

RESEARCH ARTICLE

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, for example, 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 microclimatic and spoil physicochemical and microbial properties were measured, and responses analysed using regression and multivariate (nonmetric multidimensional scaling) 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 midsuccession, 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—whereas 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.

KEYWORDS

coal mining, ecological restoration, ecosystem development, species diversity, spoil physicochemical properties, tropical rainforest

1 | 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 (del Moral & Walker, 2007; del Moral, Walker, & Walker, 2007; Marrs & Bradshaw, 1993). 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, Walker, & del Moral, 2007).

Early successional trajectories are sensitive to site-specific conditions, founder effects, and life-history attributes of the species involved (del Moral & Titus, 2018; Walker & del Moral, 2003), producing different trajectories even when in close proximity (Alday, Marrs, & Martinez-Ruiz, 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 is particularly true for tropical areas because information concerning restoration is lacking; most studies of succession on degraded mine spoils come from temperate regions (Alday, Marrs, & Martínez-Ruiz, 2012; Harantová et al., 2017; Marrs & Bradshaw, 1993).

Natural primary succession has been studied under tropical conditions, especially on islands produced by volcanic activity (Marler & del Moral, 2011; Sutomo, Fardila, & Eka Putri, 2011; Whittaker, Bush, & Richards, 1989). 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 $\sim 21.1 \times 10^9$ tons (Prasodjo, 2011), coal mining in Indonesia is a major industry that contributes 4% to the country's gross domestic product (RBA, 2011). Most coal is extracted by open-cast mining (Matsui, Shimada, Kramadibrata, & Rai, 2001), with approximately 7×10^6 ha of land impacted (Anon., 2014; Nugroho & Adman, 2011; 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 (Alday et al., 2012; Maryati, Shimada, Hamanaka, Sasaoka, & Matsui, 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 postmining plan that includes recontouring, topsoil soil spreading, installing appropriate drainage, and revegetation (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 (Alday et al., 2012; Maryati 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 are 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, Paul, & Singh, 2011), and a soil texture formed of loosely mixed shale, stones, boulders, and cobbles (Gogoi, Pathak, Dowarah, Deka, & Boruah, 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 (Maiti, 2007; Rai et al., 2011). 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, Tichý, Vítovcová, & Řehouňková, 2017). The information gained from a description of the colonizing species and the factors limiting them should assist in designing future restoration operations on the basis of 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 as follows:

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).

2 | METHODS

2.1 | Study site

The study was conducted at the Satui, coal mine in South Kalimantan, Indonesia (Figure 1; $115^{\circ}07'51.34''$ – $115^{\circ}26'50.01''$ E; $03^{\circ}46'20.78''$ – $03^{\circ}34'52.77''$ S). The overburden heaps are at an elevation of 30–120 m asl with slopes of 30–45°. The climate is a tropical rainforest climate (Af, Köppen classification; Peel, Finlayson, & McMahon, 2007) with a mean annual temperature of 27°C, a mean annual rainfall of 1,856–3,654 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).

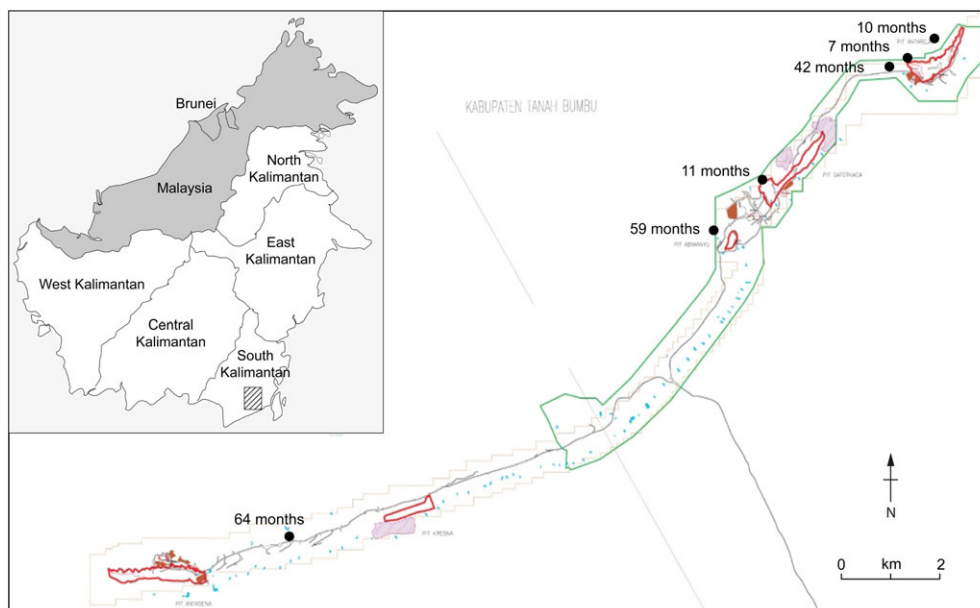


FIGURE 1 The study area in South Kalimantan, Indonesia, illustrating the overburden spoil heaps (from PT. Arutmin Indonesia) [Colour figure can be viewed at wileyonlinelibrary.com]

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 that the range of variation within each spoil dump was sampled, that is, the range of microtopography, for example, peaks, slopes, and valleys with contrasting moisture conditions (Novianti, 2013). The number of transects sampled on each heap differed ($n = 38\text{--}101$), 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 15000 ft, 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 overburden 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.

2.3 | Measurement of environmental factors

Light intensity (Lux, Extech 407026 Heavy Duty Light Meter with PC, USA), air temperature ($^{\circ}\text{C}$) and relative humidity (%), Elcometer 116C Sling Hygrometer, England), overburden temperature ($^{\circ}\text{C}$), 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-Kjeldhal methods, respectively (Allen, 1989). Exchangeable cations and available concentrations of P and S were measured using 1-M 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 & Parks, 1993) and the dominant bacterial and fungal species estimated by chemical tests (Alexopoulos, Mims, & Blackwell, 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: (a) density, (b) relative density, (c) frequency of occurrence, (d) relative frequency, (e) cover, (f) relative cover, and (g) importance value index. 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, that is, unbroken versus broken overburden (Martínez-Ruiz, Fernández-Santos, & Gómez-Gutiérrez, 2001), that is, pioneer species occurred in coarse materials (cobbles >256 mm,

boulder > 256 mm, cobble 64–256 mm, and pebble 4–64 mm), and followers were found on spoil with a large fraction <4 mm, usually where there was also an undulating surface that caused faster substrate breakdown and a greater moisture retention.

Second, a combination of linear regression, generalized linear modelling 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 nonmetric multidimensional scaling 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 1,000 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 (Table S1). Vegetation cover increased linearly from 14% to 60% in the early stages (7–11 months) reaching a maximum of 178% after 64 months ($y = 16.80 + 2.15x$, $F(1, 4) = 11.31$, $p = 0.028$; Figure 2a). Bare ground decreased linearly from 86% to <25% after 42 months, with the lowest being found in the 59–

month old plot ($<4\%$, $y = 80.88 - 1.18x$, $F(1, 4) = 13.56$, $p = 0.021$; Figure 2b). There was significant increase in plant species richness with spoil age ($y = 3.139 + 0.305x$, $F(1, 4) = 19.18$, $p = 0.012$) and diversity index (Shannon-Weiner, $y = 0.590 + 0.011x$, $F(1, 4) = 12.83$, $p = 0.023$). The rate of increase was greatest for species richness (Figure 2c,d,e).

The dominant species by sample time, that is, 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, that is, 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 nonmetric multidimensional scaling 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

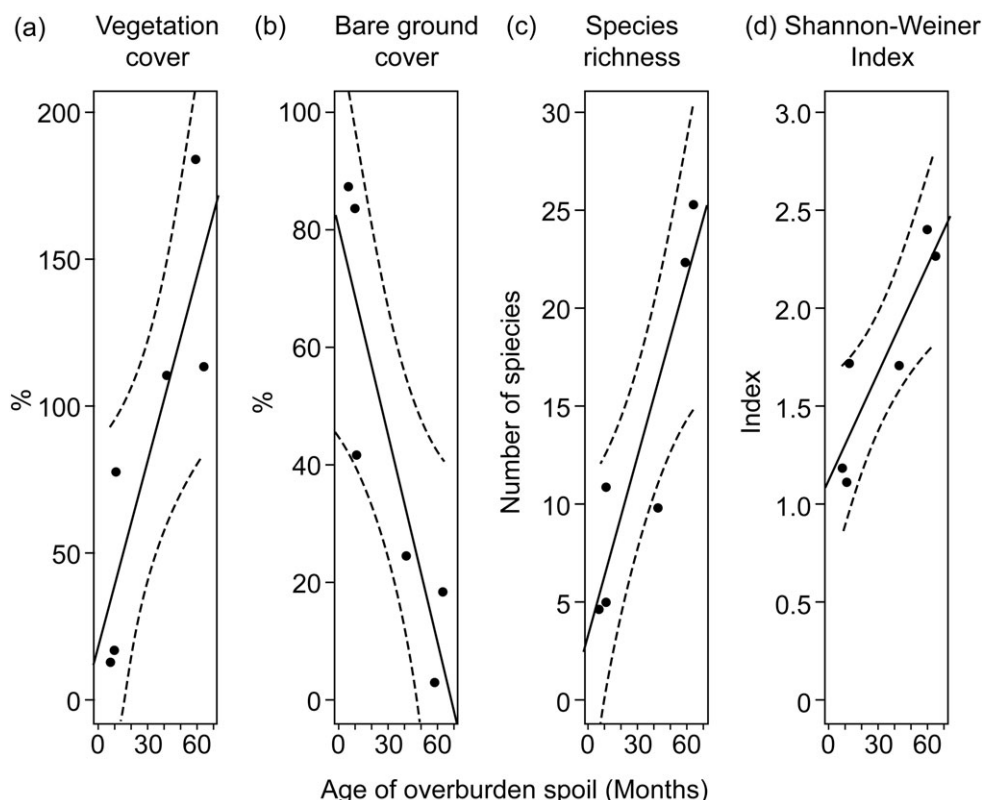


FIGURE 2 Change in (a) vegetation cover, (b) bare ground cover, (c) species richness, and (d) Shannon-Weiner diversity index. Mean values for each stage are presented (filled circles) along with fitted linear regression lines ($\pm 95\%$ CL)

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

($r^2 = 0.61$, $p < 0.001$), with a slight positive movement for the 42-month site, but much greater movement towards the positive end for the 59- and 64-month sites (Figure 3a).

The dominant species occurred in four broad groups (Figure 3b) on the basis of position along axis 1 from left to right. Group 1 consist of early-successional species, including Poaceae (*Echinochloa colona*, *Paspalum conjugatum*), Typhaceae (*T. angustifolia*), Cyperaceae (*Fimbristylis dichotoma* and *Rhynchospora corymbosa*), and the herb (*Alternanthera sessilis*). Group 2 consist of early to mid-seral species, that is, graminoids (*Paspalum dilatatum*, *Imperata cylindrical*, *Cyperus sulcinus*). Group 3 consist of late to midsuccessional species, such as graminoids (*Scleria sumatrensis*, *Paspalum scrobiculatum*), ferns (*Pityrogramma calomelanos*, *Pteris vittata*), lianas (*Passiflora foetida*, *M. pudica*), and shrubs (*Clibadium surinamense*, *T. orientalis*, *Chromolaena odorata*). Group 4 consist of late-successional species, such as graminoids (*Neyraudia reynaudiana*, *Fimbristylis littoralis*, *Cyperus polystachyos*), trees (*Homalanthus populneus*, *A. 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 microclimatic 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 (25–31°C for both variables) through to 42 months (spoil = 29–45°C, air = 28–36°C); after which there was a decline (spoil = 25–33°C, air = 27–34°C; Figure S1). Air humidity averaged around 80%, although the 42-month site showed a marked reduction (Figure S1). Importantly, spoil moisture content showed no significant effects with time since dumping, with values ranging from 60% to 100%.

Spoil properties showed one of five directional responses during the chronosequence; examples are illustrated in Figure 4; the others

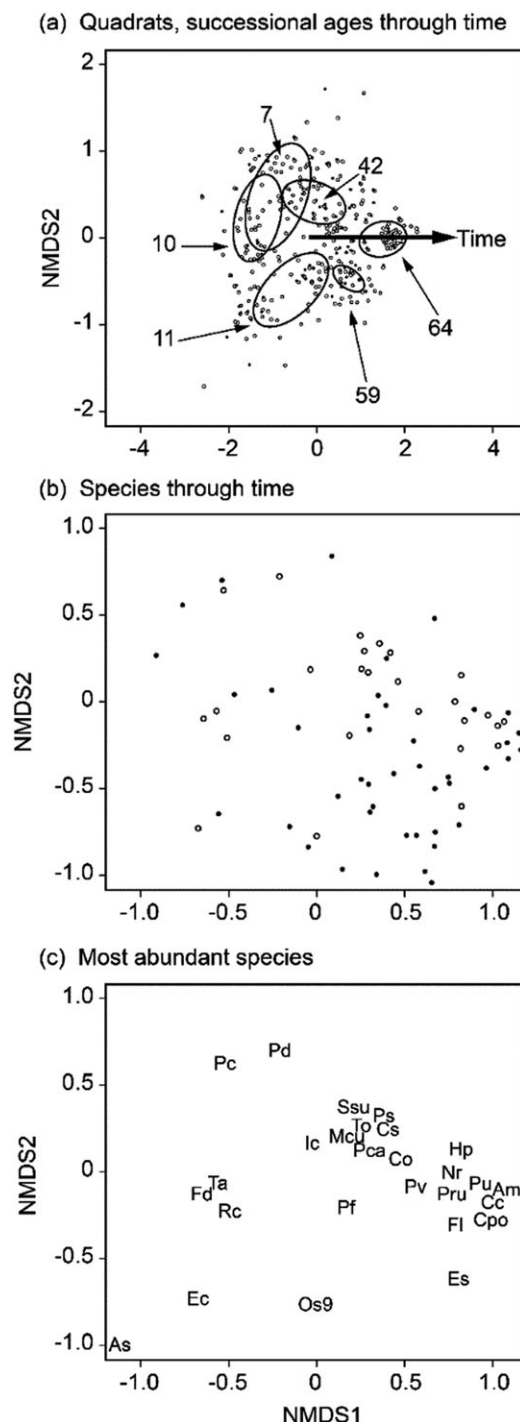


FIGURE 3 Nonmetric multidimensional scaling (NMDS) biplots of species density in a chronosequence on overburden spoil heaps in Indonesia: (a) quadrats correlated with time with 2D-SD ellipses for each site age; (b) dominant species. Species codes: Pc = *Paspalum conjugatum*, Fd = *Fimbristylis dichotoma*, Ta = *Typha angustifolia*, Rc = *Rhynchospora corymbosa*, Ec = *Echinochloa colona*, Pd = *Paspalum dilatatum*, Ic = *Imperata cylindrica*, Cs9 = *Cyperus sulcinus*, 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 ruderales*, Fl = *Fimbristylis littoralis*, Es = *Emilia sonchifolia*, Pu = *Phyllanthus urinaria*, Cc = *Cyanthillium cinereum*, Am = *Acacia mangium*, Cpo = *Cyperus polystachyos*

along with the statistical properties of the fitted curves are illustrated in the Supporting Information (Figure S2, Table S2):

- 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.
- 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 100 g⁻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.
- 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).
- 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 100 g⁻¹) at between 10 and 42 months.
- 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-Ciešlik, Pietrzykowski, Szostak, & Szulczewski, 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 (<×10¹ CFU g⁻¹) than typical values for bacteria, actinomycetes, and fungi in fertile soils (×10⁹, ×10⁴, and ×10⁵ 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, and *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.

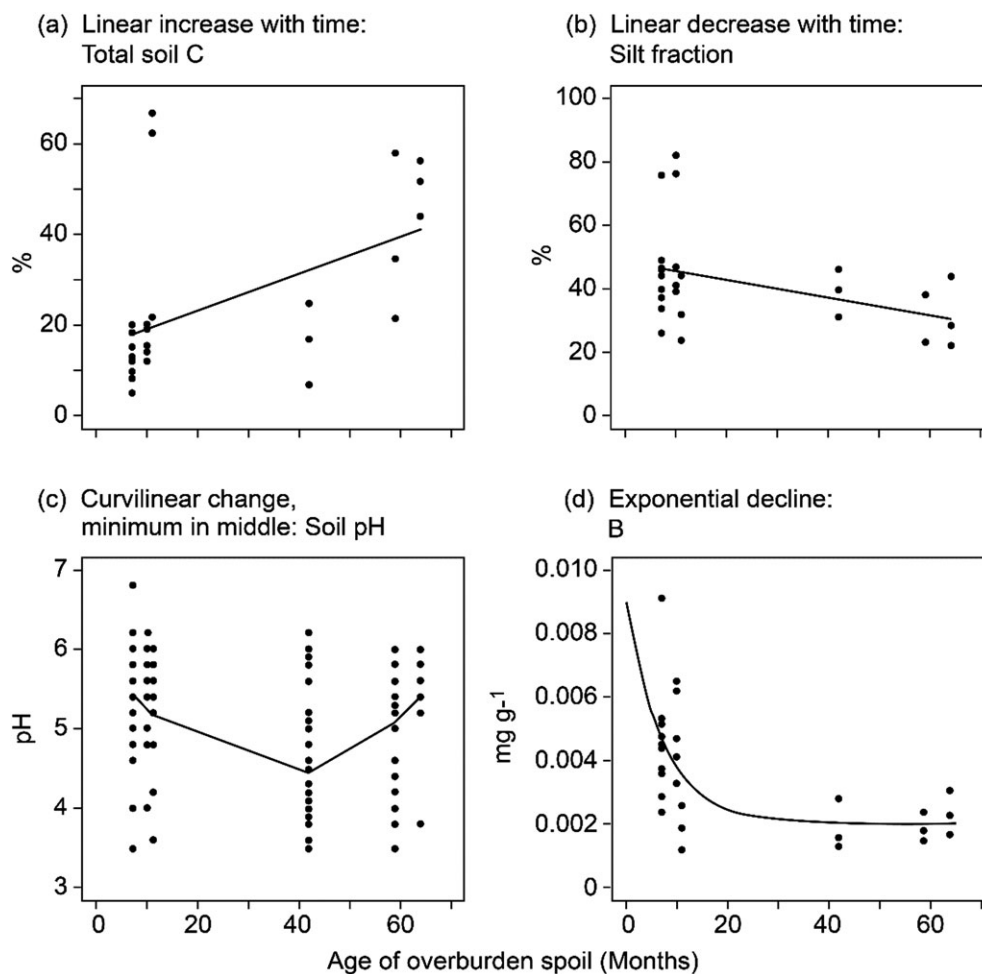


FIGURE 4 Change in selected soil properties illustrating four temporal responses: (a) linear increase, total C; (b) linear decrease, silt fraction; (c) curvilinear responses dip in middle, spoil pH, and; (d) Exponential decrease, total B. Raw data are presented (filled circles) along with modelled responses.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

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 (Glenn-Lewin, Peet, & Veblen, 1992; Huston & Smith, 1987). Here, the succession although dominated by graminoids in the early stages and then sequentially replaced by forbs, shrubs (*P. ruderalis*, *C. 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: (a) low densities of N-fixing species in the surrounding forests, (b) poor seed dispersal, and (c) a lack of *Rhizobium* bacteria in the spoil (Franco & de Faria, 1997). Second, there was colonization by shrubs (e.g., *C. odorata*, *T. micrantha*, *T. orientalis*) and trees (*Ochroma pyramidale*, *H. 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 & Grishin, 1999; del Moral & Wood, 1993).

Here, however, and again in contrast to other studies of primary succession (Lichter, 2000; Tsuyuzaki, Titus, & del Moral, 1997), 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., *O. pyramidale*, *Morinda citrifolia*, *Piper aduncum*), birds (e.g., *Melastoma malabathricum*, *Leea indica*, *Lantana camara*, *Solanum torvum*, *T. 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., *E. colona*, *F. dichotoma*, *F. littoralis*), nitrogen fixation (*D. heterophyllum*, *M. pudica*, *Calopogonium mucunoides*, *Senna alata*), or substrate reshuffling through root expansion and acid root secretions that break up rocks and gravel (e.g., *O. pyramidale*; Novianti, 2013).

We also produced a qualitative classification of all 123 species on the basis of observed occurrence and performance during the succession (detailed in 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 them.

The temperatures experienced were warm (25–48°C) as would be expected in a near-equatorial site, but they peaked in the midsuccessional 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 year⁻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 microclimatic 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 (Palmer, Morgan, & Williams, 1985; Williams, 1975).

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 such as that described for “moribund” grassland found on restored wastes in the United Kingdom (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 (Jakovljević, Kostić, & Antić-Mladenović, 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 midsuccession. 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).

5 | 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 (Chapin, Walker, Christopher, & Lewis, 1994; Marrs & Bradshaw, 1993), 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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SUPPORTING INFORMATION

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