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Dynamics of density fractions of macro-organic matter after forest conversion to sugarcane and woodlots, accounted for in a modified Century model

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Abstract

Soil organic matter (SOM) is the major controlling factor of soil fertility for low external input agriculture. However, most models describing SOM dynamics are based upon pools which are not directly measurable. We developed a SOM submodule for the CENTURY model based on Ludox particle size density fractions. The turnover rates of these easily measurable fractions were determined by assessing their ^{13}C isotope signatures in a chronosequence under surgane after rainforest conversion.

The net monthly decomposition rates of light (L), intermediate (I) and heavy (H) fractions of macro-organic matter (150 µm – 2 mm size) under sugarcane cultivated for 2–10 years following forest removal ranged from 0.0162 and 0.0154 month^{-1} for forest-derived L and I fractions to 0.0118 month^{-1} for H fractions, while for unfractionated forest soil organic matter it was 0.0068 month^{-1}. The soil carbon of the CENTURY model was reconstructed and the 'slow' (SOM2) pool was divided into L, I, H and R fractions, where the R (resistant) fraction represents the 50–150 µm size fraction. The modified CENTURY model simulated the dynamics of L, I and H fractions as well as total organic carbon (C%) under sugarcane with a coefficient of determination (R^2) of 0.90, 0.95 and 0.98, respectively. Without further adjustments the model was applied to woodlots of *Gliricidia sepium* and *Peltophorum dasyrrachis*. The model accounted for 60% of the variation in measured light (L) fraction in the 0–5 cm layer under *Gliricidia* and *Peltophorum*, but only for 40% of the variation in the I and H fraction data. Results thus show some progress in linking SOM models to measurable soil organic matter fractions, but are not yet satisfactory for the heavier fractions, more strongly associated with mineral particles. Experimental data for these fractions show a considerable spatial variability, possibly linked to activity of soil fauna, not covered by the model.

Keywords: Model, light fraction, density fractionation, soil organic matter, SOM, CENTURY, sugarcane, forest

Introduction

Soil organic matter (SOM) plays a major role in soil fertility, particularly in traditional agricultural systems with low-external-input management, as found on upland soils in Indonesia. Improved understanding of SOM dynamics and especially of the transformations between fresh organic inputs of different quality and SOM pools of intermediate turnover time is needed to guide the search for sustainable practices. Despite considerable progress in this field (Smith *et al.*, 1997; Paustian *et al.* 1997a,b; Whitmore & Handayanto, 1997) however, a clear gap remains between models and independently measurable pools (Van Noordwijk *et al.,* 1997). A range of models of SOM dynamics has recently been compared on a number of data sets from the temperate climatic zone (Smith *et al.*, 1997), with models such as RothC, CANDY, DNDC, CENTURY, DAISY and NCSOIL performing better than the SOMM, ITE and Verberne model. It is not known whether or not similar results would be obtained in tropical regions, but the CENTURY model has been applied successfully in several tropical ecosystems (Woomer, 1993; Parton *et al.*, 1994). Model validation and improvement could become more efficient if a closer link can be obtained between SOM fractions of intermediate turnover time postulated in models and those actually measured. So far, model validation is based on total SOM and/or on N mineralization as a by-product of SOM turnover. Total SOM is not very sensitive to changes in land use practices. For example, Boonchee & Anecksamphant (1993) found little change in total SOM on upland soils in Thailand more than ten years after forest removal. Van Noordwijk *et al.* (1997) found that land use effects on total SOM in Sumatra are much smaller than often assumed. Spatial variability in total SOM content (partly linked to variation in texture) can exceed changes over time in many studies, reducing options for critical model testing.

A further problem is the different definitions of the total SOM pool (Anderson & Ingram, 1989). The DAISY model includes added (fresh) organic matter in its total (SOMT) pool, but SOMT is confined to decomposed organic matter in other models such as the CENTURY (Smith *et al.*, 1997). Active microbial biomass is a key factor in organic matter decomposition, but maybe it is too dynamic to be used for routine validation due to the rapid response of microbes to organic matter supply and changing environmental conditions (Cadisch & Ehaliotis, 1996) and the very short turn over time of microbial biomass. This pool forms only a small portion of SOMT, with a dynamic that can be clearly distinct from that of SOMT (Sitompul *et al.*, 1996). SOM pools with an intermediate turnover rate seem to be the best alternative of all presently proposed SOM pools as a parameter for model validation. The CENTURY model (Parton *et al.*, 1987) includes a 'slow' pool (SOM2), which has been thought to be equivalent to the particulate organic matter (POM) with a particle size from 50µm to 2mm. The POM fraction can be easily measured indeed and in as far as it is reasonably homogeneous in its dynamics can be used for model initialization and testing (Woomer, 1993). There are questions, however, on the homogeneity of the POM fraction and it may be worthwhile to fractionate further.

CENTURY defines the slow pool as the result of the breakdown of structural material modified by soil texture attributes (protection). The breakdown of the primary cell wall, containing mainly cellulose, hemicellulose, pectin and extensin, leaves secondary wall characterized by lignin with a higher molecular weight. This process results in slow pools of different densities. Activity of the soil fauna can contribute to a comminution of plant residues and the formation of relatively tight associations of organic and mineral particles with a reduced turnover of these heavier fractions. Meijboom *et al.* (1995) developed a particle density fractionation (PDF) method to fractionate the 150μm–2mm fraction obtained by sieving into three fractions based on physical density: light (L), intermediate (I) and heavy (H) macro-organic matter. This fractionation scheme is linked to the notion that organic matter in differently sized aggregates differs in function (Gestel & Merckx, 1994). The mineral-free L fraction consists of partly decomposed plant residues and is the major carbon substrate for active microbes. The L fraction exerts a dominant influence on soil nutrient dynamics, based on a positive correlation between C & N mineralization and the amount of N & C in the L fraction and active microbial biomass (Hassink, 1993). Initial application of this size-density fractionation method to acid upland soils under various land covers in Lampung showed that the response of fractions was more sensitive to land use than SOMTC (Hairiah *et al.*, 1995).

In this contribution we explore how the CENTURY model can be modified to include pools corresponding with the particle density fractions obtained with the method of Meijboom *et al.* (1995). Data are presented on the changes in these fractions when forest in Lampung, Sumatra was converted into sugarcane plantations. For this transition the ^{13}C isotopic signature of the SOM fractions can indicate their forest or sugarcane origin. This is due to the fact that C3 plants (rainforest) discriminate stronger against the naturally occuring isotope than C4 plants (sugarcane) and hence the derived soil organic matter has different ^{13}C signatures (Cadisch *et al.*, 1996). Empirical data on turnover time of the fractions was used to calibrate a model in which the slow pool of the CENTURY model has been split into four fractions. The model was tested on data obtained under improved woodlot fallows with various amounts of litter inputs of two tree species, substantially differing in litter quality.

Materials and methods

Experiments

SOM data to be simulated were obtained from a study of SOM dynamics under sugarcane following forest removal and a fallow experiment with leguminous trees (woodlot) at the Biological Management of Soil Fertility (BMSF) research station in northern Lampung, Sumatra (Van der Heide *et al.*, 1992). Soil, Grossarenic Kandiudult with a low pH (<5), and climate of the location were reported by Van Noordwijk *et al.* (1992). These climatic (rainfall and temperature) and evapotranspiration data were used as model inputs, but model inputs for soil characteristics were obtained from measured data of the fields under study. These included silt, sand and clay content which were 12.5%, 69% and 18.5% under sugarcane, and 21%, 67% and 12% under woodlot trees in the fallow area. Bulk density of 0–20 cm layer was

1.1 g cm^{-3} under forest and 1.25 g cm^{-3} under woodlot trees, but varied from 1.1 to 1.4 g cm^{-3} under sugarcane crops cultivated for 2–10 years.

Sugarcane Timeseries

The sugarcane plots were part of a plantation belonging to Bungamayang sugar factory, surrounding the BMSF research station (Van der Heide *et al.*, 1992), established after forest clearing. During the forest phase, the inputs of organic matter into the soil were fallen leaves and decaying roots. In the first year after forest removal main inputs consisted of forest plant roots left as all aboveground parts of plants were burnt and cleaned out. The amount of fallen forest leaves measured in the field was 68 g DM (dry matter) m^{-2} $month^{-1}$, while decayed roots and roots left at forest removal were estimated to be 10 g DM m^{-2} $month^{-1}$ and 2000 g DM m^{-2} respectively (Hairiah, unpublished; Sitompul *et al.*, 1996). During sugarcane cultivation, stripped leaves from shoot stalks and roots of sugarcane were the potential sources of SOM and measured to be 1500 g DM m^{-2} and 1000 g DM m^{-2} respectively (Palm *et al.*, 1994). These were assumed to decline by as much as 100 g DM m^{-2} yr^{-1} in parallel with the yield decline observed in the field. As young sugarcane leaves are usually taken out of plots for cattle feed and other residues burnt, we estimated that only 1% of the shoot DM remained as aboveground input at harvest. At ratoon preparation, the amount of dead roots was assumed to be 70% of the whole roots. During the sugarcane cycle, it was assumed that the inputs of organic matter from fallen leaves were 10, 30 and 100 g DM m^{-2} and from decayed roots 5, 20 and 70 g DM m^{-2} in month 3, 2 and 1 before harvest. The carbon, nitrogen and lignin contents of fallen sugarcane leaves were measured (Mahabratha, 1996) at 45%, 0.3% and 12%, and those of sugarcane roots were 40%, 0.5% and 10% respectively (root lignin estimated). The same values were used for the organic matter inputs during forest growing in the first year.

Woodlot fallow

The improved fallow consisted of *Gliricidia sepium* and *Peltophorum dasyrrachis* trees grown at a spacing of 4 m between and 1 m within rows for 7 years. The input of organic matter under the trees at the start of simulation was standing litter which was 230 and 947 g DM m^{-2} under *Gliricidia* and *Peltophorum* respectively. The input of organic matter from fallen leaves (50 and 120 g DM m^{-2} respectively) was based on litter trap measurements in the field (Hairiah, 1997), whereas that from roots was estimated to be 15% of the fallen leaves based on results of the CENTURY model. The carbon, nitrogen and lignin content of brown surface litter varied with time and was 45–51%, 2.77–3.42% and 13–31% under *Gliricidia*, and 35–39 %, 1.49–1.85% and 39–50 % under *Peltophorum*, respectively. These C, N and lignin contents were used to estimate those of fallen leaves by multiplying with 1.15, 1.34 and 0.65 respectively. The C, N and lignin content of roots were assumed to be 25%, 95% and 80% of that of fallen leaves. These estimations were based on previous information on the leaf quality of corresponding species (Hairiah *et al.*, 1996; Handayanto *et al.*, 1994).

SOM fractionation

A fractionation procedure developed by Meijboom *et al.* (1995) on the basis of colloidal silica suspensions (Ludox) was employed. The procedure involved the following steps: 1. Dry sieve the soil through a 2 mm mesh sieve to remove roots and coarse litter particles; 2. Re-wet 500 g of soil and leave it for 24 hours; 3. Wash the samples on a 150 µm sieve under a gentle stream of water; a 250 µm sieve can be placed on top of the finer one to avoid clogging of the sieve; fine aggregates may be crushed on the coarser sieve during the washing; the silt and clay sized particles passing through the 150 µm sieve are discarded; 4. Collect material from both sieves and separate the coarse mineral sand particles from fractions which contain organic material by 'decantation' in swirling water; the mineral fraction is discarded; 5. The remaining sand-sized fractions are separated into three fractions, by sequential immersion into silica suspensions (Ludox) of two physical densities: 1.13 g cm^{-3} and 1.3 g cm^{-3}. In the method description by Meijboom *et al.* (1995) a density of 1.37 g cm^{-3}, was used, but its viscosity may cause problems and a suspension of 1.3 g cm^{-3} is preferred (Hairiah *et al.*, 1995). The three fractions were indicated as 'light' (floating on 1.13 g cm^{-3}), 'intermediate' (floating on a 1.3 g cm^{-3} suspension, but not on 1.13 g cm^{-3}) and 'heavy' (not floating on either). The material coming to the surface on a given suspension within a specified time is scooped off, rinsed and dried. These fractions were analysed for total C and ^{13}C signatures using an automated CN analyzer coupled to an Europa 20–20 mass-spectrometer (Europa Scientific, Crewe, UK).

Model construction

The present SOM model is a modification of the SOM submodel of the CENTURY model, based on the description in Parton *et al.* (1987) and Metherell *et al.* (1993). The modification was confined to dividing the slow pool (SOM2) into light (L), intermediate (I), heavy (H) and resistant (R) fractions (Figure 1). The R fraction was introduced as the difference between the POM (50µm – 2mm) and the L+I+H fractions, reflecting the 50–150 µm size range (Hairiah *et al.*, 1996). The turnover rate of the L fraction was thought to be higher than that of SOM2 used in the CENTURY Model (0.0167 month^{-1} at a temperature of 20°C) and lower than that of surface structural material (0.325 month^{-1}). This was based on the notion, firstly, that SOM2 pool is the sum of L, I, H and R pools. Secondly, the L fraction having a coarse texture is plant residues that have been partly decomposed (Meijboom *et al.*, 1995).

Actual turnover rates (k values) were obtained from the Ludox fractionations and ^{13}C isotopic analysis of the sugarcane timeseries (Hairiah *et al.* 1995; Figure 2) which allowed the decomposition pattern of forest derived organic matter in the different density fractions to be calculated by fitting the data to the following decomposition model:

$$Y = e^{-kt}$$

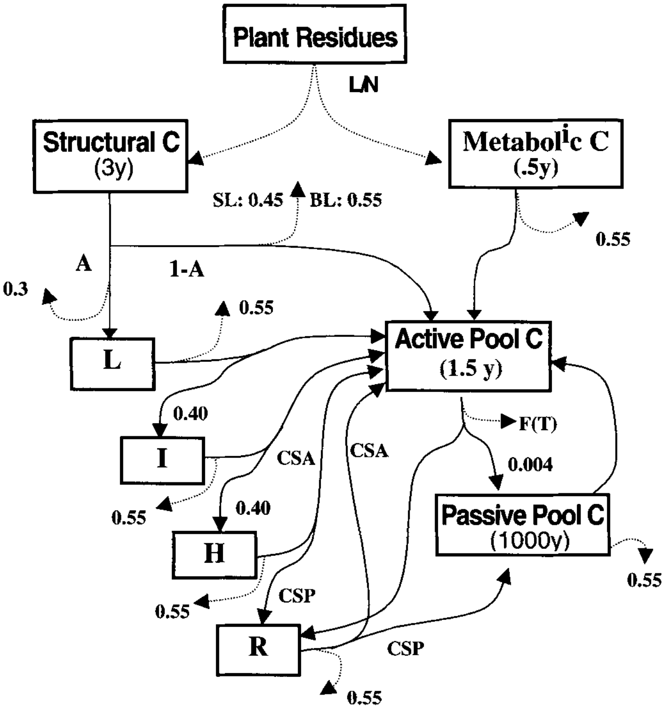

Figure 1. Flow diagram for carbon flow model. L = light fraction pool, I = intermediate fraction pool, H = heavy fraction pool, R = resistant fraction pool, dashed lines = respiratory CO_2 evolution & L/N = lignin to nitrogen ratio, A = lignin fraction, F(T) = 0.85–0.68 T, T = silt + clay content (fraction), CSP = 0.003–0.009 Tc, Tc clay content (fraction) and CSA = 1-CSP-0.55. The numbers in the boxes indicate turnover time (years) according to the CENTURY model. Turnover time for other C pools (see text).

using the nonlinear procedure of Genstat, where k is the turnover rate and t is time in months since forest conversion. Resulting actual k values were 0.0162, 0.0154 and 0.0118 month^{-1} for L, I and H respectively (Table 1). With these values as starting points, the best maximum turnover rates of L, I, H and R fractions obtained from model-calibration procedures were 0.0305, 0.0284, 0.0175 and 0.0115 month^{-1}.

The input of carbon to L, I, H and R pools derives from the decomposition of structural material, and of L, I and H pools respectively (Figure 1). In the CENTURY model, some C flow from active (SOM1) pool is allocated to SOM2, and the

Table 1. Decomposition constants for forest soil organic matter (C_{org}) and for the Light (L), Intermediate (I) and Heavy (H) fraction of macro-organic matter obtained with the Ludox method based on an analysis of $\delta^{13}C$ of soil organic matter 1–10 years after conversion of forest to sugarcane in Lampung, Indonesia (Hairiah *et al.*, 1995).

Fraction	Decomposition constant, k (yr^{-1})	Standard error of estimated k	Percentage of variance accounted for (R^2)
Light	0.194	0.026	91
Intermediate	0.185	0.049	73
Heavy	0.142	0.013	96
L + I + H	0.168	0.024	90
C_{org}	0.082	0.029	58

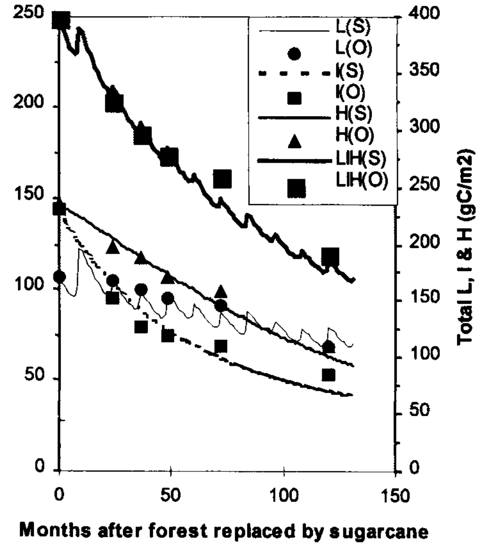

Figure 2. The dynamics of simulated (lines) and observed (symbols) light (L), intermediate (I), heavy (H) and LIH fractions within 0–20 cm depth under sugarcane. LIH = L + I + H.

same flow is confined to the R pool in the present model. It was assumed that the fraction of C flow from L and I pools allocated to SOM1 was lower than that from structural and higher than that from H or R pools, and hence was estimated to be 10% of the C flow (minus respiration), therefore the remaining 90% were allocated to the I or H pools. The fraction of C flow from H and R allocated to R and passive (SOM3) pools, respectively was determined by sand and clay content as in the CENTURY model.

Results and discussion

Turnover time of Ludox fractions

A direct assessment of the turnover of the size-density Ludox fractions of the original forest soils was obtained from a chronosequence of sites where forest had been converted to sugarcane in the past ten years (Hairiah *et al.*, 1995). Analysis of the stable carbon isotope ratio $^{12}C/^{13}C$ of the Ludox fractions allowed distinction of the organic matter in the three size density fractions derived from the forest vegetation (a C3 photosynthetic pathway) and from the sugar cane (with a C4 photosynthetic pathway). From these time series decomposition constants could be derived (Table 1), for the total C_{org} pool (0.082 yr^{-1}) as well as for the various fractions (0.194, 0.185 and 0.142 yr^{-1} for the light (L), intermediate (I) and heavy (H) fractions respectively). These decomposition parameters, however, are a net effect of transformations between pools and decomposition (release of CO_2); current data do not allow a full separation of inter-pool conversions. On the basis of the apparent turnover time, the light and intermediate fractions can be clearly distinguished from the heavy fraction and the total C_{org} pool, and the regression lines for the decay of the various fractions were better defined (larger R^2 values) than for C_{org}. The decomposition rate of the H fraction was similar to that found by Hassink (1995) for a temperate grassland soil. However, the decomposition rates of the L and I fractions were considerably lower than those measured by Hassink (1995) under laboratory conditions. Additionally, the differences in turnover rate between the fractions were smaller. Ten years after forest conversion 25, 40 and 60% of the light, intermediate and heavy fractions still had a forest carbon signature. This may have been because of the presence of charcoal due to the burning activity. Cadisch *et al.* (1996) found a significant amount of charcoal present in their size-density fractions after rainforest conversion to pastures in Brazil.

SOM dynamics under Sugarcane

The importance of L (light), I (intermediate) and H (heavy) pools to be incorporated in a SOM model to obtain a better understanding of nutrient supply from SOM was emphasized by Meijboom *et al.* (1995). These size-density pools appear to be to more sensitive to changes in land use compared with SOM2 (slow pool) as well as easy to measure. Thus relatively small changes in the organic matter supply into the soil is expected to be expressed more clearly by these pools than others. However, no attempts so far have been made to simulate the dynamics of these fractions due to the absence of models at present equipped with such pools. The model used in the present study is a modification of the SOM submodel of CENTURY in which SOM2 (slow pool) was divided into L, I, H and R (resistant) fractions obtained by size-density fractionation.

The derived turnover rates of the forest fractions were used as inputs for the modified CENTURY model (Figure 1) after adaption for maximum turnover rates (see Material and Methods). The dynamics of the light (L), intermediate (I) and heavy (H) fraction of the slow SOM pool under sugarcane cultivated for 2–10 years following forest removal were all captured well by the modified CENTURY Model (Figure 2) without further adjustments. The coefficient of determination (R^2) for the relationships between observed and simulated light, intermediate and heavy fractions were 0.90, 0.95 and 0.98 respectively. Similarly the relationship between observed and simulated total LIH (L+I+H) was close with a coefficient of determination of 0.98. The model was also sufficiently capable of simulating the dynamics of total soil organic matter when changes in soil bulk density were taken into consideration (Figure 3). When soil bulk density was maintained at 1.1 g cm^{-3} (fine line Figure 3) as in the forest the model failed to predict the longer term changes in total SOM content. However, when the actual bulk density measurements were used, the model captured (thick line, Figure 3) the measured values in the older plantations. The combination of these two lines, using corresponding values of soil bulk density, picked up most of the total SOM data points.

The effect of a large organic matter supply at forest removal by the slash and burn method in the first year, leaving most roots in the soil (2000 g m^{-2}), was clearly expressed (first sharp increase, Figure 2) by the LIH and especially the light fraction

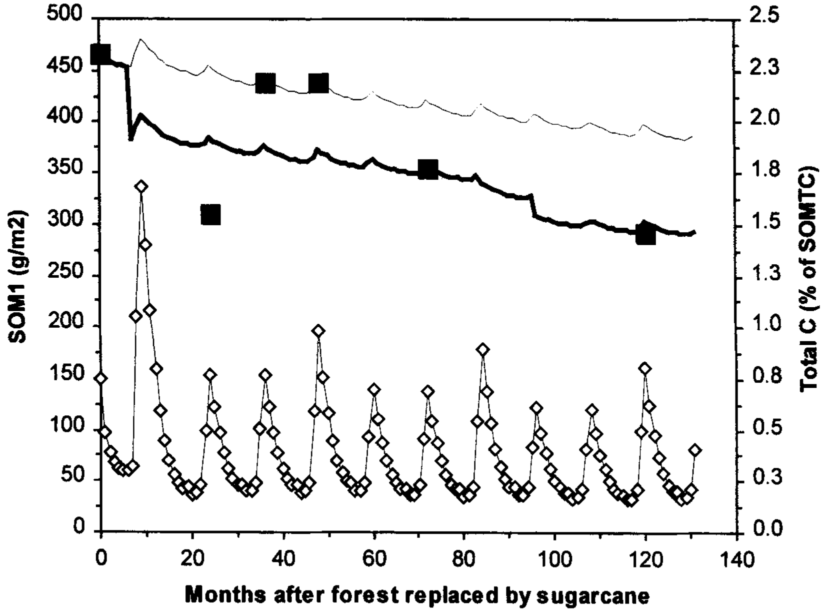

Figure 3. The dynamics of simulated (lines) and observed total organic C (%; ■, SOMTC) and simulated active pool (◊, SOM1) within 0-20 cm depth under sugarcane following forest removal on an Ultisol in Lampung. (Note: fine/tick line simulation with bulk density 1.1/measured g cm^{-3} respectively).

simulations. Subsequently inputs of organic matter during sugarcane cultivation in the following years were less, derived mostly from roots at harvest (≤1000 g DM m^{-2}) as nearly all shoot parts were removed or burnt. These root inputs also apparently had a marked effect on LIH fractions as demonstrated by their regular fluctuation on a yearly basis. However, the most marked effect of organic inputs resulting either from forest removal or from sugarcane harvest was exhibited by variations in the active pool (SOM1, Figure 3), presumed to be microbial biomass and metabolites, which were not measured in the present experiment.

Woodlots

The observed dynamic of light (L), intermediate (I) and heavy fractions in the 0–5 cm layer varied considerably between the treatment of organic matter input without any clear trend (Figure 4). Statistical analyses showed no effect of organic matter input (litters) either from aboveground or from belowground on any of the SOM2 fractions (L, I, H, R) independent of tree species. The effect of time was significant, and all fractions under both species showed a tendency to decline with time. As there was no significant effect of organic matter inputs on SOM2, the dynamic of the SOM2 fractions was simulated only for that under the treatment without organic matter input (obtained by root and above-ground litter exclusion). This model validation showed a declining trend similar to the trend of observed data (Figure 4), but

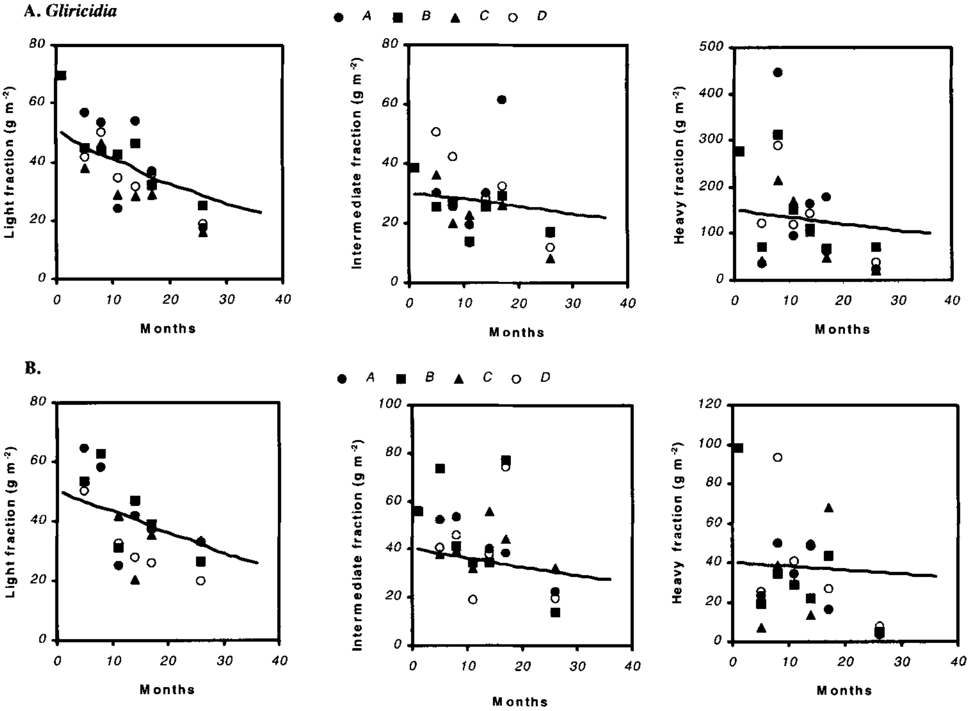

Figure 4. The dynamics of simulated (lines) and observed (symbols) light (L, left), intermediate (I, middle) and heavy (H, right) fractions within 0–5 cm depth under A) *Gliricidia* and B) *Peltophorum* with treatments A (+aboveground + belowground input), B (–aboveground + belowground input), C (+aboveground – belowground input) and D (–aboveground – belowground input).

the average rate of decrease was higher in the observed than in the simulated data particularly in the intermediate and heavy fractions. The relationship between observed and simulated data was significant in all fractions, but the total variation in the intermediate and heavy fraction that was accounted for by a linear function was low (Figure 5).

The present model was derived from CENTURY which was designed to simulate SOM dynamics in the 0–20 cm layer including SOM on the soil surface. Hence it may have some shortfalls in applying it to the data obtained from the 0–5 cm layer under the fallow woodlot which excluded SOM on the soil surface due to litter traps. This is supported by the lack of evidence for any input of below-ground organic matter to the SOM2 fractions under study in that layer. Therefore the 0–5 cm layer was not a representative layer for general SOM2 studies due to the very small amount of decaying roots in that layer. This was likely to have been associated with the root distribution of *Gliricidia* and *Peltophorum*, which was mainly below 10 cm depth as observed by Hairiah *et al.* (1992) in the same field. There was also an absence of an effect of organic matter inputs from aboveground, but the possible reason for this was the very small transfer of decomposed organic matter into the soil from the soil

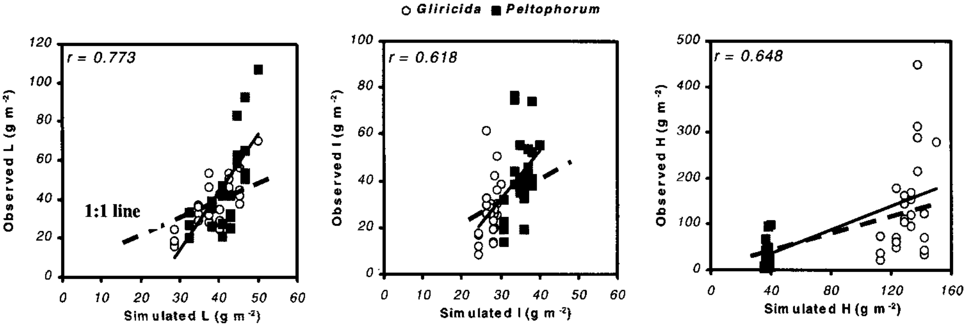

Figure 5. Relationships between simulated and observed light (L, left), intermediate (L, middle) and heavy (H, right) fractions under *Gliricidia* and *Peltophorum* for all treatments (see Figure 4).

surface as litter falls were relatively high. The quantitative transfer of decomposed organic matter from soil surface into the soil under undisturbed soil is not well understood but it is thought to be mainly a function of soil fauna and rainfall.

In spite of the discrepancies in soil depth, the model captured the average dynamic of light SOM fraction in both tree species, but was less able to simulate the dynamics of heavy and intermediate fractions. The latter effects could be due to our limited understanding of the fate of decomposing material from the lighter fractions to the heavier ones and physical protection mechanisms (Hassink & Whitmore, 1997). A better insight into these dynamics could be obtained by pulse labelling (^{13}C or ^{14}C) the soil with labelled plant material. However, a significant relationship was found between observed and simulated data in all fractions and species (Figure 5). This suggests that the model could be applied to simulate the dynamic of SOM2 fractions under *Gliricidia* and *Peltophorum*, and better results would be expected when considering SOM2 fractions in the 0–20 cm layer.

The simulated amounts of SOM2 and its fractions were within the range of corresponding SOM fractions observed under various land covers in other study areas in Lampung and Malang which included forest, sugarcane, *Gliricidia* and *Peltophorum* (Hairiah *et al.*, 1996). This suggests that data observed under sugarcane and fallow trees, including organic matter inputs used in the simulation were within the range of general conditions in Lampung, Sumatra. In other words, the declining trend of SOM with time may be expected under other land covers in Sumatra due to insufficient amounts of organic matter inputs. Thus the ability of the model to mimic the main behaviour of the system controlling SOM dynamics under sugarcane may also apply to other land covers.

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