatum* L. | Poaceae | Perennial | + | + | + | + | + | + |
| 68 | *Phyllanthus urinaria* L. | Euphorbiaceae | Perennial |  |  |  |  | + | + |
| 69 | Poaceae sp.2 | Poaceae |  |  |  |  |  |  |  |
| 70 | *Polygala paniculata* L. | Polygalaceae | Annual |  |  |  |  |  | + |
| 71 | *Porophyllum ruderale* (Jacq.) Cass. | Asteraceae | Annual |  | + | + | + | + | + |
| 72 | *Pteridium esculentum* (G. Forst.) Cockayne | Dennstaedtiaceae | Perennial |  |  |  | + |  |  |
| 73 | *Rhynchospora corymbosa* (L.) Britton | Cyperaceae | Perennial | + | + | + | + | + | + |
| 74 | *Saccharum spontaneum* L. | Poaceae | Perennial |  |  |  |  | + | + |
| 75 | *Sacciolepis indica* Chase | Poaceae | Perennial | + | + |  |  |  | + |
| 76 | *Sacciolepis striata* Nash | Poaceae | Perennial |  | + |  |  |  |  |

Table S1 (continued).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | **Name** | **Family** | **Nature** | **Age of OB heap (month)** | | | | | |
| **7** | **10** | **11** | **42** | **59** | **64** |
| 77 | *Schoenoplectus mucronatus* (L.) Palla | Cyperaceae | Perennial |  | + | + | + |  |  |
| 78 | *Scleria ciliaris* Nees | Cyperaceae | Annual |  |  |  |  |  | + |
| 79 | *Scleria sumatrensis* Retz. | Cyperaceae | Annual | + | + | + | + | + | + |
| 80 | *Typha angustifolia* L. | Typhaceae | Perennial | + | + | + | + | + | + |
| **Liana** |  |  |  |  |  |  |  |  |  |
| 81 | *Araujia hortorum* E. Fourn. | Asclepiadaceae | Perennial |  |  | + |  | + | + |
| 82 | *Benincasa hispida* (Thunb.) Cogn. | Cucurbitaceae | Perennial |  |  | + |  |  |  |
| 83 | *Centrosema molle* Mart. ex Benth. | Fabaceae | Perennial |  |  |  |  | + | + |
| 84 | *Centrosema pubescens* Benth. | Fabaceae | Perennial |  |  |  |  | + | + |
| 85 | *Citrullus lanatus* (Thunb.) Matsum. & Nakai | Cucurbitaceae | Annual |  |  |  | + |  |  |
| 86 | *Hodgsonia heteroclita* Hook f. & Thomson | Cucurbitaceae | Perennial |  | + |  |  |  |  |
| 87 | *Merremia peltata* (L.) Merr. | Convolvulaceae | Perennial | + |  |  |  | + | + |
| 88 | *Mikania micrantha* Kunth | Asteraceae | Perennial |  |  | + |  |  | + |
| 89 | *Mimosa pudica* L. | Fabaceae | Annual |  |  | + | + | + | + |
| 90 | *Passiflora foetida* L. | Passifloraceae | Perennial | + |  | + | + | + | + |
| 91 | *Sphagneticola trilobata* (L.) Pruski | Asteraceae | Perennial |  |  | + |  | + |  |
| **Bryophyta** | |  |  |  |  |  |  |  |  |
| 92 | Bryophyta |  |  | + |  | + | + | + | + |
| **Ferns & Allies** | |  |  |  |  |  |  |  |  |
| 93 | *Blechnum orientale* L. | Blechnaceae |  |  |  | + |  |  | + |
| 94 | *Lycopodiella cernua* (L.) Pic.Serm. | Lycopodiaceae |  | + |  |  |  | + |  |
| 95 | *Lygodium microphyllum* (Cav.) R.Br. | Schizaeaceae |  |  |  | + | + |  |  |
| 96 | *Nephrolepis* sp. | Oleandraceae |  |  |  |  | + |  |  |
| 97 | Ferns sp.1 |  |  |  |  |  |  | + |  |
| 98 | *Pityrogramma calomelanos* (L.) Link | Adiantaceae |  | + |  | + | + | + | + |
| 99 | *Pteris vittata* L. | Pteridaceae |  |  |  | + | + | + | + |

Table S1 (continued).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | **Name** | **Family** | **Nature** | **Age of OB heap (month)** | | | | | |
| **7** | **10** | **11** | **42** | **59** | **64** |
| **Shrubs** | |  |  |  |  |  |  |  |  |
| 100 | *Blumea balsamifera* DC. | Asteraceae | Perennial | + |  |  |  | + | + |
| 101 | *Chromolaena odorata* (L.) R.M.King & H.Rob. | Asteraceae | Perennial | + | + | + | + | + | + |
| 102 | *Clibadium surinamense* L. | Asteraceae | Perennial | + | + | + | + | + | + |
| 103 | *Lantana camara* L. | Verbenaceae | Perennial |  |  |  |  |  | + |
| 104 | *Leea indica* (Burm.f.) Merr. | Leeaceae | Perennial |  |  | + |  |  | + |
| 105 | *Melastoma malabathricum* L. | Melastomataceae | Perennial | + | + | + |  | + |  |
| 106 | *Piper aduncum* L. | Piperaceae | Perennial |  |  |  |  |  | + |
| 107 | *Solanum torvum* Sw. | Solanaceae | Perennial | + | + | + |  | + | + |
| 108 | *Trema micrantha* (L.) Blume | Cannabaceae | Perennial | + | + | + | + | + | + |
| 109 | *Trema orientalis* (L.) Blume | Cannabaceae | Perennial | + | + | + | + | + | + |
| **Trees** | |  |  |  |  |  |  |  |  |
| 110 | *Acacia mangium* Willd. | Fabaceae | Perennial |  |  | + |  | + | + |
| 111 | *Homalanthus populneus* Kuntze | Euphorbiaceae | Perennial | + |  | + | + |  | + |
| 112 | *Macaranga gigantea* Müll.Arg. | Euphorbiaceae | Perennial |  | + |  |  |  |  |
| 113 | *Macaranga tanarius* (L.) Müll.Arg. | Euphorbiaceae | Perennial |  |  |  |  | + | + |
| 114 | *Mallotus paniculatus* (Lam.) Müll.Arg. | Euphorbiaceae | Perennial |  |  | + |  |  | + |
| 115 | *Morinda citrifolia* L. | Rubiaceae | Perennial |  |  |  |  |  | + |
| 116 | *Neolamarckia macrophylla* (Roxb.) Bosser | Rubiaceae | Perennial |  |  |  |  | + |  |
| 117 | *Ochroma pyramidale* (Cav. ex Lam.) Urb. | Bombacaceae | Perennial | + |  |  |  |  |  |
| 118 | *Palaquium gutta* (Hook.) Burck | Sapotaceae | Perennial |  |  |  |  |  | + |
| 119 | *Psidium guineense* Sw. | Myrtaceae | Perennial |  |  |  |  |  | + |
| 120 | Tree sp.1 |  | Perennial |  |  | + |  |  |  |
| 121 | Tree sp.2 |  | Perennial |  |  | + |  |  |  |
| 122 | Tree sp.3 |  | Perennial |  |  |  |  | + |  |
| 123 | Tree sp.4 |  | Perennial |  |  |  |  | + |  |

Table S2. Fitted parameters derived from the regression (glm and non-linear) analysis of environmental response variables through time on the chronosequence on coal overburden spoils in Indonesia. Non-linear equation was y=a-be-cx.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Regression model** | **Vector** | **Intercept** | **X1** | **X12** | **ΔAIC** |
| glm | Overburden spoil Temperature | 31.622  ± 0.198  \*\*\* | 29.505  ± 2.774  \*\*\* | -24.025  ± 2.774  \*\*\* | 129.6 |
| glm | Air Temperature | 30.007  ± 0.183  \*\*\* | 7.754  ± 2.019  \*\*\* | -18.593  ± 2.019  \*\*\* | 70.2 |
| glm | Air Humidity | 75.738  ± 0.653  \*\*\* | -3.961  ± 7.213  ns | 85.367  ± 7.213  \*\*\* | 91.1 |
| glm | Silt fraction | 48.5101  ± 3.9887  \*\*\* | -0.2829  ± 0.1209  \* | - | 3.41 |
| glm | Spoil pH | 5.02703  ± 0.06066  \*\*\* | -1.40641  ± 0.73790 | 4.70116 ± 0.73790  \*\*\* | 35.39 |
| glm | Aggregate stability | 15.1862  ± 4.5417  \*\* | 0.4110  ± 0.1377  \*\* | - | 6.23 |
| glm | Total Soil C | 1.61730  ± 0.88188 | 0.11709  ± 0.02674  \*\*\* | - | 13.38 |
| glm | C:N | 2.70673  ± 2.41097 | 0.31785  ± 0.07309  \*\*\* | - | 13.21 |
| glm | Exchangeable Ca | 4.64341 0.73343  \*\*\* | -0.06767 0.02224  \*\* | - | 6.51 |
| glm | Exchangeable Mg | 3.54569  ± 0.44154  \*\*\* | -0.04612  ± 0.01339  \*\* | - | 8.49 |
| glm | Exchangeable Na | 2.58436  ± 0.45635  \*\*\* | -0.03060  ± 0.01383  \* |  | 2.82 |
| glm | Exchangeable K | 0.635972  ± 0.045294 \*\*\* | -0.003351  ± 0.001373  \* | - | 3.33 |
| glm | Al | 0.033303  ± 0.003985  \*\*\* | -0.000328  ± 0.00012  \* | - | 4.99 |
|  |  |  |  |  |  |
|  |  | a | b | c | r2 |
| nlm | Electrical  Conductivity | -0.01232  ± 0.24933 | 5.04847  ± 4.33488 | -1.73348  ± 0.65697  \* | 48.9 |
|  |  |  |  |  |  |
| nlm | B | 0.0020333  ±0.000529  \*\*\* | 0.0090136 ± 0.006292 | -1.9802857  ± 0.863223  \* | 31.7 |

Table S3**.** Comparison of the spoil chemical concentrations between the chronosequence and comparison sites for those variable that did not show a significant temporal response in the chronosequence; mean values (±SE) and t values derived from Welch’s two-sample t- test for unequal sized samples and probability values are presented.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Element** | **Chronosequence** | **Comparison site** | **t** | **P-value** |
| Cd (mg g-1) | 0.003±0.001 | 0.0010±0001 | 3.09 | P<0.001 |
| Co (mg g-1) | 0.011±0.001 | 0.0014±0.0008 | 6.09 | 0.001 |
| Mn (mg g-1) | 0.643±0.052 | 0.221±0.084 | 4.10 | 0.013 |
| Pb (mg g-1) | 0.086±0.037 | 0.002±0.001 | 2.14 | 0.042 |
| SO4 (mg kg-1) | 3361±860 | 882±52 | 2.88 | 0.010 |
| Total Ca (mg g-1) | 8.9±1.2 | 14.9±1.7 | 2.80 | 0.039 |

Table S4.Microbial species detected in both the chronosequence and the comparison sites on coal overburden spoil heaps in South Kalimantan, Indonesia.

|  |  |  |
| --- | --- | --- |
| **Microbial group** | **Time (months)** | **Common species detected** |
| Bacteria/ | 7 | *Bacillus badius, Bacillus cereus, Micrococcus lylae* |
| Actinomycetes | 10 | *Streptomyces* sp., *Pseudomonas pseudomallei*, *Flavobacterium odoratum* |
|  | 11 | *Streptomyces* sp. |
|  | 42 | *Streptomyces* sp., *Flavobacterium odoratum*, |
|  | 59 | *Streptomyces* sp., *Staphylococcus* sp. |
|  | 64 | *Streptomyces* sp., *Micrococcus luteus*, *Micrococcus lylae*, *Bacillus licheniformis* |
| Fungi | 7 | *Penicillium* sp., *Acremonium* sp., *Cladosporium* sp. |
|  | 10 | *Penicillium* sp., *Fusarium* sp. |
|  | 11 | *Penicillium* sp., *Aspergillus* sp. |
|  | 42 | *Penicillium* sp., *Fusarium* sp. |
|  | 59 | *Penicillium* sp., *Aspergillu*s sp. |
|  | 64 | *Penicillium* sp. |

Table S5.Classification of all species into ”Pioneers” and “Followers” based on subjective “observations” (Novianti, 2013).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Pioneer** |  | **Follower** | | | | | | |
| **Rough/Dry substrate** |  | **Smooth-substrate/Flooded** |  | **Moist** |  | **Moist/Dry** | | |
| *Celosia argentea* |  | *Blyxa Japonica* |  | *Desmodium heterophyllum* |  | *Acacia mangium* | *Eulophia graminae* | *Phyllanthus urinaria* |
| *Echinochloa colona* |  | Bryophyta |  | *Eclipta prostrata* |  | *Ageratum conyzoides* | Fern sp.1 | *Piper aduncum* |
| *Paspalum conjugatum* |  | *Cyperus babakan* |  | *Ipomoea aquatica* |  | *Alternanthera pungens* | *Hodgsonia heteroclita* | Poaceae sp.2 |
| *Pityrogramma calomelanos* |  | *Cyperus compactus* |  | *Lindernia crustacea* |  | *Alternanthera sessilis* | *Homalanthus populneus* | *Polygala paniculata* |
| *Pteris vittata* |  | *Cyperus compressus* |  | *Ludwigia hyssopifolia* |  | *Andropogon chinensis* | *Hyptis capitata* | *Porophyllum ruderale* |
|  |  | *Cyperus difformis* |  | *Rhynchospora corymbosa* |  | *Araujia hortorum* | *Imperata cylindrica* | *Psidium guineense* |
|  |  | *Cyperus entrerianus* |  | *Scleria ciliaris* |  | *Axonopus compressus* | *Lantana camara* | *Pteridium esculentum* |
|  |  | *Cyperus haspan* |  | *Scleria sumatrensis* |  | *Benincasa hispida* | *Leea indica* | *Saccharum spontaneum* |
|  |  | *Cyperus iria* |  |  |  | *Blechnum orientale* | *Leersia hexandra* | *Sacciolepis indica* |
|  |  | *Cyperus javanicus* |  |  |  | *Blumea balsamifera* | *Lycopodiella cernua* | *Sacciolepis striata* |
|  |  | *Cyperus michelianus* |  |  |  | *Centotheca lappacea* | *Macaranga gigantea* | *Selaginella microphylla* |
|  |  | *Cyperus polystachyos* |  |  |  | *Centrosema molle* | *Macaranga tanarius* | *Solanum torvum* |
|  |  | *Cyperus pulcherrimus* |  |  |  | *Centrosema pubescens* | *Mallotus paniculatus* | *Sphagneticola trilobata* |
|  |  | *Cyperus rotundus* |  |  |  | *Chloris barbata* | *Melastoma malabathricum* | Tree sp.1 |
|  |  | *Cyperus* sp.1 |  |  |  | *Christella dentata* | *Melochia corchorifolia* | Tree sp.2 |
|  |  | *Cyperus* sp.2 |  |  |  | *Chromolaena odorata* | *Merremia peltata* | Tree sp.3 |
|  |  | *Cyperus* sp.3 |  |  |  | *Chrysopogon aciculatus* | *Mikania micrantha* | Tree sp.4 |
|  |  | *Cyperus* sp.4 |  |  |  | *Citrullus lanatus* | *Mimosa pudica* | *Trema micrantha* |
|  |  | *Cyperus* sp.5 |  |  |  | *Clibadium surinamense* | *Mitracarpus hirtus* | *Trema orientalis* |
|  |  | *Cyperus* sp.6 |  |  |  | *Conyza sumatrensis* | *Morinda citrifolia* |  |
|  |  | *Cyperus sulcinux* |  |  |  | *Cyanthillium cinereum* | *Neolamarckia macrophylla* |  |
|  |  | *Eleocharis dulcis* |  |  |  | *Cynodon dactylon* | *Nephrolepis* sp. |  |
|  |  | *Fimbristylis dichotoma* |  |  |  | *Dactyloctenium aegyptium* | *Neyraudia reynaudiana* |  |
|  |  | *Fimbristylis littoralis* |  |  |  | *Digitaria ciliaris* | *Ochroma pyramidale* |  |
|  |  | *Fimbristylis schoenoides* |  |  |  | *Elaphoglossum blumeanum* | *Palaquium gutta* |  |
|  |  | *Fimbristylis* sp.1 |  |  |  | *Eleusine indica* | *Panicum repens* |  |
|  |  | *Fimbristylis* sp.2 |  |  |  | *Emilia sonchifolia* | *Paspalum dilatatum* |  |
|  |  | *Kyllinga brevifolia* |  |  |  | *Eragrostis amabilis* | *Paspalum scrobiculatum* |  |
|  |  | *Schoenoplectus mucronatus* |  |  |  | *Eragrostis japonica* | *Passiflora foetida* |  |
|  |  | *Typha angustifolia* |  |  |  | *Eragrostis leptostachya* |  |  |
|  |  |  |  |  |  | *Eragrostis uniloides* |  |  |
|  |  |  |  |  |  | *Erecthites valerianifolia* |  |  |

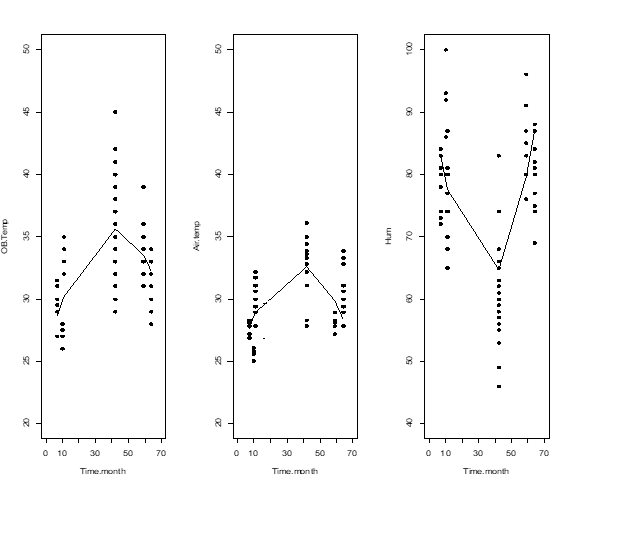


Figure S1**.** Changes in microclimatic factors (a) overburden and (b) air temperatures, and (c) atmospheric humidity in a chronosequence on overburden spoil heaps in Indonesia. Raw data are presented for main chronosequence are presented (filled circles) along with fitted modelled responses (glm). Fitted values from the modelling analyses are presented in Table S2.

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Figure S2. Significant relationship between soil properties in a chronosequence on overburden spoil heaps in Indonesia classified according to type of response: (a) linear increase, aggregate stability and C:N ratio; (b) linear decrease, silt fraction, Al and exchangeable Ca, Mg, K and Na, and; (c) Exponential decrease, electrical conductivity. Raw data are presented for main chronosequence (filled circles) along with modelled responses (glm, nlm). Fitted values from the modelling analyses are presented in Table S2.