

Litter layer residence time in forest and coffee agroforestry systems in Sumberjaya, West Lampung

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Abstract

Forest conversion to coffee-based agroforestry leads to sudden disappearance of the litter layer and a decrease in the rate of litter fall, reducing food for ecosystem engineers such as earthworms. With time, however, a new litter layer is created potentially returning to forest-like conditions at the soil surface. This research quantified litter thickness, earthworm populations and soil macroporosity in response to land use change in the Sumberjaya benchmark area (West Lampung, Indonesia) by comparing: (a) remnant forest (control); (b) multistrata shaded coffee with fruit and timber trees, as well as nitrogen-fixing shade trees; (c) shaded coffee (nitrogen-fixing shade trees, but less than five tree species per plot); and (d) sun coffee ('monoculture') with coffee forming more than 80% of total stem basal area. Plots were selected with tree ages of 7–10 years in three slope classes: (a) flat (0–10°); (b) medium (10–30°); and (c) steep (>30°). The mean standing necromass was 6.1, 4.5, 3.8 and 3.0 Mg ha⁻¹ for forest, multistrata, shade coffee and sun coffee, respectively, without significant influences of slope. Fine, partly decomposed litter was 33–40% of total necromass, coarse leaf litter 14–16%, and twigs and branches comprised the remaining 43–52%. Soil organic carbon content (C_{org}) was highest in the forest. The largest annual litter input was found in the remnant forest (14 Mg ha⁻¹ year⁻¹), followed by multistrata, shaded and monoculture coffee systems, i.e., 9.8, 6.6 and 4.0 Mg ha⁻¹ year⁻¹, respectively. The population density of earthworms in the forest was 50% lower than in multistrata coffee gardens (150 individuals m⁻²), but its biomass (31 g m⁻²) was twice that in the multistrata coffee gardens. The lowest population density of earthworms was found in the shade coffee system (150 individuals m⁻²) with a biomass of 7 g m⁻². A simple model suggests that the standing litter in the various land use systems is consistent with measured litter inputs and decay rates, but that the soil organic matter (SOM) content and macroporosity of the shade and multistrata systems are less than predicted. The recovery of a surface litter layer in sun coffee systems can provide protection from erosion with time, but will not be sufficient to restore macroporosity at the level of forest soils, leading to hydrologic alterations that favor overland flow.

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1. Introduction

Forest conversion to coffee-based agroforestry through slash and burn land clearing affects a number of processes operating at different time scales that jointly determine the level of 'watershed functions' maintained. Conversion has immediate effects on the presence of a protective leaf canopy as well as surface litter layer. In the absence of a surface litter layer, the soil surface lacks protection against raindrop impact (splash), which causes the breakdown of aggregates to transportable

sizes and can lead to clogging surface-connected infiltration pores ('sealing') (Morgan, 1986; Nill and Nill, 1993; White, 1997). Surface litter is also a key food resource for earthworms (Lavelle et al., 2001), from epigeic (litter transformers) and anecic groups that redistribute surface litter over the soil profile and influence soil structure and hydraulic properties (Swift and Bignell, 2000). The anecic and endogeic earthworms (soil feeding) are 'ecosystem engineers' often exerting a regulatory force in soil function (Lavelle and Spain, 2001). Other soil fauna included in this functional group are termites and ants. The activities of those soil fauna are important to reduce soil runoff from hillslopes. During the first years of the new coffee gardens, green leaf (canopy) cover develops faster than the surface litter layer. Protection from splash erosion may occur relatively quickly. Decay of soil structure, however, may

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continue to exceed recovery by soil engineers until a new balance between collapse of existing macropores and formation of macropores, linked to litter fall and litter decay, is achieved. Reduction of soil macroporosity is likely related to an increase in overland flow (Suprayogo et al., 2004), with initially a higher chance of detachment and transport of soil particles in the absence of a surface litter layer.

The various components of the overall determinants of erosion are thus likely to change over different time scales. Farmers can influence the rate and quality of litter fall through the choice of trees that are planted along with the coffee, and by selection of a pruning regime. This research focuses on how negative effects of erosion can be minimized by the choice and management of companion trees, based on an understanding of the processes linking soil structure to litter inputs. Our conceptual framework for understanding the effect of land use change on soil properties is presented in Fig. 1.

A mulch-based strategy of erosion control (Agus et al., 2002) may work when two required conditions are provided, i.e., sufficient inputs of organic materials and a sufficiently long residence time of litter on the soil surface, together ensuring that the soil is protected at all times, especially during very intense rains. The degree of protection of the soil surface by litter depends on its residence time in the system (inversely related to its decomposition rate and hence to its ‘quality’) and its position on the slope (depending on where litter moves between litter fall and decomposition).

Aspects of plant litter quality which play clear roles in governing the immediate rates of decomposition, and particularly N mineralization, are the concentration of N (or C/N ratios), lignin, and polyphenols (Giller, 2000; Schrot, 2003). Organic materials with a low C/N ratio (<25) and low concentrations of lignin (<15%) and polyphenolics (<3%) (Palm and Sanchez, 1991) are considered to be high-quality (i.e., material decomposes and nutrients are rapidly released). Due to their high N content, litter from leguminous trees mostly decompose rapidly (e.g., *Gliricidia sepium* and

Leucaena leucocephala) (Handayanto, 1994). However, leguminous trees with high polyphenol (‘tannin’) content such as *Peltophorum dassyrachis*, *Calliandra calothyrsus* and *Erythrina orientalis* decompose slowly over periods of 16 weeks (Handayanto et al., 1992). For *Erythrina* the decomposition apparently slows down when about 20% of the original litter remains, and for *Calliandra* and *Peltophorum* when 45 or 70% remains, respectively. Leaf litter of most non-legume trees grown for timber and/or fruit has a lignin concentration (>20%), and is expected to decompose slower than the leguminous trees. Such ‘low quality’ litter potentially contributes more to soil conservation than the more rapidly disappearing litter of legume trees of higher ‘litter quality’ (Hairiah et al., 1996), creating a more stable soil temperature and soil moisture condition which suits *ecosystem engineers*. Tree diversity can thus contribute to non-additive effects on soil function.

The quality of litter input may affect the abundance and diversity of earthworms from the *ecosystem engineer* group which modify soil structure (Lavelle et al., 1994; Wardle and Lavelle, 1997). Depending on the species, earthworms can either improve or impede soil structure through the net effect of channel and macro-aggregate formation on one hand, and conversion of micro-aggregates to granular casts, on the other hand. Bulk density (BD) can either increase or decrease as a net effect. Research has shown that *Pontoscolex* species produce granular casts that destroy the soil structure as large aggregates are broken down into smaller pieces, reducing soil macroporosity and increasing soil micropores (Lavelle and Spain, 2001).

Soil organic matter (SOM) is considered to be a key characteristic in judging the sustainability of land use systems (Albrecht et al., 2004). Yet, total soil organic matter content is not a very sensitive indicator as it changes relatively slowly under different management regimes and often has a high spatial variability linked to variability in soil texture, pH and elevation (Van Noordwijk et al., 1997).

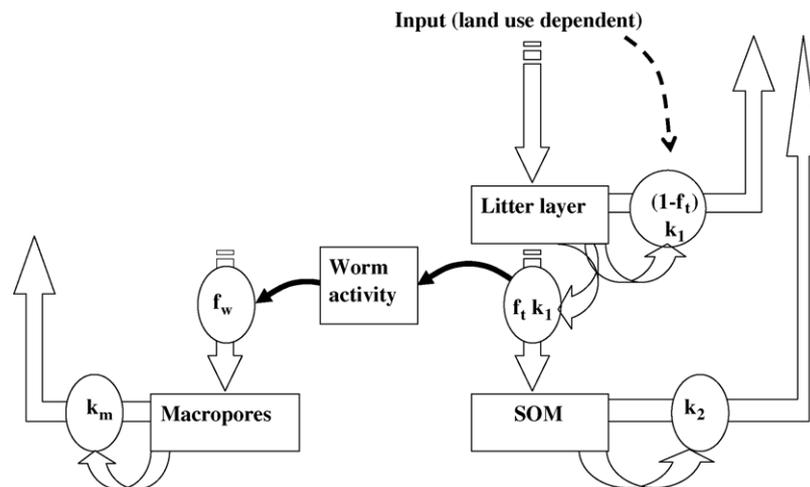


Fig. 1. Conceptual framework for understanding the effect of land use change on soil organic matter (SOM) content and soil structure via (1) quantitative changes in the inputs to the litter layer and (2) effects of litter quality on decay rate (k_1) and transfer fraction of the decay rate (f_t) and/or rate of macropore formation per unit litter transfer to SOM (f_w). The rate of macropore decay (k_m) may depend on other aspects of the land use; the relative rate of decomposition of soil organic matter (k_2) is assumed to be independent of land use.

Based on the conceptual model of Fig. 1, two hypotheses were tested:

- 1) Differences in standing stock of litter layer and soil organic matter between forest and derived land use types can be understood from differences in the annual amount of litter inputs and from well-established relations amongst litter quality, temperature and decomposition rates.
- 2) Differences in soil macroporosity between land use types can be understood from differences in the total amount of litter inputs and its impact on earthworm biomass.

To test these hypotheses we focus on surveys of standing litter, soil organic matter stocks, and worm population densities and their biomass across land use types as well as on the apparent dependence on land use type of the rate constants (k_1 , k_2 , k_m , f_t and f_w) in the conceptual model.

2. Materials and methods

2.1. Research components

Three components of a more comprehensive study are reported here:

1. A survey on thickness and chemical quality indicators of the litter layer in 7–10-year-old coffee gardens and in remnant forest, in relation to soil properties and population counts of earthworms.
2. A study of litter layer residence time for field conditions by measuring decomposition of standing litter.
3. Operationalizing the conceptual model of Fig. 1 for prediction of soil macroporosity based on annual litter input and its quality.

2.2. Site description

The study was conducted from November 2001 to August 2003 in the Way Besai catchment in Sumberjaya subdistrict (West Lampung, Indonesia), which drains to the Tulang Bawang River. The area (bounded by 104°25'46.50"–104°26'51.40"E, 5°01'29.88"–5°02'34.20"S) has a mean annual rainfall of 2614 mm, an average daily air temperature of 21.2 °C, and relative humidity in the range of 81–89% (Dariah et al., 2004). On the climatic map of Oldeman et al. (1979), the study site is within zone B1, with 7 months of wet season (>200 mm rainfall) and 1 month dry (rainfall <100 mm). Rainfall data collected in 2001–2002 confirmed the long-term trend, with a rainy season from October until May; the month of February 2002, however, was unusually dry with a total rainfall of only 90 mm (Afandi et al., 2003).

Four land use systems were compared: (a) remnant forest as a control; (b) multistrata coffee with fruit and timber trees as well as nitrogen-fixing shade trees (*Erythrina sububrams* and/or *G. sepium*); (c) shaded coffee with the same nitrogen-fixing *E. sububrams* and/or *G. sepium* as shade trees; and (d) sun ('monoculture') coffee. Each coffee-based system was repre-

sented by three different farmer's plots (owned and managed by farmers)—one plot of each coffee treatment was located in each of three villages: Bodong, Simpangsari and Tribudisukur. Each measurement in the remnant forest was performed in three different places.

As an operational definition of sun coffee systems we used a relative coffee basal area >80%. Within the 'shaded' coffee systems with relative coffee basal areas <80%, we distinguished the multistrata system, comprised of more than five trees species, and simple shaded systems with five or less tree species per plot. Relative coffee basal area is calculated based on the total tree basal area and the proportion of this area occupied by coffee 'trees':

$$\frac{\sum \pi D_{\text{coffee}}^2}{\sum \pi D_{\text{coffee}}^2 + \sum \pi D_{\text{non coffee}}^2}$$

where D is the tree diameter (cm) and the factor π cancels from the equation. Tree diameters of all trees within a 40 m × 5 m sampling area were measured; for coffee trees measurement height was 0.25 m above the ground (below the first branching); a standard height of 1.3 m for DBH measurements was used for unbranched stems and a measurement height halfway between the ground and the first branch for others (including most coffee trees). Plots for the survey were selected with a minimum age of 7 years in three slope classes: (a) flat (0–10°); (b) medium (10–30°); and (c) steep (>30°). The measurements of each land use type were replicated 3 times within the sample area. Some of the farms on flat and steep slopes were later selected for the decomposition study.

2.3. Step 1: Survey on thickness of standing litter

2.3.1. Understorey vegetation and standing litter

Methods for quantifying standing litter, dead wood, and understorey vegetation were used as specified in The Alternatives to Slash and Burn (ASB) protocol (Hairiah et al., 2001). Understorey vegetation were measured in ten 0.25 m² (0.5 m × 0.5 m) quadrats; total fresh weight was measured and subsamples were collected, dried in the oven at 80 °C for 48 h to determine dry matter content. Standing litter is defined as all (bio)-litter found on the soil surface (above the mineral soil), and includes all types litter such as dead leaves, branches, twigs, flowers, fruit, half decomposed litter, and roots. Standing litter was sampled within the 40 m × 5 m transect by collecting all litter on soil surface of 10 (25 cm × 25 cm) quadrat samples. The standing litter was separated based on its size by sieving it with a mesh size of 5 mm: (a) coarse litter (>5 mm) mainly containing undecomposed and half decomposed litter and (b) disintegrated (decomposed) fine litter (<5 mm) relatively more resistant to decomposition. Litter was dried in the oven at 80 °C for 48 h; a subsample of about 2 g was used for correction of contamination with mineral soil by drying it in muffle furnace at 650 °C for 24 h.

To estimate the rate of aboveground litter inputs of coffee agroforestry systems, 1 m × 3 m litter traps made of fine fish net (2 mm mesh size) were installed in each plot below the

canopy, 25 cm above the ground. The trapped litter was collected weekly and was sorted into leaves, branches, fruits and flowers of each species, and dried in the oven at 80 °C. Measurement commenced in March 2004; data reported here is based on 7 months of measurement. About a 10 g composite litter sample from each land use was used for analysis of chemical quality indicators: total C (wet oxidation method of Wakley and Black), total N (Kjeldahl distillation method), concentration of lignin (Goering and Van Soest, 1970) and polyphenolics (Anderson and Ingram, 1993).

2.4. Soil properties

2.4.1. Soil organic matter

Soil samples were collected from 10 sample points at the 0–5 cm and 5–15 cm depth intervals below the litter layer. Soil properties were analyzed for a composite sample of each plot and included analysis of soil texture (% sand, silt, and clay) using the pipette method, pH (1 N KCl), pH (H₂O), C_{org} (Wakley and Black method; Anderson and Ingram, 1993), and N_{tot} (Kjeldahl method; Anderson and Ingram, 1993). The soil carbon contents (C_{org}, %) were compared with the C_{ref} values for forest soils of the same texture and pH at the same elevation (Van Noordwijk et al., 1997). The equation for C_{ref} for upland soils in Sumatra (excluding peat and wetland soils, as well as recent volcanic Andisols) is:

$$C_{\text{ref (adjusted)}} = \left(\frac{Z_{\text{sample}}}{7.5} \right)^{-0.42} \exp(1.333 + 0.00994 \times \% \text{Clay} + 0.00699 \times \% \text{Silt} - 0.156 \times \text{pH}_{\text{KCl}} + 0.000427 \times \text{Elevation}) \quad (1)$$

where Z_{sample} is the soil depth, i.e. 0–5 cm and 5–15 cm. The elevation of the study area is about 850 m above sea level (m.a.s.l) for the various coffee gardens and about 1050 m.a.s.l for the remnant forest.

2.4.2. Soil bulk density and macro porosity

Soil samples of each plot were collected randomly from 10 point samplings at the 0–15 cm depth using a metal ring (volume = 100 cm³); the soil was dried and weighed in the laboratory of Soil Science, Brawijaya University, Malang.

To interpret soil bulk density data (g cm⁻³) as an indicator of soil compaction relative to the BD of forest soil of the same texture, the concept of BD/BD_{ref} was used. A ‘reference’ value (BD_{ref}) was derived from the pedotransfer function of bulk density from soil texture data (sand, silt, clay and organic matter content), based on a large dataset for mostly agricultural soils (Wosten et al., 1998). As a first estimate, we may expect topsoils in natural forests to have a bulk density of about 70% of this reference value, while severely compacted soils may reach 1.3 times the reference value. Surface-connected soil macroporosity was measured based on the infiltration pattern of methylene blue dye (Suprayogo et al., 2004). The methylene blue solution (0.05 g l⁻¹ of water) was applied to a slope-adjusted frame over a soil surface area of 1 m × 0.5 m and allowed to infiltrate overnight (Fig. 2); the distribution of methylene blue was traced on plastic sheets for both a vertical and a sequence of horizontal soil profiles (Van Noordwijk et al., 2000); these maps were digitized and the stained area was calculated using the IDRISI program. The relative area stained was interpreted as the fraction of surface-connected soil macropores within the total soil volume.

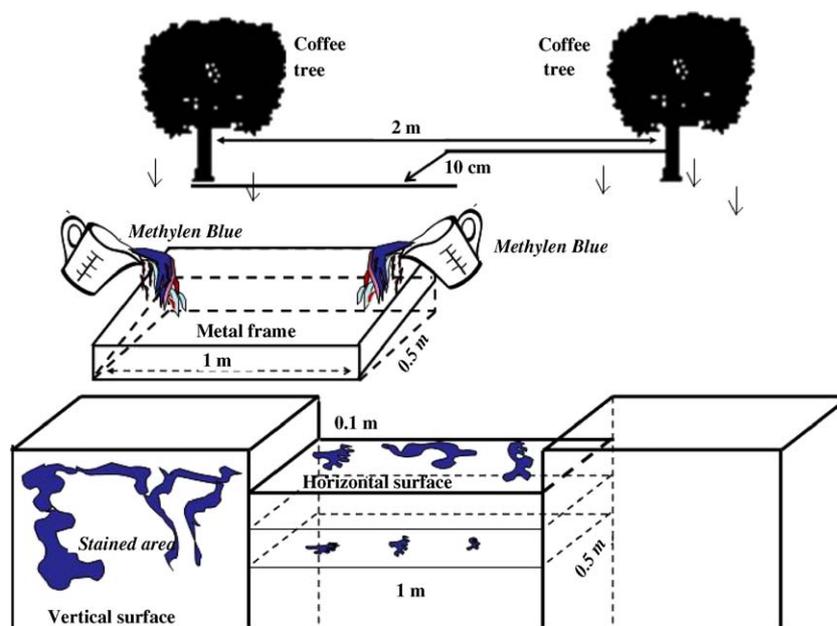


Fig. 2. Schematic diagram of the visualization of surface-connected macroporosity using methylene blue dye; the shaded area reflects the continuous soil macropores in the soil profile (Suprayogo et al., 2004; Van Noordwijk et al., 2000).

2.4.3. Population density and biomass of earthworms

The population density of earthworms was determined from soil monoliths at five point measurements of the 40 m × 5 m transect, at soil depths of 0–10 cm, 10–20 cm, and 20–30 cm, respectively, according to a sampling procedure described by Susilo (1999). Earthworms samples were collected by hand sorting and classified based on ecological function, i.e. ‘ecosystem engineer’ (anecic and endogeic morphospecies) and ‘decomposer’ (epigeic morphospecies), and weighed for dry weight (biomass, g/individual) measurement. The earthworm classification into functional groups was based on external characteristics, i.e. body color and the soil depth where the earthworms were found (Fragoso et al., 1997).

2.5. Step 2: Decomposition study

The decomposition rate of standing litter was studied during the rainy season (March–July 2003), comparing standing litter collected from the four investigated land use systems: (a) remnant forest; (b) multistrata coffee with fruit and timber trees as well as nitrogen-fixing shade trees (*E. sububrams* and/or *G. sepium*); (c) shaded coffee with the same nitrogen-fixing *E. sububrams* and/or *G. sepium* as shade trees; and (d) sun coffee. The measurements were performed in farmers plots on relatively flat land (0–10°) and steep slopes (>30°) in each of the three replicate farms.

Rainfall, air temperature and soil temperature were monitored during the experiments. Rainfall was monitored by collecting water in simple rain gauges at each site after rain events, while soil moisture, air and soil temperature were recorded every 3 days at each site. For soil moisture a composite soil sample was collected close to each litterbag, weighed at field moisture content, and dried in the oven at 105° for 48 h. Soil temperature at 0–5 cm depth was measured once every 3 days between 09:00 and 11:00 h.

To measure the absolute decomposition rates of standing litter, polyvinyl bags with a mesh size of 5 mm were used (Anderson and Ingram, 1993; Tian, 1992). A composite of standing litter was collected from each land use system and sieved (5 mm mesh) to homogenize the organic materials: the fraction retained on the sieve was classified as ‘coarse litter’, while the fraction <5 mm was labeled ‘fine litter’ (Anderson and Ingram, 1989). Standing coarse litter collected from the field still contained some adhering mineral soils; the ash-free dry weight was determined by subtraction with the remaining dry weight after ashing in a muffle furnace at 650 °C for 24 h. About 2 g of a composite sample of standing litter for each land use was used for analysis of chemical quality indicators: total C (Wakley and Black method; Anderson and Ingram, 1993), total N (Kjeldahl method; Anderson and Ingram, 1993), concentration of lignin (Goering and Van Soest, 1970) and polyphenolics (Anderson and Ingram, 1993).

Each litter bag was filled with a certain amount of mixed standing litter according to the mean actual amount found in the field (dry weight basis), and placed randomly on the soil surface. In fact, part of the decrease in the remaining dry weight at the first measurement can be attributed to a ‘handling effect’

rather than to decomposition per se. At 1, 2, 4, 8 and 16 weeks after placement, the remaining litter was dried (100 °C for 24 h) and weighed; each sample was corrected for its contamination with mineral soil by ashing it in a muffle furnace at 650 °C for 24 h. To describe the loss of litter (dry weight), a two-phase exponential decay function (Weider and Lang, 1982) was:

$$\frac{Y_t}{Y_0} = \text{slowfrac} \times \exp(-k_{\text{slow}}t) + (1 - \text{slowfrac}) \exp(-k_{\text{fast}}t) \quad (2)$$

where Y_t/Y_0 is the fraction of the initial dry weight remaining in the litter bag at time t (weeks) and k the decomposition constant; slowfrac is the (empirically determined) fraction of the initial sample that decomposes at rate k_{slow} as complemented by the fraction that decomposes at rate k_{fast} . The ‘handling effect’ is embedded in k_{fast} . If the complement of the slow fraction is indeed rapidly lost, the second term of the equation becomes negligible after about 1 week. To evaluate this equation for k_{slow} , the natural logarithm of the ratio of Y_t (mass at time t) divided by Y_0 (initial mass) was used:

$$\ln\left(\frac{Y_t}{Y_0}\right) = \ln(\text{slowfrac}) - k_{\text{slow}}t \quad (3)$$

The intercept of this linearized regression (Eq. (3)) is the natural logarithm of the remaining fraction, which provides an estimate of the handling effect plus rapidly decomposable fraction. The mean residence time of litter is calculated as $1/k_{\text{slow}}$. The mean residence time of the forest floor is the standing stock divided by the annual litter inputs. The time required for a 50% loss of dry weight (half-life of standing litter) is calculated as $\ln(0.5)/k_{\text{slow}}$.

2.6. Step 3: Prediction of soil macroporosity based on litter input

The simple conceptual model (Fig. 1) of macropore formation and decay relates the formation of macropores to soil fauna transferring organic matter from the litter layer to the soil pools. Using a first-order decay function for litter layer, soil organic matter and macropores, the resulting macroporosity (dimensionless, v/v) is related to the standing litter layer and SOM pool size. The conceptual model is described by a set of differential equations:

$$\begin{aligned} \frac{d\text{Litter}}{dt} &= \text{Input} - k_1(f_i + (1 - f_i)) \times \text{Litter} \\ &= \text{Input} - k_1 \times \text{Litter} \end{aligned} \quad (4)$$

$$\frac{d\text{SOM}}{dt} = f_i \times k_1 \times \text{Litter} - k_2 \times \text{SOM} \quad (5)$$

$$\frac{d\text{Macropores}}{dt} = f_w \times f_i \times k_1 \times \text{Litter} - k_m \times \text{Macropores} \quad (6)$$

where f_w is the formation of macropores (dimensionless) per unit transfer from litter to soil organic matter pools, $\text{Mg}^{-1} \text{ha}; f_i$

the litter to soil organic matter transfer as a fraction of the apparent litter decay rate (dimensionless); input the annual rate of litter fall (and other organic inputs), $\text{Mg ha}^{-1} \text{ year}^{-1}$; k_1 and k_2 the apparent decomposition (decay) rates for litter and soil organic matter, respectively, year^{-1} ; k_m the rate of compaction of existing macropores, year^{-1} ; litter the standing stock of litter, Mg ha^{-1} ; macropores the existing volumetric fraction of macropores in the topsoil, (v/v); and SOM is the standing stock of soil organic matter, Mg ha^{-1} .

With equilibrium values depicted as simple proportions of the annual inputs:

$$\text{Litter} = \frac{\text{Input}}{k_1} \quad (7)$$

$$\text{SOM} = f_t \times k_1 \times \frac{\text{Litter}}{k_2} = f_t \times \frac{\text{Input}}{k_2} \quad (8)$$

$$\text{Macropores} = f_w \times f_t \times k_1 \times \frac{\text{Litter}}{k_m} = f_t \times \text{Input} \times \left(\frac{f_w}{k_m} \right) \quad (9)$$

The model was operationalized for non-equilibrium conditions in a STELLA™ model (available from the authors on request).

As ‘default’ parameters we chose: k_1 is the $0.08 \text{ year}^{-1} = 0.000219 \text{ day}^{-1}$, k_2/k_1 ratio is 50, f_t is 0.3, k_m is 0.01 day^{-1} , f_w is the 0.1.

The response of predicted pool sizes was tested for variation in parameter values around these default values as a form of sensitivity analysis.

2.7. Statistical analyses

Results were analyzed with analysis of variance (ANOVA) by using the GENSTAT 6.0 computer program (Payne et al., 1987), and a *t*-test was applied to separate means when significant ($p < 0.05$) overall treatment effects were found.

3. Results

3.1. Litter dry weight in established (>7 years) coffee-based agroforestry system

As expected, the remnant forest had the highest surface necromass (Fig. 3), statistically significantly higher ($p < 0.05$) compared to the coffee gardens. The forest sites also had the largest understorey vegetation and root biomass in the litter layer, helping to keep the litter in place. The ‘sun coffee’ system had the lowest total surface necromass, followed by the simple shade coffee. Overall, the proportions of decomposed fine litter, brown (i.e., non-green) leaves and twigs and branches did not differ amongst the land use types. In another survey that included younger coffee gardens (data not shown), we found the twig and branch fraction to be a smaller proportion of the total. The twig and branch fraction probably has a longer residence time than leaf litter and can reduce movement of surface litter rather than directly protecting the soil. As the twigs and branches tend to be heterogeneously distributed, we

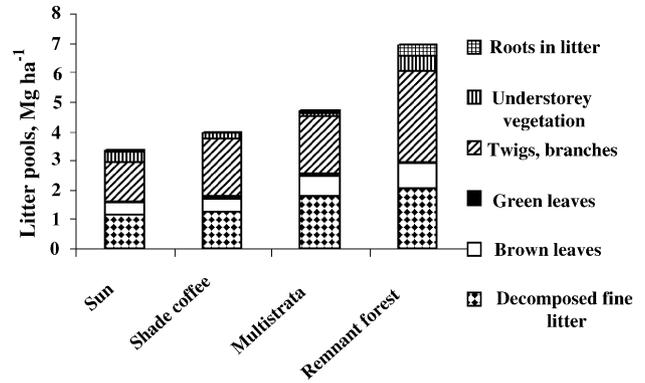


Fig. 3. Components of the litter layer (necromass) and the root biomass in the litter layer plus understorey vegetation for the various cover conditions.

focused on decomposed fine litter plus brown leaves (coarse leaf litter). The mean litter dry weight in these combined fractions was 2.1, 1.8, 1.2 and 1.2 Mg ha^{-1} for forest, multistrata, shade, and sun coffee, respectively, expressed as means across the three slope classes and two soil positions. Overall, no significant effect of slope or soil position was found on litter dry weight (Fig. 4(a)).

3.2. Soil properties

Neither soil pH nor texture of the remnant forest plots differed from these values under coffee agroforestry systems (Table 1). The coffee-based systems had significantly ($p < 0.05$) lower total C and total N contents. All sampled plots had clay contents in the relatively narrow range of 42–58%, and sand contents of 13–18%.

The C content of the 0–5 cm layer in the forest plots was 1.85 times that of the 5–15 cm depth layer, while in the various coffee-based systems it was only 1.3–1.4 times higher. The $C_{\text{org}}/C_{\text{ref}}$ ratio in the forest plots did not differ between the 0–5 cm and 5–15 cm depth layers, suggesting that the correction for sample depth in the C_{ref} Eq. (1) is appropriate (Fig. 4(a)). The average $C_{\text{org}}/C_{\text{ref}}$ ratio under remnant forest was about 0.55, indicating either that the soil carbon status declined compared to undisturbed conditions or that parameters in the C_{ref} do not apply (e.g., the elevation parameters). The $C_{\text{org}}/C_{\text{ref}}$ ratio of the coffee-based systems was about half that of the remnant forest. Slope or position on the upper or lower part of a slope had no significant effect on the $C_{\text{org}}/C_{\text{ref}}$ ratio for any of the land uses (Fig. 4(b)). No statistically significant difference between the three types of coffee gardens was found for both C_{org} and the $C_{\text{org}}/C_{\text{ref}}$ ratio of the 0–5 cm depth layer. For multistrata, simple shade and sun coffee systems, the mean C_{org} in the 0–5 cm layer was 1.98, 1.76 and 1.65%, respectively (Table 1), with a corresponding $C_{\text{org}}/C_{\text{ref}}$ ratio of 0.23, 0.20 and 0.18. Treatment differences within the 5–15 cm depth were small and, when averaged over a conventional sampling depth of 15 cm, no statistically significant effect emerges (as the land use effect becomes ‘diluted’ in the larger and more variable sample).

Soil bulk density differed significantly ($p < 0.05$) amongst land use types; BD in the remnant forest was 40% lower

Table 1
Average soil properties in the 0–5 cm and 5–15 cm soil layers in forest and coffee-based systems in Sumberjaya

Land use systems	Soil depth (cm)	pH (H ₂ O)	pH (KCl)	Tot. C (%)	Tot. N (%)	C/N	Sand (%)	Silt (%)	Clay (%)
Remnant forest	0–5	4.87 b	3.98 ab	4.99 a	0.44 a	11.5 a	16.8 a	41.2 ^{NS}	42.1 ^{NS}
	5–15	4.99 ab	3.96 ab	2.69 b	0.27 b	10.3 a	18.2 ab	35.0	46.8
Multistrata	0–5	5.18 ab	4.08 ab	1.98 b	0.26 b	7.8 b	15.6 ab	35.3	49.1
	5–15	5.16 ab	4.02 ab	1.54 b	0.20 b	7.8 b	14.4 ab	31.9	53.7
Simple shade	0–5	5.22 a	4.12 a	1.76 b	0.24 b	7.9 b	15.3 ab	35.3	49.4
	5–15	5.17 ab	4.04 a	1.22 b	0.19 b	7.0 b	13.5 ab	33.2	53.3
Sun coffee	0–5	4.98 ab	3.94 b	1.65 b	0.27 b	7.0 b	14.1 ab	34.1	51.8
	5–15	5.05 ab	3.97 ab	1.28 b	0.20 b	6.9 b	12.9 b	29.3	57.7

Numbers followed by different letters indicate significant ($p < 0.05$) differences; NS, not significantly different ($p > 0.05$).

compared to coffee-based agroforestry systems (Fig. 4(c)). Among coffee-based systems, no significant differences were found. The average bulk density in coffee gardens ($\approx 1.0 \text{ g cm}^{-3}$) had a $\text{BD}/\text{BD}_{\text{ref}}$ ratio of about 0.85.

3.2.1. Relations between litter layer and soil properties

Across the various land uses the value of $C_{\text{org}}/C_{\text{ref}}$ was correlated with litter dry weight on soil surface ($C_{\text{org}}/C_{\text{ref}} = 0.0687e^{0.2959\text{Necromass}}$, $R^2 = 0.7058$, $n = 8$ land use

means). Extrapolating this equation, standing litter dry weight must increase up to 9 Mg ha^{-1} to achieve a $C_{\text{org}}/C_{\text{ref}}$ ratio of 1. Using the information of individual sampling points, no clear relations emerge, but the remnant forest data points differ substantially from the coffee gardens in the relationships between total necromass or fine litter and $C_{\text{org}}/C_{\text{ref}}$ or $\text{BD}/\text{BD}_{\text{ref}}$ (Fig. 5).

3.3. Litter input, quality and rate of decomposition

3.3.1. Litter Input

The average litter fall production in the forest was estimated as $27 \text{ g m}^{-2} \text{ week}^{-1}$, 3 times higher than that in the sun coffee system ($8 \text{ g m}^{-2} \text{ week}^{-1}$), while estimates for multistrata and simple shade coffee systems were intermediate at 12–20 $\text{g m}^{-2} \text{ week}^{-1}$ (Table 2).

The weekly input of litter did not show a strong monthly pattern, so tentative extrapolations can be made from the 26-week data to annual litter fall estimates. Extrapolated annual litter production in the forest is about $14 \text{ Mg ha}^{-1} \text{ year}^{-1}$ comprised of $8.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$ leaf and $5.6 \text{ Mg ha}^{-1} \text{ year}^{-1}$ branch, flower and fruit litter fall. Annual litter production under multistrata coffee is estimated to be $9.8 \text{ Mg ha}^{-1} \text{ year}^{-1}$, under shaded coffee system with *G. sepium* (commonly used as shade trees) about $6.6 \text{ Mg ha}^{-1} \text{ year}^{-1}$, and the lowest annual production is expected for the sun coffee system, around $4.0 \text{ Mg ha}^{-1} \text{ year}^{-1}$.

3.3.2. Litter quality

The quality of standing litter in the remnant forest and sun coffee is slightly lower than that in the multistrata and shaded coffee systems, as shown by the higher ratio (lignin + polyphenol) to N was 22 compare to 19 (multistrata) and 17 (shaded coffee) (Table 3). A (lignin + polyphenol) to N ratio > 10 is classified (Van Lauwe et al., 1997) as ‘low quality’. Based on these criteria, all of the standing litter used in this study are classified as ‘low quality’. In the Century model of soil carbon dynamics that has been widely used and tested across temperate and tropical agro-ecosystems (Parton et al., 1987), about 45–55% of litter inputs would be allocated to the metabolic pool on the basis of the (lignin + polyphenol) to N ratios of four land cover types.

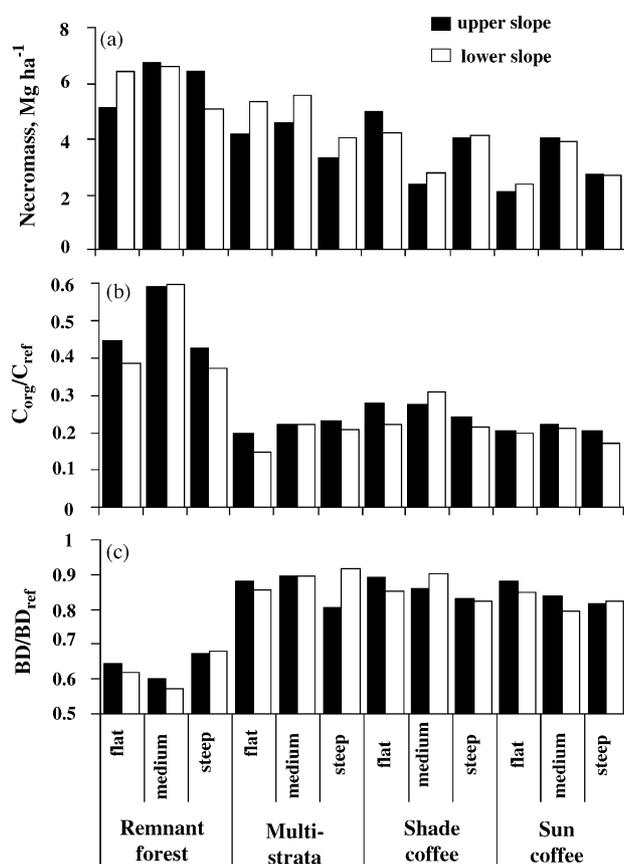


Fig. 4. (a) Surface necromass (fine + coarse litter dry weight); (b) ratio of $C_{\text{org}}/C_{\text{ref}}$ at 0–15 cm depth; and (c) ratio of $\text{BD}/\text{BD}_{\text{ref}}$ at the 0–15 cm depth of remnant forest, multistrata coffee, shaded coffee and sun coffee systems on three slope classes and two sampling positions in Sumberjaya (means of three replicates per land use, slope class and sampling position).

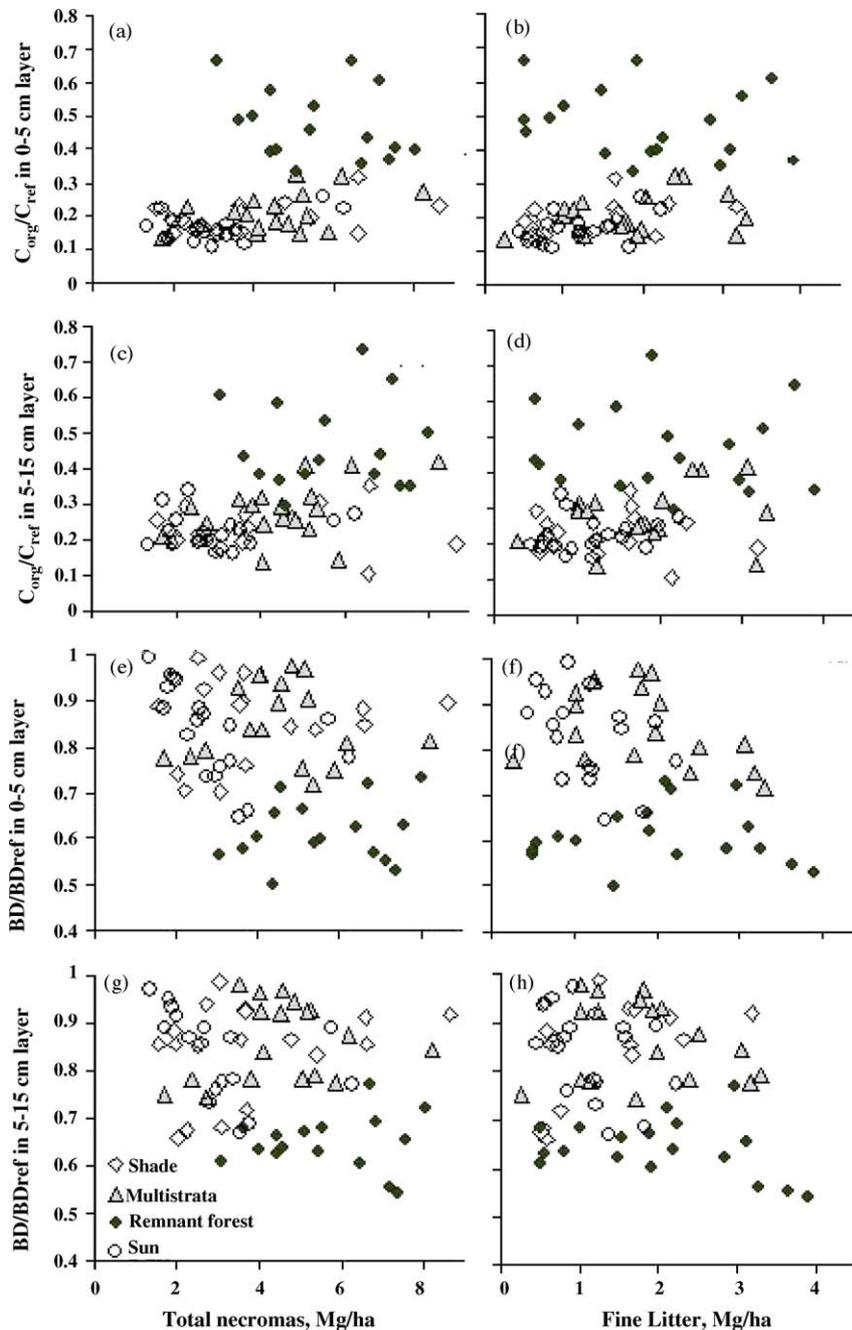


Fig. 5. Correlations between C_{org}/C_{ref} and total necromass (a and c), C_{org}/C_{ref} and dry weight of standing fine litter (b and d), BD/BD_{ref} and total necromass (e and g), and BD/BD_{ref} and dry weight of standing litter (f and h) in remnant forest and three types of coffee-based land use systems.

3.3.3. Litter decomposition

The decomposition rate of standing litter was very slow; none of the tested litter lost 50% of its biomass after 16 weeks. During the 16 weeks of the litterbag decomposition study only 30–40% of the dry weight was lost from the bags, by decomposition and/or transfer to the soil. A substantial part of this loss occurred in the first week, and may be due to the processing of the litterbags, with some loss of fine material. Losses in the first week were 29, 11, 25 and 17%, respectively, for the remnant forest, multistrata, simple shade and sun coffee systems. Decomposition and soil transfer during the subsequent 15 weeks of the study further reduced the remaining dry weight

by 9, 17, 16 and 20%, respectively, for these four land uses. However, individual replicates of the litterbags exhibited considerable variation (Fig. 6). Slope gradient had no significant impact on the remaining dry weight after 16 weeks, but there were significant ($p < 0.05$) differences amongst the land uses.

The usual monocomponent exponential decay model did not apply to the data due to the rapid initial loss, and a two component version was used to fit the data (Eq. (3), the 1-component model would have an intercept of $Y/Y_0 = 1$ for $t = 0$). The combined equation (Table 4) suggests a rapid loss of 10–21% of the dry weight (partly attributable to ‘handling

Table 2

Weekly litter input (litter fall) for different land use systems during the rainy season (March–July 2004) (mean and standard deviation of 4(3) replicates per land use)

Land use systems	Average litter fall ($\text{g m}^{-2} \text{ week}^{-1}$)					Annual estimate ($\text{kg m}^{-2} \text{ year}^{-1}$)
	Fruit	Flower	Leaf	Branch	Total	
Remnant forest						
Mean	1.05	0.18	16.42	9.44	27.09	1.41
St. dev.	0.92	0.17	6.23	6.71	13.00	
Multistrata						
Mean	5.10	0.54	10.58	2.56	18.78	0.98
St. dev.	3.65	1.08	1.43	1.60	5.24	
Shaded by <i>Gliricidia</i>						
Mean	1.89	0.84	7.69	2.31	12.73	0.66
St. dev.	2.32	1.62	2.30	1.56	5.14	
Sun coffee						
Mean	0.49	0.00	4.87	2.41	7.77	0.40
St. dev.	0.32	0	2.91	1.66	3.39	

Table 3

Quality of standing litter for different land use systems (based on composite samples across the replicates of the same land use); the calculated 'metabolic fraction' relates to the Century model (on the basis of $0.85 - 0.018 (L + Pp)/N$; Parton et al., 1987) and its use in the WaNuLCAS model (Van Noordwijk and Lusiana, 1998)

Land use systems	Total N (N) (%)	Lignin (L) (%)	Polyphenol (Pp) (%)	C/N	L/N	Pp/N	(L + Pp)/N	Calculated 'metabolic' fraction
Remnant forest	1.24	21.1	6.37	31	17	5	22	0.45
Multistrata	2.20	34.9	6.12	16	16	3	19	0.51
Simple shade	2.15	32.3	4.25	17	15	2	17	0.54
Sun coffee	1.95	37.7	5.19	18	19	3	22	0.45

effect'), followed by a slow loss of at a rate of $0.0071 - 0.0104 \text{ week}^{-1}$, with a mean residence time for the litter in the range of 95–141 weeks (2–3 years). The fitted model for the four land use types suggests a mean residence time of 141 and 130 weeks for the remnant forest and multistrata coffee gardens, and 96 and 95 weeks for the simple shade and sun coffee systems, respectively.

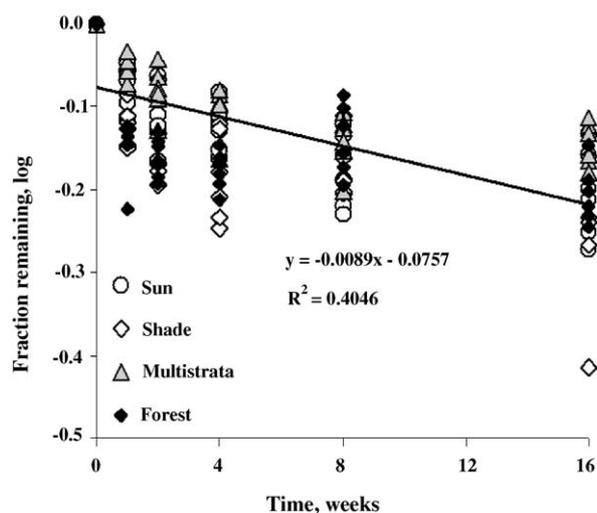


Fig. 6. Loss of dry weight of litter for different land use types over 16 weeks under sun, shaded, and multistrata coffee systems, and remnant forest (six replicates per land use).

3.4. Earthworm population density

Earthworm biomass and population density differed amongst the four land use systems (Table 5). In general, earthworm biomass in the remnant forest was significantly ($p < 0.05$) larger than in the coffee gardens, but its population density was the lowest. The ratio of earthworm biomass to population density in the forest ($0.41 \text{ g/individual}$) was about 3 times larger than in the multistrata or sun coffee systems ($0.13 \text{ g/individual}$), the smallest was found in the shaded coffee system ($0.08 \text{ g/individual}$). The larger earthworms in the forest may create a bigger size of soil macropore compared to the coffee gardens, however, more detailed observation is needed. Taxonomic identification of earthworm species at this stage of the research is not available.

Based on morphotypes as indicators of the ecological function of earthworms, all land use types were dominated by 'ecosystem engineers' (anecic + endogeic types), rather than decomposers (epigeic type). The sun coffee system had the highest fraction of 'decomposer' earthworms (13%).

3.5. Microclimatic conditions

Morning air temperature in the forest was virtually constant during the measurement period, with a mean of 21°C . The morning air temperature in all coffee-based systems varied more between observation times, with a mean of $25 - 26^\circ\text{C}$.

Table 4
Decomposition rates and residence times (measured in weeks) of standing litter in monoculture, shaded and multistrata coffee systems compared to natural forest

Land use system	Equation for remaining litter mass: $\log(Y/Y_0) = a - kt$	R^2	Slow fraction	Residence time ($1/k$) slow fraction, week	Half life time slow fraction, week
Remnant Forest	$-0.0623 - 0.0071t$	0.299	0.79	141	98
Multistrata	$-0.0920 - 0.0077t$	0.570	0.90	130	90
Simple shade	$-0.0467 - 0.0105t$	0.424	0.81	96	66
Sun	$-0.1017 - 0.0104t$	0.594	0.87	95	67

Table 5
Population density (P) and biomass (B) of earthworms, and classification based on ecological type

Land use system	Population (P), Individual m^{-2}	Biomass (B), $g m^{-2}$	B/P, $g/individual$	Ecological type			
				Epigeic (EP), Individual m^{-2}	Endogeic (En), Individual m^{-2}	Anecic (A), Individual m^{-2}	(A + En)/P, %
Remnant forest	75 a	31 c	0.41	5 a	36 a	34 a	93
Multistrata coffee	149 b	18 b	0.12	14 a	77 b	59 b	91
Simple shade coffee	83 a	7 a	0.08	7 a	38 a	38 ab	92
Sun coffee	88 a	12 ab	0.14	11 a	51 ab	25 a	87

Values followed by different letters are significantly different at $p < 0.05$.

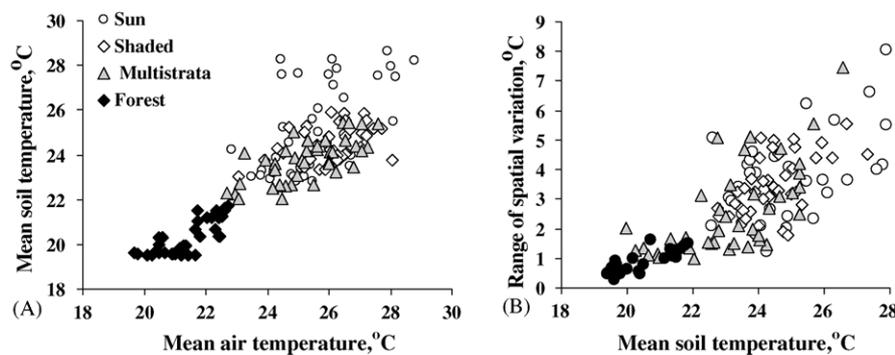


Fig. 7. (A) Relationship between air and soil (5 cm depth) temperatures for different land use types during experiments (March–July, 2003) in Bodong, Sumberjaya; (B) relationship between mean soil temperature and the temperature range (maximum–minimum) among 10 replicate measurements.

Soil temperature (at 5 cm depth) in the forest, multistrata and shaded coffee systems almost exactly matched the air temperatures measured on the same day (Fig. 7(A)). In the sun coffee systems soil temperature tended to be higher relative to air temperature, compared to the other coffee systems. A higher mean soil temperature in the sun coffee systems was associated with a larger range between lowest and highest measured values in ten replicate readings around the same litter bags (Fig. 7(B)).

3.6. Prediction of requirement of litter input to maintain soil macroporosity

Using our measured values of litter fall and decay rates in litter bags, the model slightly overpredicted the amount of standing litter in the remnant forest and in the 7–10-year-old coffee gardens (Table 6). One parameter (f_t , the ‘transfer fraction’ of the measured surface litter decay rate) was fitted to

Table 6
Predictions of standing litter necromass, soil organic matter and macroporosity (using the model based on Fig. 1) compared to measured values, assuming measured rates of litter fall and decay of surface litter, a macropore decay rate of 0.006 day^{-1} , a litter incorporation fraction 0.3 times the daily rate of disappearance, and a macropore formation per unit litter incorporation of 0.1

Land use systems	Surface necromass, $Mg ha^{-1}$		C_{org} relative to forest		Macroporosity, %	
	Measured	Predicted	Measured	Predicted	Measured	Predicted
Remnant Forest	4.2	4.5	1	1	12.3	14.5
Multistrata coffee	3.3	2.5	0.44	0.83	3.6	10.1
Shade coffee	3	1.7	0.55	0.71	3.5	6.8
Sun coffee	1.6	2.5	0.43	0.61	3.0	4.1

nm, not measured.

the data to predict soil carbon values (assuming a constant organic matter decay rate of 8% per year for all land use types). One further parameter group (f_w/k_m) was fitted to predict soil macroporosity.

While this fitting process achieved reasonable approximations of the measured macroporosity and relative carbon contents of the forest and sun coffee systems, it overpredicted carbon content and macroporosity of the multistrata and simple shade coffee gardens.

4. Discussion

Regarding hypothesis 1, our data and the model indeed suggest that differences in standing necromass stock between forest and converted land use types can be understood from differences in the annual amount of litter inputs and measured decomposition rates. For the soil organic matter portion of the hypothesis, the simple model overpredicted the levels in the ‘intermediate’ systems (multistrata and simple shade coffee). The decomposition rate of litter in the remnant forest, multistrata and simple shade coffee ranked in agreement with the ‘lignin plus polyphenol to nitrogen’ ratio, but the measured decomposition rate in sun coffee systems was faster than expected on the basis of litter quality alone.

Apart from climatic conditions, decomposition of plant residues is known to be influenced by edaphic factors (soil texture and bulk density), decomposer organisms and resource quality (i.e., ratio of C to N, lignin to N, and polyphenolics to N) (Tian et al., 1997). Freshly pruned materials of *C. calothyrsus* and *P. dasyrrachis* on acid soils in North Lampung decomposed slowly (Handayanto et al., 1992) due to a low litter quality; ratios of C:N, lignin:N, and polyphenol:N for *Calliandra* have been reported as 16.0, 9.3 and 0.69, respectively, while for *Peltophorum* these ratios were 18.4, 15.6 and 1.59, respectively (Hairiah et al., 1996). In our study, the ratios of C:N, lignin:N and polyphenol:N for standing litter in the forest were 31, 17 and 5, respectively; for sun coffee systems these ratios were 18, 19 and 3, respectively (Table 3). Litter from multistrata and shaded coffee gardens had slightly lower ratios (higher quality) than sun coffee with values of 16, 15 and 2, respectively. Van Lauwe et al. (1997) reported the results of an incubation study on decomposition of fine litter fraction (>0.25 mm) of agroforestry species in Nigeria; decomposition rates were closely related to the ratio of (lignin + polyphenol) to N. A low litter quality with a ratio (lignin + polyphenol) to N > 8 or 10, would not cause substantial changes in the short-term microbial C (i.e., implying that microbial activity would not be diminished). In this study, all litter samples from the various cover types had ratios of (lignin + polyphenol) to N > 10 (Table 3) indicating slow decomposition (Van Lauwe et al., 1997). Such materials are potentially ideal for providing soil cover and protecting the soil surface against raindrop impact, which causes surface sealing and compaction. The relationship between litter decomposition rate and its quality, shown by the ratios of (lignin + polyphenol) to N, polyphenol to N, lignin to N and C to N, appear to be linear for a limited range of litter quality (data not shown). The best-fit linear relationship

was found for the ratio of (lignin + polyphenol) to N ($Y = 5.3615X - 49.907$; $R^2 = 0.739$, $n = 8$).

The higher soil temperatures in sun coffee systems and the frequency of ‘sunflecks’ may account for differences in decomposition rates. The temperature effect on decomposition as used in the Century (Parton et al., 1987) and derived models (including WaNuLCAS; Van Noordwijk and Lusiana, 1998) suggest a near-linear increase from a relative value of 0.5 at 20 °C to a value of 0.7 (40% higher) at 25 °C. The 2–3° higher soil temperature in sun coffee can thus be expected to compensate for the lower ‘litter quality’ by its effect on the decay rate. The main issue remaining in hypothesis 1 is thus the relation between litter input and soil organic matter in the intermediate systems.

Regarding hypothesis 2, our data suggests that the relative merit of the intermediate systems (compared to sun coffee) for maintaining soil macroporosity via enhanced earthworm biomass in response to increasing organic material inputs and soil organic matter stocks is less pronounced than expected. The (dimensionless) relative soil bulk density (BD/BD_{ref}) of the various coffee gardens was substantially higher than that of the forest ‘controls’, but remained <0.9, a rather low value, perhaps due to the high volcanic ash content, and may thus be below critical thresholds. The simple model based on a constant ‘rate of collapse’ of macropores may need to be expanded to account for the compacting effect of farmers working their land. Where forest soils have very low bulk densities, compaction due to people walking on the land will rapidly occur.

Measurements of surface runoff and erosion in the same area (and partially the same coffee gardens) (summarized by Widiyanto et al., 2004; Khasanah et al., 2004) showed that even recently cleared coffee gardens had 6–10 times more surface runoff than forest controls. Soil loss appears to peak in the first 2–4 years after land clearing. While surface runoff only gradually decreases with increasing age of the coffee gardens, the erosion rate rapidly declines with time. These results can be understood from the strong protective, filter effect of thick surface litter, and improvement of soil infiltration (Suprayogo et al., 2004). A continuous food supply through litter fall and root decay as found in the forest increased earthworm biomass (Hairiah et al., 2004). Declining soil macroporosity in coffee gardens was closely linked to the population density of earthworms from the anecic rather than endogeic groups. The anecic species removes litter from the soil surface through their feeding activities (Lavelle and Spain, 2001) and considerable amounts of soil, mineral soil and organic matter may be redistributed through these activities, accompanied by physical effects on soil structure and hydraulic properties (Swift and Bignell, 2000). Annual litter input in the forest ($14 \text{ Mg ha}^{-1} \text{ year}^{-1}$) was higher than in the multistrata coffee system ($9.8 \text{ Mg ha}^{-1} \text{ year}^{-1}$) (Table 2); litter inputs in a rain forest in West Sumatra were $11.4 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Hermansah et al., 2002). Leon et al. (2003) reported changes in earthworm diversity and community structure along a chronosequence of abandoned tropical pastures in the Cayey Mountains of Puerto Rico. These results indicate that earthworm density was highest in the active pastures ($273 \text{ individuals m}^{-2}$), decreased as forest

regeneration proceeded, and was lowest in the mature forests (88 individuals m^{-2}). Native earthworms, however, were replaced with exotic species of soil-feeding earthworms (*Pontoscolex corethrurus*) as a consequence of the lower standing litter biomass. We obtained similar results: population density of anecic earthworms in multistrata coffee systems (59 individuals m^{-2}) was significantly higher than in the forest (34 individuals m^{-2}) (Table 5), unfortunately a more detailed identification of the species composition was not performed (but data will be forthcoming).

Ongoing research in Sumberjaya on the relationships between soil properties and the geological origin of the parent material may cast some doubt on the validity of the ‘remnant forest’ plots as true ‘controls’ for the coffee garden. Although texture and pH are similar, the remnant forest is located higher on the slope and may have more volcanic ash in its parent material than the coffee gardens that were sampled. Elsewhere in the Sumberjaya catchment, on soils with a large component of volcanic ash in the parent material, coffee gardens of all ages and types maintained high infiltration rates and exhibit minimal erosion. Even a bare plot, set up as a control for the measurement of soil erosion, survived without the usual signs of gully formation and had erosion rates much below our measurement series in Bodong, Sumberjaya (Widianto et al., 2004). While these new insights may lead us to reconsider the forest versus coffee garden differences as real ‘effects’ of land use change, the comparison amongst different types of coffee gardens within the Bodong area remains valid. Our overall conclusion is that the recovery of litter layers during the establishment period after forest conversion in coffee gardens is important for reducing soil erosion. The relation between surface litter, the soil biological activity it supports and the macroporosity that results from both root turnover (Van Noordwijk et al., 2004) and the activity of ecosystem engineers requires further study. Differences in both size and number of earthworms merit a further exploration at the species level rather than simply ‘ecological groups’.

Selecting more diverse coffee gardens with litter of varied ‘quality’ may be expected to cater for both the soil biota that depend on rapidly decomposable sources, as well as provide the resilient soil cover that reduces splash erosion and enhances filter effects to prevent widespread overland flow. For the time being, the presence of the litter layer, as such, may be the key criterion. The relationship of this litter layer to tree density and species composition is the subject of further investigation.

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