COMPARISON OF CARBON SEQUESTRATION BETWEEN MULTIPLE-CROP, SINGLE-CROP AND MONOCULTURE AGROFORESTRY SYSTEMS OF *MELALEUCA* IN JAVA, INDONESIA

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BUDIADI & ISHII HT. 2010. Comparison of carbon sequestration between multiple-crop, single-crop and monoculture agroforestry systems of *Melaleuca* in Java, Indonesia. We compared aboveground C accumulation and C cycling of three types of cajuput (*Melaleuca leucadendron*) agroforestry plantations producing cajuput oil in Java, Indonesia. In the study site in east Java, where cajuput trees were planted with cassava and maize in a multiple-crop agroforestry system, cassava was the largest component of aboveground total C accumulation in the plantation. In the site in west Java, where trees are planted with rice in a single-crop agroforestry system, both cajuput and rice contributed similar amounts to aboveground total C accumulation. Aboveground net C accumulation was highest in the multiple-crop system, where it averaged 18.5 and 7.1 Mg C ha^{-1} year^{-1} in the 7- and 25-year old stands respectively. In the plantations, relative amounts of harvested (leaf–twigs and branches of cajuput and edible crop biomass) and returned (non-edible crop biomass) C were similar and did not change with stand age. This indicated that although crop harvesting removed large amounts of C from the system, an almost equal amount of organic waste was returned, thus, establishing a dynamic C cycle. The C:N ratio of returned waste was high, suggesting that decomposition rate was slow and that C accumulated in the soil. Compared with more complex agroforestry systems, carbon sequestration of cajuput plantations was low. Our results, however, suggested that C accumulation may be increased and a sustainable C cycle established by returning more biomass waste and maintaining multiple crop systems.

Keywords: Carbon cycle, cajuput, non-timber forest product, sustainable production

BUDIADI & ISHII HT. 2010. Perbandingan pensekuesteran karbon antara sistem-sistem perhutanan tani tanaman pelbagai, tanaman tunggal dan monokultur *Melaleuca* di Jawa, Indonesia. Kami membandingkan akumulasi C atas tanah serta kitaran C bagi tiga jenis ladang perhutanan tani *Melaleuca leucadendron* yang menghasilkan minyak kayu putih di Jawa. Pokok *M. leucadendron* di tapak kajian Jawa timur ditanam bersama-sama ubi kayu dan jagung dalam sistem perhutanan tani tanaman pelbagai. Di sini ubi kayu menyumbang jumlah C atas tanah yang terbanyak di ladang tersebut. Di tapak Jawa barat pula pokok *M. leucadendron* ditanam bersama-sama padi dalam sistem perhutanan tani tanaman tunggal. Di tapak ini, pokok *M. leucadendron* dan padi menyumbang jumlah C atas tanah yang sama banyak. Nilai bersih bagi akumulasi C atas tanah paling tinggi dalam sistem tanaman pelbagai dengan nilai purata masing-masing sebanyak 18.5 Mg C ha^{-1} tahun^{-1} dan 7.1 Mg C ha^{-1} tahun^{-1} bagi dirian berusia tujuh dan 25 tahun. Di ladang, jumlah C relatif yang dituai (daun, ranting serta dahan *M. leucadendron* dan biojisim tanaman makanan) serta yang dikembalikan (biojisim tanaman yang tidak boleh dimakan) adalah serupa dan tidak berubah dengan usia dirian. Ini menunjukkan bahawa walaupun penuaian tanaman makanan mengeluarkan jumlah C yang besar daripada sistem, jumlah sisa organik yang hampir sama banyak dikembalikan. Ini membentuk satu kitaran C yang dinamik. Nisbah C:N bagi sisa dikembalikan adalah tinggi dan ini mencadangkan bahawa kadar pereputan adalah perlahan dan C terkumpul dalam tanah. Jika dibandingkan dengan sistem perhutanan tani yang lebih kompleks, pensekuesteran C di ladang *M. leucadendron* adalah rendah. Namun keputusan kajian ini mencadangkan bahawa akumulasi C dapat ditingkatkan dan satu kitaran C yang mampan dapat diwujudkan jika lebih banyak sisa biojisim dikembalikan di samping mengekalkan sistem tanaman pelbagai.

INTRODUCTION

An important issue concerning landuse systems in current decades is the role and capability of the systems to sequester atmospheric CO_2. Several countries have adopted the clean development mechanism (CDM) in an effort to reduce the effect of global warming. One of the goals of

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CDM is to increase the capacity of tropical ecosystems to sequester atmospheric CO_2. CDM is especially important in tropical regions where degradation and loss of tropical forest ecosystems have resulted in increasing CO_2 emission as well as decreasing carbon sequestration.

In tropical regions, agroforestry systems provide various environmental services including carbon sequestration (Pandey 2002, Jose 2009, Nair *et al.* 2009). Development of agroforestry plantations in the tropics, especially on private lands, gives opportunity to both local farmers and investing developed countries to reap the benefits of CDM, i.e. income and credit respectively for the sequestered carbon in the systems (Adi *et al.* 2004, Verchot 2004). In agroforestry systems, trees accumulate large amounts of C in woody biomass. Large amounts of C are lost from the system through harvesting of crops and timber products, while relatively slow release occurs through decomposition of leaf litter and fine roots (e.g. Nair 1993, Wild 1993, Farrel & Altieri 1997, Huxley 1998). Recent studies have shown that agroforestry systems have potential to sequester greater amounts of C than traditional farming systems (e.g. Gupta *et al.* 2009, Kaonga & Bayliss-Smit 2009, Takimoto *et al.* 2009). However, in tropical agroforestry systems, productivity may decline as a result of continuous removal of plant biomass (Sanchez & Palm 1996, McDowell 2001, Budiadi *et al.* 2005). Harvesting of plant biomass from the system removes nutrients and may lead to slow degradation of soil fertility (McDonald & Healey 2000, Shanmughavel *et al.* 2001). In tropical agroforestry systems, appropriate management of the nutrient cycle is important for maintaining productivity and preventing nutrient loss from the system (Montagnini 2000, Shanmughavel *et al.* 2001, Nolte *et al.* 2003).

Previous studies on C sequestration of tropical agroforestry systems have yielded highly variable results ranging from 0.29 Mg C ha^{-1} year^{-1} in a fodder bank agroforestry system in West African Sahel to 15.21 Mg ha^{-1} year^{-1} in mixed species stands in Puerto Rico (Nair *et al.* 2009). Still higher values have been reported for the moist tropical zone (Jose 2009). More studies are needed to document and compare how C sequestration capabilities vary among different types of tropical agroforestry systems (Alifragis *et al.* 2001).

In Java Island, Indonesian cajuput (*Melaleuca leucadendron* (Myrtaceae), is locally known as kayu putih tree or swamp-tea tree. Plantation of cajuput represent one type of agroforestry system (taungya) that resembles a shifting cultivation between trees and crops (Budiadi *et al.* 2005). Cajuput grows well in a wide range of soils and environmental conditions and has been planted to reforest areas with poor soils (Kartawinata & Satjapradja 1983). The leaves and twigs of cajuput contain an essential oil (cajuput or white tea tree oil) that is used widely in medical and cosmetic products in Indonesia and South-East Asian countries (Axtell & Fairman 1992). Harvesting for oil extraction involves intensive pruning of branches. This creates relatively open forest conditions and in many regions, farmers surrounding the forest area cultivate crops such as maize (*Zea mays*), cassava (*Manihot esculenta*) and lowland rice (*Oryza sativa*) between the tree rows. In very poor soils and dry areas, the trees are planted in a monoculture system.

Agroforestry systems with multiple crops generally yield higher production than monocultures (Nair 1993, Gajaseni 1997, Kelty 2000, Nolte *et al.* 2003, Pearce & Mourato 2004) and, thus, may accumulate more C and nutrients. However, in cajuput plantations, intensive harvesting of leaves, small branches and twigs (hereafter leaf–twigs) for oil extraction and branches for fuelwood, in addition to crop harvesting, may lead to substantial losses of C and nutrients from the system. In this study, we compared C accumulation in crop parts between three cajuput plantations with different planting systems, namely, multiple crop, single crop and monoculture. We also measured the relative amount of C in different crop parts, which were harvested and removed or returned to the system in order to evaluate C budget in the cajuput agroforestry plantations.

MATERIAL AND METHODS

Research sites

Research sites were selected from managed cajuput plantations owned by Perum Perhutani, the forest enterprise, in Java to represent the three agroforestry systems studied. The sites are Ponorogo in east Java (site P), Indramayu in west Java (site I) and Gundih in central Java (site G). There are several differences in environmental conditions and plantation management between the three sites. However, harvesting methods and management of the tree products are similar. All three plantations aim to produce commercial cajuput oil as a non-timber forest product (NTFP).

Site P is a 2370-ha plantation located in east Java (7° 52' S, 111° 27' E, 200–300 m asl). Average annual rainfall in the area was 1952 mm year^{-1} from 1994 to 2004. The soil of the site is clayist volcanic ash soil with organic material content ranging 3–4%. In site P, trees were originally planted in a 3 × 1 m-spacing. Between the tree rows, farmers cultivate cassava and maize as permanent companion crops and sometimes groundnut (*Arachis hypogaea*). We categorised site P as a multiple-crop agroforestry system.

Site I is a 2740-ha plantation located in west Java (6° 23' S, 108° 17' E, 200–400 m asl). Average rainfall in the area was 1615 mm year^{-1} from 1994–2004. The soil is alluvial soil with organic material content ranging 2–5%. Trees in site I are planted in a 3 × 1 m-spacing, except in stands younger than 10 years where trees were planted in 6 × 1 m spacing. Site I represents a lowland cajuput plantation which is characterised by permanent shifting cultivation between cajuput trees and lowland rice. In rainy season, site I is covered by stagnated water similar to a paddy field. Trees grow well in stagnated water, thus, the name swamp-tea trees. We categorised site I as a single-crop agroforestry system.

Finally, site G is a 1308-ha plantation located in central Java (6° 59' S, 111° 00' E, 0–40 m asl). It is the driest between the three sites, although no data on rainfall were available. The soil is volcanic ash with organic material content less than 5%. In site G, trees were commonly planted at higher density (2 × 1 m spacing) than in the other two sites. Here, agroforestry is practised for the first two years only (similar to teak plantations in Java) because of limited water and poor soil conditions. After the third year, the trees are planted in monoculture system.

Every year, biomass and nutrients are removed from the plantations by harvesting of leaf–twigs and branches of cajuput and edible crop parts (cassava tuber and maize grain in site P and rice grain in site I). In the two plantations with taungya agroforestry systems (sites P and I), the remaining non-edible crop biomass (stem and leaf of cassava, stem, leaf, husk and cob of maize and rice stover) is returned to the soil as green manure.

Biomass sampling and nutrient analysis

In each site, we selected seven age classes of cajuput stands. The stand ages ranged between 7 and 40 years old in site P, 7 and 37 years old in site I, and 10 and 35 years old in site G. In each stand, we established three study plots (20 × 20 m). In each plot, stem diameter at ground level (D_0) was measured for each tree. Based on the size distribution of D_0, 7 to 10 representative trees were selected in each plot. Branches of sample trees were cut at about 10 cm above the sprouting part. Leaf–twigs were separated from large branches and weighed in the field. Subsamples of the leaf–twigs and branches were taken from each sample tree for dry mass measurement in the laboratory. In each plot, one representative tree with D_0 close to the plot average was chosen for stem biomass estimation. Fresh weight of the stem was measured in the field and disc samples were taken for dry mass estimation in the laboratory.

To estimate crop biomass, we established subplots of 5 × 5 m for cassava, 3 × 3 m for maize and 2 × 2 m for rice in the same locations as the tree biomass sampling. All biomass in the subplots was harvested at crop maturity (approximately three months for maize and rice, eight months for cassava). For nutrient analysis, crop biomass was separated into subsamples of harvested crop parts (cassava tuber, maize grain and rice grain) and returned crop parts (stem and leaf of cassava, stem, leaf, husk and cob of maize, and rice stover). The samples were then washed and dried at 60 °C for 24 hours for measurement of dry mass.

To measure the C content of dried samples, wooden subsamples were chipped and all samples were passed through a grinder with 40-mesh sieve and mixed thoroughly. The ground samples were redried in the oven to constant weight and cooled before weighing for C analysis. Organic carbon content (%) was determined using Walkley–Black method (Allison 1965). Nitrogen content (mg g^{-1}) in composite samples of the returned crop biomass was determined by estimating the C:N ratio using Kjeldahl digestion method (Bremner & Mulvaney 1982).

Data analysis

Biomass of the leaf–twigs and branches of cajuput in each plot was determined by multiplying the mean dry mass of leaf–twigs and branches of the 10 sample trees by the tree density (tree ha^{-1}). The stem biomass of cajuput in each plot was determined by multiplying the stem dry mass of the representative tree by the tree density. The biomass of the crops in each plot was determined by multiplying the biomass in the subplots (kg m^{-2}) by the crop area. Carbon accumulation (Mg C ha^{-1}) in the trees and crops was calculated by multiplying the dry mass of each crop part by its C content (%). In each plot, the aboveground total C accumulation was calculated as the sum of C accumulation in the cajuput trees and the crops. The aboveground net C accumulation in the cajuput stems was calculated by dividing the C accumulation by the stand age. This was added to the C accumulation in returned biomass to obtain aboveground net C accumulation for each plot.

We compared C accumulation between study sites using ANCOVA, with site as the main factor and stand age as covariate. The relationship between stand age and C accumulation was investigated using regression analysis. Budiadi *et al.* (2005) found that stand productivity in the study sites reached maximum between 15 and 35 years and fitted quadratic models to biomass accumulation in the plantations. Therefore, we first tested for linearity of the relationship and then fitted quadratic equations where applicable to estimate the stand age when maximum C accumulation was reached. We calculated relative amounts of C (% of the total C accumulation in the stand) in standing, harvested and returned biomass. We transformed the percentages of each biomass component using arcsine transformation to normalise the variance (Zar 1984) and then compared relative C accumulation in each biomass component between study sites using ANCOVA. The relationship between stand age and relative C accumulation was investigated using regression analysis as indicated above. All analyses were conducted using SPSS for Windows Version 10.0.1.

RESULTS

Carbon accumulation in cajuput stands

The aboveground total C accumulation in the system was highest in the multiple-crop system (site P) where cassava and maize accumulated large amounts of C; maximum total accumulation was 48.4 Mg ha^{-1} for a seven-year-old stand (Figure 1, $F = 53.92$, $p < 0.001$). The majority of C accumulation in site P was in the crops and C accumulation in the cajuput trees was less than in the other two sites ($F = 7.48$, $p = 0.001$). In site P, cassava contributed the largest component of C accumulation, followed by maize. For all stands in site P, C accumulation in the cajuput trees was less than 25% of the stand total. In the single-crop system (site I), rice and cajuput trees contributed equally to C accumulation. The difference between sites in the amount of C accumulation in the cajuput trees was mostly in the stems and branches ($F = 5.84$, $p = 0.005$ and $F = 22.60$, $p < 0.001$ for stem and branch respectively). Accumulation in the leaf–twigs was greater in site I than in the other two sites ($F = 12.60$, $p < 0.001$). Total C accumulation was lowest for the monoculture (site G).

In sites P and G, total C accumulation in the cajuput stems increased with increasing stand age (Table 1). In site I, C accumulation in the stems and branches reached maximum at 27 years. C accumulation in leaf–twigs reached maximum between 24 and 29 years in all the sites (Figure 1).

We also observed age-related variation in C accumulation for cassava and maize in the multiple-crop system (site P). In contrast to accumulation in the cajuput trees, the greatest C accumulation in cassava was observed in the youngest stands (31.9 Mg C ha^{-1} in a seven-year-old stand) and accumulation then decreased with increasing stand age (Table 1), with a minimum value at 25 years. Carbon accumulation in maize varied between stand ages ($F = 5.062$, $p = 0.008$) but did not show a clear age-related trend. In the single-crop system (site I), C accumulation in rice did not vary with stand age ($F = 0.327$, $p = 0.912$).

Between the three study sites, the multiple crop system (site P) had the highest annual aboveground net C accumulation (Figure 1). Net C accumulation was highest in the 7-year-old stands (18.5 ± 1.4 Mg C ha^{-1} $year^{-1}$) and lowest in the 25-year-old stands (7.1 ± 0.1 Mg C ha^{-1} $year^{-1}$). In the single-crop system (site I), net C accumulation did not change with stand age. In the monoculture (site G) net C accumulation increased with increasing stand age.

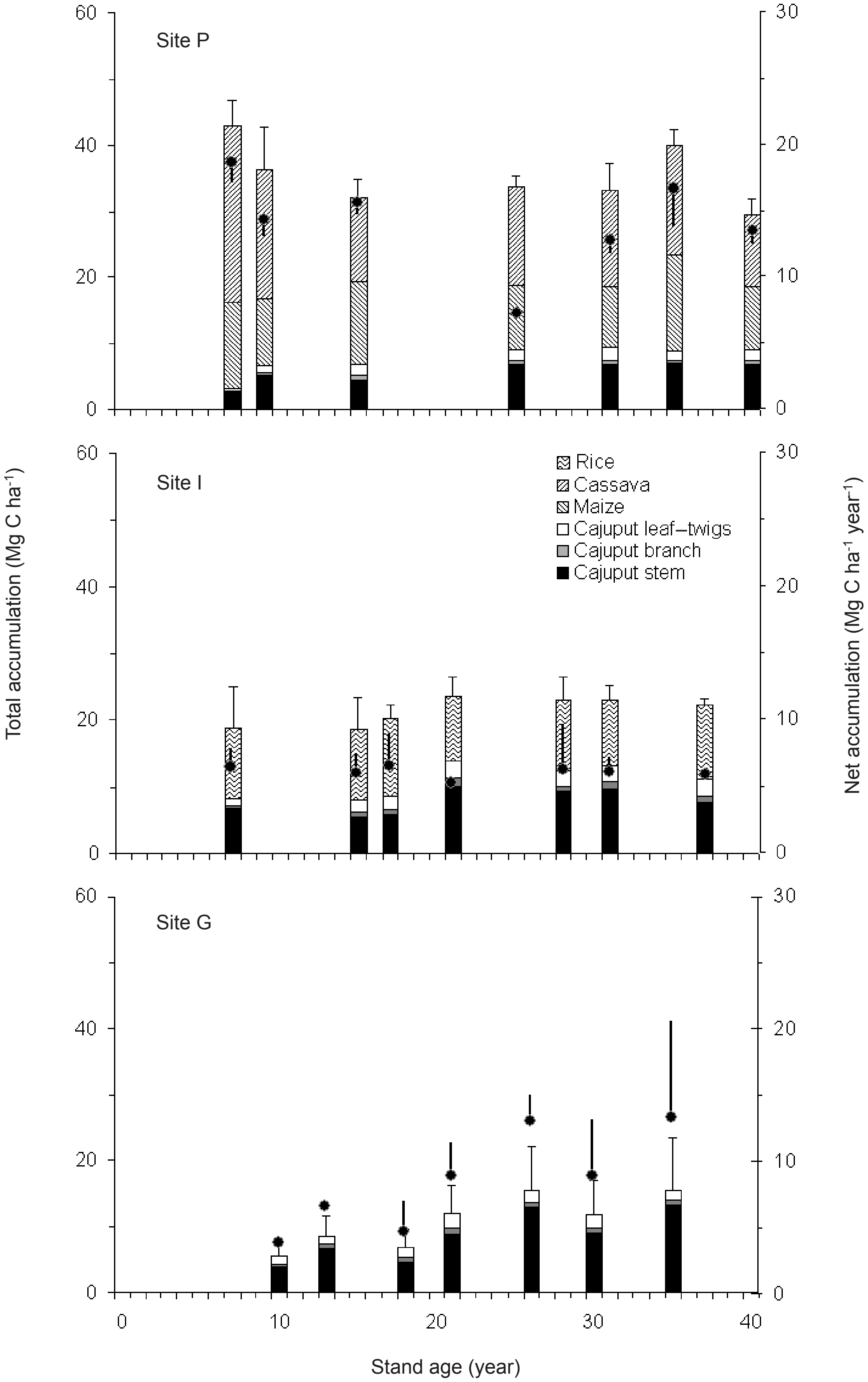

Figure 1 Carbon accumulation in crops and cajuput (*Melaleuca leucadendron*) trees in the three agroforestry plantations in Java, Indonesia. Bars indicate aboveground total accumulation while points indicate annual net accumulation (excluding harvested biomass). Error bars indicate one standard deviation.

Carbon budget of cajuput agroforestry systems

As shown in Figure 1 and Table 1, the amount of standing C (i.e. cajuput stem) increased with increasing stand age in all the sites. In site P, the amount of harvested C (leaf–twig of cajuput, cassava tuber, maize grain and rice grain) decreased linearly with increasing stand age reflecting the trend observed in cassava tuber and maize grain ($r^2 = 0.243$, $p = 0.023$). In sites I and G, harvested C reached maximum at 30 and 26 years respectively, reflecting the trend observed for the branches and leaf–twigs of cajuput ($r^2 = 0.588$, $p = 0.033$ and $r^2 = 0.541$, $p = 0.007$ for sites I and G respectively). In site P, returned C (stem and leaf of cassava, stem, leaf, husk and cob of maize and rice stover) decreased with increasing stand age and reached minimum at 24 years, reflecting the trend observed for cassava stem ($r^2 = 0.339$, $p = 0.013$). In site I, returned C did not change with stand age. There was no returned biomass in site G.

Table 1 Regression analysis of carbon accumulation in trees and crops of cajuput *(Melaleuca leucadendron)* agroforestry plantations in Java, Indonesia

Site	Crop	C accumulation* Max/Min**	r^2	p
P	Cajuput			
	Stem	+	0.545	0.001
	Branch	+	0.265	0.017
	Leaf–twig	27^+	0.526	0.006
	Maize			
	Stem–leaf	±	NA	NA
	Husk–cob	±	NA	NA
	Grain	−	0.217	0.033
	Total	±	NA	NA
	Cassava			
	Stem-leaf	25^-	0.541	0.001
	Tuber	−	0.268	0.016
	Total	−	0.342	0.005
	Site total	±	NA	NA
I	Cajuput			
	Stem	27^+	0.652	0.001
	Branch	27^+	0.628	0.003
	Leaf–twig	29^+	0.713	0.003
	Rice			
	Stover	±	NA	NA
	Grain	±	NA	NA
	Total	±	NA	NA
	Site total	28^+	0.597	0.009
G	Cajuput			
	Stem	+	0.473	0.006
	Branch	+	0.364	0.005
	Leaf–twig	24^+	0.691	< 0.001
	Site total	+	0.550	0.004

*Indicates whether C accumulation increased (+), decreased (−), or did not change (±) with stand age (linear regression); **number indicates the estimated stand age when maximum ($^+$) or minimum ($^-$) C accumulation was reached (quadratic regression); NA = data not available

The relative amount of standing C increased linearly with increasing stand age in site P (r^2 = 0.579, $p < 0.001$), reached maximum at 27 years in site I (r^2 = 0.593, p = 0.003) and did not change with stand age in site G (Figure 2). The relative amount of harvested C decreased linearly with increasing stand age in site P (r^2 = 0.219, p = 0.032), reached minimum at 27 years in site I (r^2 = 0.645, p = 0.002) and did not change with stand age in site G. The relative amount of returned C decreased with increasing stand age and reached minimum at 23 years in site P (r^2 = 0.268, p = 0.019), whereas it did not change with stand age in site I. There was no returned biomass in site G. In sites P and I, the relative amount of returned C was nearly equal to the harvested C for all stand ages (F = 0.009, p = 0.923).

Among the returned crop biomass, stem and leaf of maize had the highest C:N ratio (Table 2). The C:N ratios of husk and cob of maize, stem and leaf of cassava and rice stover were similar.

DISCUSSION

The C accumulation in the cajuput plantations in this study ranged from 4.5 Mg C ha^{-1} $year^{-1}$ in the 18-year-old stand in the monoculture system (site G) to 48.4 Mg C ha^{-1} $year^{-1}$ in the 7-year-old stand in the multiple-crop system (site P). These values are comparable to that reported for similar types of tropical agroforestry systems. For example, C accumulation in shaded coffee gardens in Lampung, Indonesia averaged 18.4 Mg C ha^{-1} $year^{-1}$ (Van Noordwijk *et al.* 2002), while that in *Leucaena leucocephala*-based Naalad fallow systems in the Philippines averaged 16 Mg C ha^{-1} $year^{-1}$ (Lasco & Suson 1999). On the other hand, C accumulation in the six-year shifting cultivation systems in Sarawak is 47 Mg ha^{-1} $year^{-1}$ (Jepsen 2006), close to the maximum value observed in this study. These observations suggest that reduced agroforestry systems such as cajuput plantations and other taungya-type systems may have lower potential for C sequestration compared with more complex systems.

Between our study sites, the amount of C accumulated in cajuput trees was lowest in the most complex agroforestry system (site P), where most of the C accumulation occurred in the crops. In contrast with other agroforestry systems that allow for full growth of trees for timber production, tree growth in cajuput agroforestry systems is restricted by annual harvesting of leaf–twigs for oil extraction. Cajuput is known as a relatively slow-growing species with high wood density (Vantomme *et al.* 2002, Serbesoff-King 2003). Annual harvesting of branches may shift the growth allocation of the cajuput trees from stem growth to branch recovery (Budiadi *et al.* 2005). As a result, oil production further reduces stem growth and thus indirectly limits C accumulation the system.

In the three cajuput plantations in this study, maximum productivity was attained at 15 to 35 years, after which productivity declined with increasing stand age (Budiadi *et al.* 2005). Although C accumulated slowly in cajuput stems in the multiple-crop system and the monoculture, C accumulation in leaf–twigs declined in the older stands paralleling the decline in productivity. This may reduce the potential for C accumulation in aboveground plant parts of cajuput (Albrecht & Kandji 2003). Continuous harvesting of leaf–twigs also leads to tree mortality, which causes further productivity decline (Budiadi *et al.* 2005).

Table 2 Average C:N ratio in composite samples of returned crop biomass in cajuput (*M. leucadendron*) agroforestry plantations in Java, Indonesia

Site	Crop	Plant part	C:N ratio*
P	Maize	Stem–leaf	78.4 ± 5.1
		Husk–cob	48.4 ± 2.0
	Cassava	Stem–leaf	43.2 ± 1.2
I	Rice	Stover	47.7 ± 1.2

*± one standard error

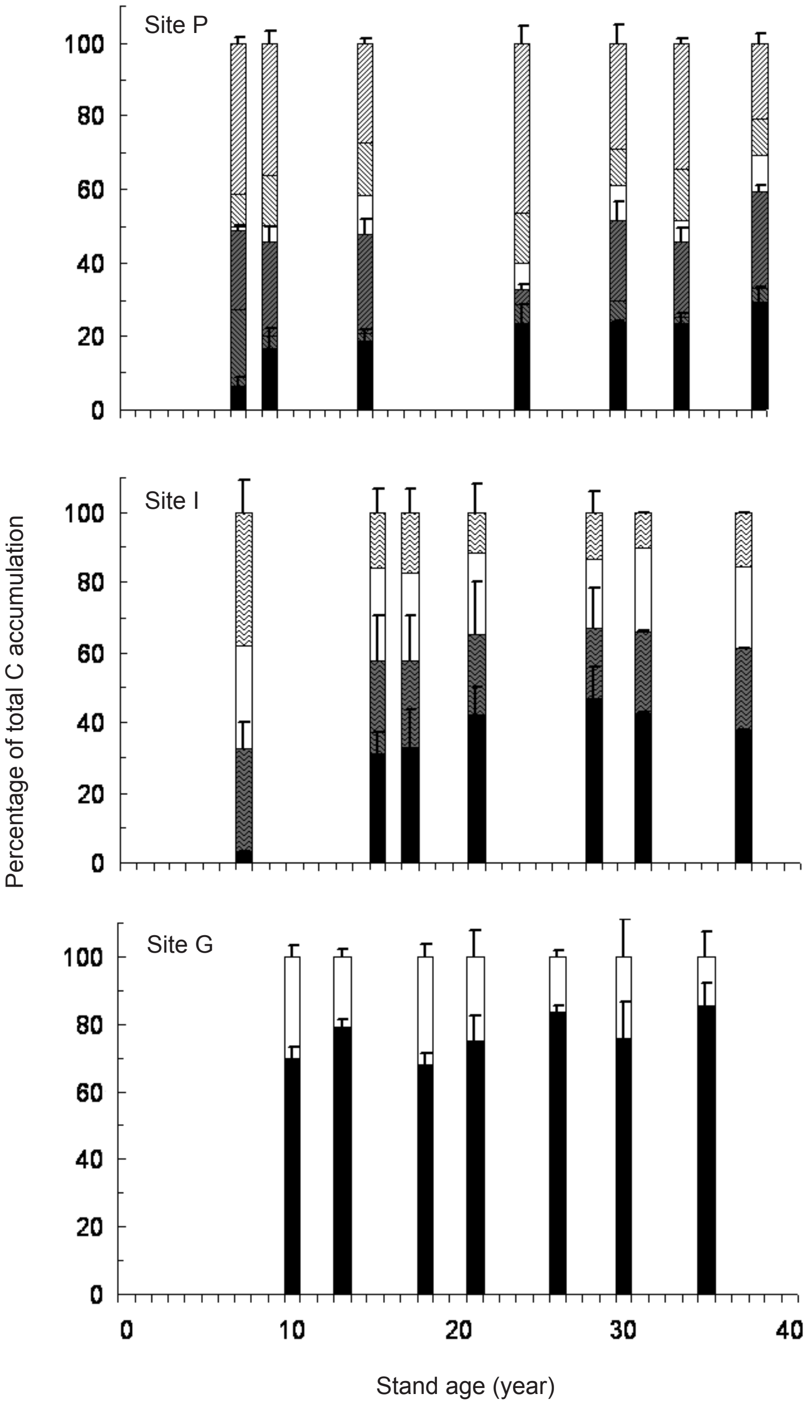

Figure 2 Relative amounts of carbon in standing, returned and harvested biomass in crops and cajuput (*M. leucadendron*) trees in the three agroforestry plantations in Java, Indonesia. Black bars indicate standing C (cajuput stem), grey bars indicate returned C (stem and leaf of cassava, stem, leaf, husk and cob of maize and rice stover), and white bars indicate harvested C (leaf–twig of cajuput, cassava tuber, maize grain and rice grain). The hatching patterns indicate crops as in Figure 1. Error bars indicate one standard deviation.

Our results showed that in complex agroforestry systems, the majority of C accumulation occurred in the seasonal crops. However, because a large proportion of the crop biomass is harvested every year, most of the absorbed C will be released through crop consumption. This emphasises the importance of returning unused crop biomass to the system to enhance C accumulation in the soil. In both the multiple- and single-crop systems, the relative amount of returned biomass was almost equal to that of harvested biomass, establishing a dynamic C cycle.

In the multiple crop system the relative amount of harvested C fluctuated with fluctuations in cassava production, while in the single-crop system it was relatively stable. In the young stands, there is less competition between trees and crops because the trees are still relatively small. As trees increase in size, there is both above- and belowground competition with crops. In addition, declining soil fertility may lead to decreasing crop yield, such as in the multiple crop system. Crop yield in the older stands may be maintained by nutrient addition from the returned biomass (Budiadi *et al.* 2006).

Annual aboveground net C accumulation was highest for the multiple-crop system and lowest for the monoculture. It should be noted that these estimates did not take into account belowground C accumulation in the soil and roots. In addition, rates of litter decomposition were not considered in this study. The decomposition rate of returned biomass is an important factor of the dynamics of C cycle in agroforestry systems. Most of the seasonal crop biomass in agroforestry systems consists of straw and stovers, which decompose slowly (Nair 1993, Huxley 1999). Most of the returned biomass in cajuput agroforestry systems in this study comprised crop parts with high C:N ratios. The quality of mulch and the rate of decomposition are affected by nutrient content and C:N ratio of the crop parts (Begon *et al.* 1996, Waring & Running 1998, Montagnini *et al.* 2000, Graca *et al.* 2005), with interaction of climatic factors (Zhang *et al.* 2008). High C:N ratio results in N immobilisation in the litter and slow decomposition rates (Huxley 1999, Hartemink & O'Sullivan 2001). Although we did not determine the decomposition rate of the returned biomass in this study, the high C:N ratios suggest that decomposition rates may be relatively slow. This would lead to slow release of C from the soil.

CONCLUSIONS

When agroforestry systems are intensively managed as multispecies systems with multiple tree–crop strata, the potential for carbon sequestration is higher than for single-crop systems. In contrast with other tropical agroforestry systems, cajuput plantations have low tree density and fewer crops. We found that cajuput agroforests in Java have less potential to sequester carbon compared with more complex agroforestry systems because the proportion of woody biomass (the permanent carbon sink) is relatively small. Although the stems are not cut for timber, annual harvesting for cajuput oil extraction seemed to suppress stem growth. Our results suggested that in cajuput agroforestry systems, carbon was released relatively quickly through the consumption of harvested biomass and relatively slowly through decomposition of returned biomass. Increasing the amount of returned biomass, therefore, would contribute to increasing C accumulation in the system.

In order to increase the C sequestration potential of cajuput agroforestry systems, we recommend that in multiple-crop systems, processed leaf–twigs and branches of cajuput be returned to the system along with crop wastes as mulch or green manure instead of burning because returned biomass contributes to C accumulation in soil as well as growth of woody stems by maintaining soil fertility. In reduced agroforestry systems and monocultures, trees other than cajuput should also be planted to increase the standing biomass. The additional tree species should be maintained to allow full growth for timber harvest so that they will continue to accumulate C in woody tissue.

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