Carbon stocks in Indonesian homegarden systems: Can smallholder systems be targeted for increased carbon storage?

James M. Roshetko, Matt Delaney, Kurniatun Hairiah, and Pratiknyo Purnomosidhi

Abstract. *Homegardens are a common smallholder agroforestry system in Indonesia and throughout the tropics. These species-rich, tree-based systems produce non-wood and wood products for both home use and market sale. Due to their high biomass, these systems simultaneously offer potential for carbon (C) storage. While small size limits the amount of C stored by individual smallholder agroforestry systems, on a per area basis these systems can storage as much C as some secondary forests. In aggregate, smallholder homegarden agroforestry systems can contribute significantly to a region's carbon budget while simultaneously enhancing smallholder livelihoods. A field study in Lampung, Indonesia indicates that homegardens with an average age of 13 years store 35.3 Mg C ha^{-1} in their above-ground biomass, which is on par with the C stocks reported for similar-aged secondary forests in the same area. However, to compare accurately the C stocks of different land-use systems a scale is required that adjusts C stocks of the systems' ages and rotation lengths to a common base. The time-averaged C stock, which is half the C stock at the maximum rotation length, serves this purpose. Our projections reveal that, depending on management options, the time-averaged above-ground C stocks of homegarden systems could vary from 30 to 123 Mg C ha^{-1}. These projected time-averaged above-ground C stocks of homegardens are substantially higher than those of* Imperata*-cassava systems (2.2 Mg C ha^{-1}), which is an extensive vegetation type in the study area. If homegarden systems and other smallholder tree-based systems were to expand in currently degraded and underutilized lands, such as* Imperata *grasslands, the C sequestration potential would be about 80 Mg C ha^{-1}, with considerable variation depending on species composition and management practices. Clear opportunity exists to induce management that leads to higher C stocks at the systems level. However, incentive mechanisms are needed that assure smallholders will benefit from selecting management practices that favor higher C stocks.*

Key words: agroforestry, agroforestation, carbon sequestration, certified emissions reductions (CERs), clean development mechanism (CDM), climate change, greenhouse gas, *Imperata* grasslands, land rehabilitation, tree farming

Introduction

Increasing levels of atmospheric 'greenhouse gases' are generally accepted to be a main contribution to global warming, which, studies indicate, is changing the Earth's weather patterns and could raise ocean levels substantially in the next 100 years (Schimel et al., 1995; Watson et al., 1996). These climatic changes can impact environmental norms and human populations, causing serious negative disturbance to the global economy. As international agreements over greenhouse gas emissions and global warming are negotiated, there is growing interest in the possibility of reducing the increase in the amount of carbon dioxide (CO_2) in the atmosphere through forest-based carbon (C) sequestration projects.

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Forest-based land-use systems—natural forests, forest plantations, and agroforestry systems—sequester CO_2, through the C stored in their biomass. By promoting land-use systems which have a higher C content than the existing plant community, net gains in C stocks (hence sequestration) can be realized. The most significant increases in C storage can be achieved by moving from lower-biomass land-use systems (e.g., grasslands, agricultural fallows and permanent shrublands) to tree-based systems. Forest-based C storage projects have been implemented by electric utilities and other industries as a means to offset the C released by their use of fossil fuels. These projects are still in their preliminary phases. As many efforts to achieve increased forest C storage may have negative implications for the rural poor, options that support human livelihoods deserve special attention. Projects implemented under the Clean Development Mechanism (CDM) of the Kyoto Protocol will offer opportunities for investors seeking 'certified emissions reductions' (CERs) to invest in developing countries for the dual objective of reducing greenhouse gas emissions and contributing to sustainable development. Forest-based C storage projects will likely be part of the CDM.

Indonesia provides an attractive environment for C investment. There are over 8.5 million hectares of *Imperata* grasslands

in Indonesia (Garrity et al., 1997). Originally forests, these lands include pure grasslands, cyclic fallows and shrublands, and are acknowledged to be underutilized. There is clear interest, at both governmental and smallholder farmer levels, to convert some of these lands to a more productive land-use, including tree-based systems (Tomich et al., 1997). Homegardens are a common smallholder agroforestry system in many parts of Indonesia. These species-rich tree-based systems usually occupy lands immediately surrounding the household and are used to produce a diverse array of food and other products. Traditionally intended to produce goods mainly for home consumption, the advent of rural infrastructure and market-economies has made homegardens more commercially oriented. Homegardens production now commonly serves both household and market demand, providing families with much needed income (Krol, 1992; Michon and Mary, 1994).

Simultaneously, homegardens, and other tree-rich smallholder systems, offer potential for C storage because of their high, woody biomass. The question we raise here is: can the role of smallholder agroforestry systems be expanded to serve global environmental goals by targeting them for increased C storage? The objective of this study was to generate C stock inventory data for homegarden systems in Lampung province, Sumatra, Indonesia. The study results are compared to C stock data for other land-use systems in Sumatra previously obtained by the global Alternatives to Slash-and-Burn (ASB) project (Tomich et al., 1998).

Methods

Study area

The study was conducted in the villages of Karang Sakti, Negara Jaya and Tegal Mukti in Pakuan Ratu district in Lampung province, Sumatra, Indonesia at one of the benchmark areas of the ASB project. Soils are well drained, deep (>1–1.5 m), acidic and of low fertility. Aluminum toxicity is common, especially below a depth of 15 cm. Root development is possible down to 1–1.5 m. The major soil groups are Oxisols/Ultisols and Inceptisols covering 64 and 29% of the area, respectively. Elevation is less than 100 m above sea level, mean annual temperature is 28°C, varying between 22 and 33°C (van Noordwijk and Purnomosidhi, 1995; van Noordwijk et al., 1996). Annual rainfall averages 2200–2500 mm, with 5–6 months greater than 200 mm and 1–4 months less than 50 mm.

The study site is a government-sponsored transmigration area for the relocation of spontaneous migrants who previously settled in mountainous areas of Lampung. Transmigrant households were each given 2 ha, including a home lot of 0.25 ha where homegardens were typically developed. The species composition of local homegardens include trees that produce fruit, vegetables, spice, oil, medicine, other non-wood products and timber; perennial understory plants that produce non-wood products; and annual crops—such as vegetables, cassava (*Manihot utilissima*), maize (*Zea mays*) and rice (*Oryza sativa*) (Gintings et al., 1996). The other major land-use classes in the area are sugarcane (*Saccharum officinarum*) plantations, cassava (grown as a cash crop for local agribusiness), other agriculture crops, *Imperata* grasslands and degraded secondary forests.

Site selection

Detailed land-use maps at the smallholder level were not available for the study area. Homegardens were selected if the farmer gave permission and the structure and species were considered typical of local homegardens. Homegardens were excluded if they contained 50% or more of: (1) annual crops (vegetables, cassava, maize, rice, etc.); or (2) one market-oriented tree crop (e.g., coffee (*Coffea robusta*), coconut (*Cocus nucifera*), sengon (*Paraserianthes falcataria*), etc.). Homegardens that contained large areas (25% or more) of rice paddies or fishponds were also excluded. Approximately 25–30% of the assessed homegardens were rejected for these reasons.

Carbon monitoring system

The carbon monitoring system used in this study was developed by Winrock International's Carbon Monitoring Program to quantify the amount of C in land-use systems using forest and agroforestry inventory principles and practices (MacDicken, 1997). Winrock's system quantifies C sequestered by measuring changes in four main carbon pools over time or comparing the C in these four pools with other land-use options. The main C pools are: above-ground biomass, litter, herbaceous material and soil. The Winrock methods are very similar to those used in the ASB project (Hairiah et al., 1999; Palm et al., 1994).

Plot installation and measurement

At each farm site, homegarden dimensions were measured and uncorrected global positioning system (GPS) coordinates taken. Most homegardens were rectangular in shape and roughly 75 m × 25 m. The center point of each homegarden was located and two subplots were laid out perpendicular to the longest borders, along a line that bisected the center point, half the distance between the center point and the short borders. Figure 1 provides a schematic of the sampling design used to locate the center point and subplots. In the few cases when homegardens were L-shaped, a third subplot was established in the middle of the short leg of the L using a modification of the center point location process described above. The agroforestry inventory methods developed by MacDicken (1997) recommend a minimum of four subplots be installed per site, but the homegardens in this study were too small to accommodate four subplots. Two subplots per homegarden provided a sampling intensity of approximately 14%.

Each subplot was a circle with a radius of 8.9 m (area 249 m^2). The diameters of all trees in each subplot with a diameter at breast height (DBH 1.3 m above the soil surface) greater than 5 cm were measured and the species recorded. For coconut and banana (*Musa* spp.), species not covered by the standard diameter-biomass relationship, in addition to DBHs, heights were measured using a clinometer. DBHs of down but intact trees—either living or dead—were also recorded. From the subplot

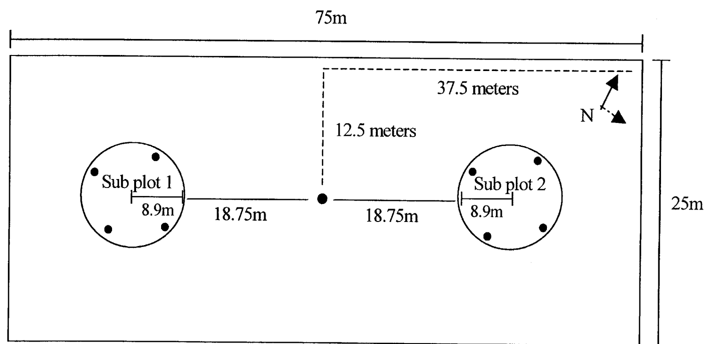

Figure 1. Schematic of sampling design used in homegarden plots. The center point and subplot are located by the following process. From the north-east corner, travel half the distance of the average length of the northern and southern borders (37.5 m in this example). From that mid-point of the northern border, travel half the distance of the average width of the eastern and western borders (12.5 m) along the bearing of the eastern border to the plot center point. Install two subplots along the line that bisects the center point, by traveling half the distance from the center point to the eastern and western border (18.75 m). Subplots are circles with radius 8.9 m. Four sample points are established on north, south and west bearings, 1 m inside the subplot boundary.

center, four points were established (north, east, south and west) 1 m inside the subplot boundary. At these four points samples were collected of herbaceous vegetation (all living plants with a DBH of less than 5 cm diameter), litter (all organic matter above the soil surface having a diameter of less than 5 cm) and soil (to 30 cm depth).

The herbaceous and litter samples were collected by placing a circular aluminum sample ring (0.28 m^2) at the sample points. All living material within the ring was cut at the soil surface. To minimize damage to farmers' crops, neither juvenile trees nor agricultural plants within the sampling ring were destructively sampled for inclusion in the herbaceous sample. This missing biomass was not estimated because: (1) the situation occurred infrequently; and (2) the herbaceous pool contains only a fraction of the total C stock of a forest-based land-use system. All herb and litter samples were weighed using a spring scale. Herb samples were mixed and subsampled for moisture content determination. The same process was used for litter subsampling. Soils samples were collected within the aluminum ring after all herb and litter materials were collected by digging a 30–cm pit and slicing a sample from the pit wall from 0 to 30 cm depth. Sample size was approximately 1 cm thick, 10 cm wide and 30 cm long. Soils were sieved through a 5–mm mesh screen, mixed to a uniform color and consistency and a subsample taken for C analysis. Walkley-Black analysis for soil organic C (Walkley and Black, 1934) was conducted at Brawijaya University, Malang, East Java. At one of the two subplots a soil bulk density sample was taken at a depth of 15 cm by hammering an aluminum cylinder into the pit wall. Bulk density was determined by drying the sample in an oven at 100°C for 24 hours. Soil C ha^{-1} was determined according the following formula: Walkley-Black value (percent C) $\times$ bulk density (g cm^{-3}) $\times$ 3000 kg m^{-2} (MacDicken, 1997).

Estimating above-ground biomass

To estimate biomass (kg) of above-ground vegetation, the following general biomass regression equation was used for most species: $\exp\{-2.134 + 2.530 \times \ln(\text{DBH})\}$ (Brown, 1997). The biomass of coconuts was estimated by calculating volume then converting to biomass by multiplying by an average density of 0.5 g m^{-3}. Biomass of banana was estimated by applying the general biomass equation and subtracting 50%. Root biomass was estimated by taking 25% of above-ground biomass (Cairns et al., 1997). Tree biomass is converted into C by multiplying by 0.5 (MacDicken, 1997).

Results

Carbon stocks

Measurements were made on a total of 19 homegardens. Homegarden ages reported by the landowners varied from 12 to 17 years, with an average age of 13 years. Tree age within the homegardens varied greatly as landowners develop homegardens over a number of years. Total C per homegarden ranged from 56 to 174 Mg C ha^{-1} with an average of 107 Mg C ha^{-1} (Table 1). Tree biomass (above-ground plus roots) and soil accounted for 98% of these C stocks (41% and 57% respectively). Above-ground C in the homegardens varied from 6.3 to 84.0 Mg ha^{-1}, with an average of 35.3 Mg ha^{-1} with a coefficient of variation (CV) of 60%. Soil C varied from 10.4 to 103.7 Mg ha^{-1}, with an average of 60.8 Mg ha^{-1} (CV of 32%). The remaining 2.2% of the C stock was in the litter (1.9%) and herbaceous (0.3%) pools.

Tree component

The homegardens were diverse, containing 45 tree species. A total of 597 trees were sampled, with an average of 34 per homegarden (2–3 plots/homegarden). The species, their predominance in the homegardens, and their primary uses are given in Table 3. Eighty percent of the species in the homegardens provide primarily non-wood products or services (NWPS)lfruits, vegetables, spice, oils, medicines, resins and soil improvement. Coincidentally, these species also account for 80% of the trees surveyed and 73% of the tree biomass (Tables 2 and 3). Twenty percent of the species in the homegardens, representing 20% of the trees sampled and 27% of the tree biomass, are grown primarily for timber and wood production (Tables 2 and 3). These species may also produce non-wood products or services, but these products and services are of secondary importance.

Inventory method

A shortcoming of the method used in this study is that subplot establishment is relegated to the interior of the plot. Thus, species that occur most often, or exclusively, near the borders are under-represented in the inventory. For example, bamboo was observed along the border in approximately one-third of the homegardens surveyed, but not in any of the subplots. A line-

Table 1. Carbon stocks by main pools for 19 homegarden systems in Indonesia.

Plot	Age	Above ground	Litter	Herbaceous	Soil	Roots	Total
	(years)	Mg C ha^{-1}					
1	15	61.9	2.4	0.4	65.7	15.5	145.9
2	15	6.3	0.3	0.2	55.3	1.6	63.7
3	15	34.1	2.7	0.1	10.4	8.5	55.8
4	15	17.6	3.2	0.2	52.1	4.4	77.5
5	12	14.4	2.5	0.1	44.9	3.6	65.5
6	12	21.6	1.9	0.3	69.3	5.4	98.5
7	12	23.0	0.2	0.2	41.2	5.8	70.4
8	13	34.8	2.3	0.1	72.5	8.7	118.4
9	12	24.9	1.6	0.3	40.3	6.2	73.3
10	12	22.6	1.2	0.5	72.5	5.6	102.4
11	14	65.3	1.7	0.3	55.3	16.3	138.9
12	17	17.1	2.7	0.4	65.7	4.3	90.2
13	13	21.6	2.8	0.5	51.6	5.4	81.9
14	13	45.4	3.6	0.2	77.5	11.4	138.1
15	13	84.0	0.0	0.0	69.3	21.0	174.3
16	12	56.2	1.4	0.8	76.1	14.0	148.5
17	13	46.3	0.8	0.3	103.7	11.6	162.7
18	13	53.8	4.0	0.1	69.3	13.4	140.6
19	13	19.3	2.9	1.4	62.1	4.8	90.5
Mean (SD)	13.4	35.3 (21.0)	2.0 (1.2)	0.3 (0.07)	60.8 (4.4)	8.8 (5.3)	107.2 (37.2)
CV	-	60%	57%	95%	32%	60%	34.7%
% of total	-	32.9 %	1.9%	0.3%	56.7%	8.2%	—

Table 2. Number of trees, average DBH, non-wood species C, and wood species C for each of the 19 homegarden systems in the study.

Plot	Trees/ subplots	Average DBH[1]	Trees ha^{-1}	NWPS[2] (trees ha^{-1})	NWPS trees (Mg C ha^{-1})	Timber (trees ha^{-1})	Timber trees (Mg C ha^{-1})
1	42	15.7	840	460	56.4	380	21.0
2	13	17.7	260	260	7.9	0	0.0
3	25	15.0	500	380	27.0	120	15.6
4	33	10.6	660	520	15.0	140	7.0
5	40	10.1	800	580	9.0	220	9.0
6	24	13.8	480	460	27.3	20	0.7
7	59	10.8	1180	720	16.5	460	12.3
8	37	12.5	740	620	19.7	120	23.8
9	34	15.8	680	680	31.1	0	0.0
10	15	18.3	300	300	28.2	0	0.0
11	35	17.0	700	300	22.9	400	58.7
12	27	15.1	540	520	18.4	20	3.0
13	27	15.4	540	540	27.0	0	0.0
14	36	14.7	720	700	55.2	20	1.6
15	48	16.9	960	820	77.9	140	27.1
16	19	19.0	380	380	70.2	0	0.0
17	17	17.0	340	280	17.0	60	40.9
18	46	12.8	920	820	60.5	100	6.7
19	20	17.3	400	320	13.7	80	10.4
Average	31.4		628.4	508.4	31.6	720	12.5
% of tree carbon				72%		28%	

[1] DBH, diameter at breast height.
[2]NWPS, non-wood products and services.

Table 3. Tree species identified in the 19 home garden systems.

Botanical (local) name	Primary uses[2]	Trees		Occurrence	
		Total no.	% of total	no. HGS[3]	%HGS
NWPS[1]					
Cocos nucifera (coconut or kelapa)[4]	ol, fr, vg, md, su, wd	66	11.1	17	89.5
Mangifera indica (mangga)[4]	fr, vg, md, wd, tn	59	9.9	15	78.9
Musa spp. (banana or pisang)	fr,	57	9.5	9	47.4
Nephelium lappaceum (rambutan)[4]	fr, ol, st, md, wd, tn	55	9.2	9	47.4
Parkia speciosa (petai)[4]	sp, vg, md, wd	39	6.5	14	73.7
Archidendron pauciflorum (jengkol)[4] (syn. *Pithocellobium jiringa*)	vg, md, wd, tn	28	4.7	11	57.9
Artocarpus heterophyllus (nangka)[4]	fr, vg, md, dy, tn	26	4.4	12	63.2
Ceiba pentandra (kapok)[4]	co, dy, ol, fr, vg, md	18	3.0	7	36.8
Gliricidia sepium (gamal)	si, or, wd	13	2.2	3	15.8
Coffea robusta (kopi)	st,	12	2.0	4	21.1
Erythrina spp. (dadap)	si, md, wd, or	12	2.0	3	15.8
Gnetum gnemon (melinjo)[4]	fr, vg, wd, dy	11	1.8	5	26.3
Hevea brasiliensis (karet)	rs, ol, fr, vg	10	1.7	3	15.8
Spondias spp. (kedongdong)	fr, vg, wd	10	1.7	3	15.8
Theobroma cacao (coklat)	ol, st, md	8	1.3	3	15.8
Syzygium aqueum (jambu air)	fr, md, wd	7	1.2	4	21.1
Anacardium occidentale (jambu mete)[4]	fr, ol, vg, sp, md, tn	5	0.8	3	15.8
Averrhoa bilimbi (belimbing)	fr, sp, md, su, wd	5	0.8	1	5.3
Garcinia parvifolia (kardis)[4]	fr, rs, wd	5	0.8	1	5.3
Leucaena leucocephala (lamtoro)	vg, si, st, wd, tn, or	5	0.8	2	10.5
Aleurites moluccana (kemiri)[4]	sp, ol, fr, md, wd, dy	4	0.7	2	10.5
Psidium guajava (jambu biji)	fr, ol, sp, st, md, su	4	0.7	4	21.1
Annona muricata (sirsak)[4]	fr, st, md, dy	3	0.5	2	10.5
Melia azedarach (mindi)[4]	md, ol, su, wd, rs, or	3	0.5	1	5.3
Artocarpus integer (cempedak)[4]	fr, vg, md, wd, dy	2	0.3	2	10.5
Persea americana (alpokat)[4]	fr, ol, wd	2	0.3	2	10.5
Annona reticulate (buah nona)	fr, md, wd, tn	1	0.2	1	5.3
Arenga pinnata (kolang kaling)[4]	su, fr, vg, st, md, wd	1	0.2	1	5.3
Cinnamomum parthenoxylon (kayulada)[4]	sp, md, wd	1	0.2	1	5.3
Flacourtia rukam (rukam)[4]	fr, vg, md, wd	1	0.2	1	5.3
Hibiscus tiliaceus (waru)	dy, md, wd, cf, or	1	0.2	1	5.3
Mangifera foetida (pakel)[4]	fr, vg, md, wd	1	0.2	1	5.3
Mangifera odorata (kurai)[4]	fr, md, wd	1	0.2	1	5.3
Tamarindus indica (kayu asam)[4]	sp, ol, fr, st, md, wd	1	0.2	1	5.3
Unknown (sanu)	–	1	0.2	1	5.3
	Subtotal	478	80.1		
Timber species					
Paraserianthes falcataria (sengon putih)	wd, si, dy	59	9.9	7	36.8
Acacia ariculiformis (akasia)	wd, si, or	18	3.0	3	15.8
Tectona grandis (jati)	wd, md, tn, cf	12	2.0	4	21.1
Acacia mangium (mangium)	wd, si, or	6	1.0	1	5.3
Alstonia spp. (pulai)	wd, st, md, rs	6	1.0	4	21.1
Peronema canescens (sungkai)	wd, med, or	6	1.0	1	5.3
Unknown (ladahan)	wd,	5	0.8	2	10.5
Peltophorum dasyrachis (sengon merah)	wd, si, tn,	3	0.5	2	10.5
Terminalia citrina (jaling)	wd, md, tn	3	0.5	1	5.3
Schima wallichii (puspa)	wd, md, tn	1	0.2	1	5.3
	Subtotal	119	19.9		
Total NWPS species		36	80.0		
Total timber species		9	20.0		
Total species		45	100		

[1] NWPS, non-wood products and services species.
[2] Key: co, cotton: cf, craftwood; dy, dye; fr, fruit; md, medicine; ol, oil; or, ornamental; rs, resin; si, soil improvement; sp, spice; st, stimulant; su, sugar; tn, tannin; vg, vegetables; wd, wood.
[3] no. HGS, number of homegarden systems.
[4] Long-lived NWPS species.
Sources: Mackey 1996 (*Acacia mangium*), Pinyopusarerk 1996 (*Acacia auriculiformis*), Leaving and de Foresta 1991 (all others).

transect or rectangular plot may be preferable for small-sized smallholder agroforestry systems.

Discussion

There is great variation in the homegarden systems studied, particularly in the soil C, which varied from 10.4 to 103.7 Mg C ha^{-1}. This wide range of soil C results from various past and present management practices. Some of the homegardens studied were established immediately after the removal of secondary forests. Others were established after the land had been intensively cultivated for sugarcane and other seasonal crop production. Management of homegarden understories also varies greatly, from intense cultivation of annual crops (mainly cassava) to forest-like natural regeneration, pasture and even bare soil. Cleaning, weeding, burning and relocation of biomass are common management practices associated with intensive cultivation that lead to a steady loss in soil C. Conversion of natural forests or grasslands to permanent agriculture may result in 20–50% loss of soil C (Sampson and Scholes, 2000). However, the conversion of agricultural soils back to forest does not quickly reverse this loss (Detwiler, 1986). Soil C levels on such sites are expected to increase for decades or centuries (O'Connell and Sankaran, 1997, cited in Schlamadinger and Karjalainen, 2000). In recognition of this condition, the discussion that follows focuses on the tree biomass, as the pool where the greatest gain in C stocks can be achieved by reforesting *Imperata* grasslands or degraded agricultural lands.

Tree density varied from 13 to 59 trees sampled per homegarden (equivalent to 260–1180 Mg ha^{-1}). On average above-ground biomass accounted for only 33% of the total C in the homegarden systems. Studies under the ASB project in the neighboring province of Jambi show that the portion of C in the tree biomass of tree-based land-use systems increases with age, up to 80% for a 120–year-old natural forest, which contains 500 Mg C ha^{-1} (Tomich et al., 1998). ASB studies in Lampung indicate that tree biomass accounts for 60–65% of total C in 30–year-old secondary forests and mature agroforests (Hairiah, 1997). Aggregated, data from the ASB project and this study show that all tree-based land-use systems accumulate similar C stocks over similar time periods. This indicates that, in terms of C sequestration, the homegardens, with an average age of 13 years, are still very young and will continue to accumulate C steadily for a long time, depending on management.

The C content of homegardens in this study compares favorably with the C content of five other land-use systems in Lampung (Hairiah, 1997). These five land-use systems are mature agroforests, secondary forests, young rubber agroforests, *Imperata* land and cassava fields. The inventory method used by Hairiah (1997) was similar to that used in this study. Both studies used the same general biomass regression equation. The main methodological difference occurs in measuring soil C, Hairiah (1997) used samples collected from a depth of 0–15 cm and our method uses samples collected from 0–30 cm. This is not a critical difference since soil C levels are peripheral to our primary analysis and discussion.

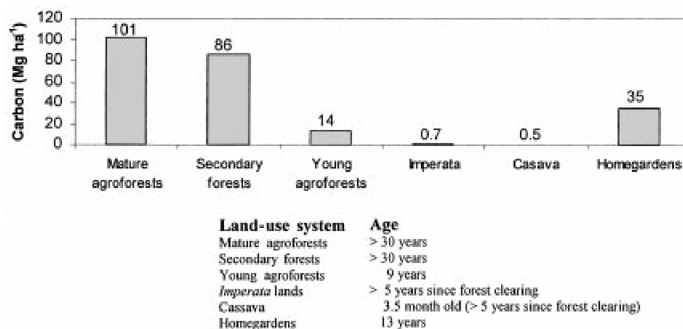

Figure 2. Comparison of above-ground carbon stocks for various land-use systems in Lampung, Indonesia.

The C stocks for the six land-use systems in Lampung are highly variable (Fig. 2). In terms of above-ground biomass, homegardens contain significantly more C ha^{-1} than *Imperata* grasslands, cassava fields and young rubber agroforests. These data indicate that homegardens had approximately 34.7 Mg C ha^{-1} more (58 times greater) than *Imperata*-cassava systems and 21 Mg C ha^{-1} more (1.5 times greater) than young rubber agroforests. *Imperata* and cassava systems maintain low woody biomass and C stock levels because of periodic fires or annual harvesting. Mature agroforests and secondary forest contain higher stocks of C than homegarden systems, by 66 Mg C and 51 Mg C ha^{-1}, respectively. This is due mainly to the presence of younger trees in homegardens.

One of the challenges of C stock estimate in homegarden systems (as well as other agroforestry systems) is accurate estimation of above-ground tree biomass. The above-ground biomass in this study was estimated using a general regression equation that was developed for tropical moist forests. The size of individual tree canopies in a forest could be smaller than those found in an open agroforestry setting, as the trees in some agroforestry systems have more space and access to light. The difference in structure could result in errors in our estimates. Likewise, trees found in homegardens could be misshapen if branches are cut for fuelwood or other uses. This could also lead to errors in our estimates. At the time of this study, local biomass equations were not available but will need to be developed in the future to reduce possible error in above-ground biomass estimation.

To accurately compare C stocks of different land-use systems a scale is required that adjusts the age and rotation length to a common base. Tomich et al. (1998) suggest using the time-averaged C stocks for comparison between systems. The time-averaged value is half a system's C stock at its maximum age (or rotation length). The time-average above-ground C stock of *Imperata*-cassava systems studied by the ASB project is about 2.2 Mg C ha^{-1} (Palm et al., 1999). For comparison, the time-averaged above-ground C stock of a homegarden at its maximum rotation length can be estimated by grouping the component species into rotation age classes, projecting linear growth to estimate tree C stock at the maximum rotation length for each class, and then taking half the above-ground C stock level for the homegarden at maximum rotation length. Based on

the inventory data we select three rotation classes: long-lived NWPS species, medium-lived NWPS species and timber species. Long-lived NWPS in Table 3 represent 57% of the homegarden species. Experience indicates that the economic rotation length of these species is greater than 60 years. The medium-lived NWPS species, 23% of the homegarden trees, are estimated to have half the economic rotation length of the long-lived NWPS species, or 30 years. The timber species, 20% of the homegarden trees, are estimated to have a rotation age of 15 years, or half the maximum rotation age reported by farmers and forestry staff in Lampung (see Table 4). Considering these species classes and rotation lengths, the time-averaged above-ground C stock for Lampung homegardens is estimated to be 56.5 Mg C ha^{-1} (see Example 1 in Table 5). This is 54.3 Mg ha^{-1} more (24.7 times greater) than the time-averaged C stock reported for *Imperata*-cassava systems (Palm et al., 1999). This projection suggests that increased C storage can be achieved by converting *Imperata* or fallow agricultural land to homegarden, or similar smallholder agroforestry systems.

Table 4. Typical harvest age of timber species in the study area (Roshetko and Purnomosidhi, 1998).

Botanical name	Rotation	Source
Acacia mangium	7–10 years	Forest office staff
Alstonia scolaris	15 years, 15–20 years	Farmers, forest office staff
Eucalyptus sp.	7–10 years	Forest office staff
Gmelina arborea	7–10 years	Forest office staff
Paraserianthes falcataria	7–8 years, 7–10 years	Farmers, forest office staff
Peronama canescens	20 years, 30 years	Farmers, forest office staff
Swietenia macrophylla	30 years	Forest office staff
Tectona grandis	+20 years, 30 years	Farmers, forest office staff

Realizing that the projection in Example 1 is based on assumptions regarding the species classes and rotation lengths that might be inaccurate, it is wise to recalculate the time-averaged above-ground C stock of homegarden systems with more conservative assumptions. If the maximum length of each rotation class is reduced by one-third, the time-averaged above-ground C stock for the homegarden systems is 38.8 Mg C ha^{-1}. If the maximum rotation lengths are reduced by half, the time-averaged above-ground C stock is still 30.2 Mg C ha^{-1} (see Examples 2 and 3 in Table 5). These conservative estimates are both greater than the time-averaged above-ground C stock reported for *Imperata*-cassava systems, by 36.6 Mg ha^{-1} (16.6 times greater) and 28.0 Mg ha^{-1} (12.7 times greater), respectively. This indicates that even under unfavorable assumptions homegardens still sequester C at much greater rate than *Imperata*-cassava systems.

It is also possible that the first projection is too conservative because it is based on current C stocks of 35.3 Mg of above-ground C ha^{-1}, the averaged C stock of 19 homegardens. It is fair to argue that this is an unreasonably low starting point from which to project future C stock levels, when the purpose of the projection is to target smallholder agroforestry systems for increased C storage. Seven of the homegardens surveyed in the study have current above-ground C stocks ranging from 45.4 to 84.0 Mg C ha^{-1}, with an average of 59.0 Mg ha^{-1}. By using this sub-set of seven homegardens and assuming a higher percentage

Table 5. Projection of time-averaged above-ground carbon stock of Lampung homegardens, assuming current species component and projected linear growth for three rotation classes for various rotation ages.

Rotation age class and other carbon pools	% of HGS[1]	Current above-ground C stock (Mg ha^{-1})	Maximum/ current age (years)	Maximum aboveground C stock (Mg ha^{-1})	Time-averaged above-ground C stock (Mg ha^{-1})
Example 1					
Long-lived NWPS[2] species	57	18.4	60 / 13	84.9	42.5
Medium-lived NWPS species	23	7.4	30 / 13	17.1	8.5
Timber species	20	9.5	15 / 13	11.0	5.5
Total	100	35.3	–	113.0	56.5
Example 2: reduce the rotation age of example 1 by one-third					
Long-lived NWPS species	57	18.4	40 / 13	56.6	28.3
Medium-lived NWPS species	23	7.4	20 / 13	11.4	5.7
Timber species	20	9.5	13 / 13[3]	9.5	4.8
Total	100	35.3	–	77.5	38.8
Example 3: reduce the rotation age of example 1 by half					
Long-lived NWPS species	57	18.4	30 / 13	42.5	21.2
Medium-lived NWPS species	23	7.4	15 / 13	8.5	4.3
Timber species	20	9.5	13 / 13[3]	9.5	4.8
Total	100	35.3	–	60.5	30.2

[1] HGS, homegarden systems.
[2] NWPS, non-wood forest products and services species.
[3] For timber species the rotation age is reduced to the current age.

of species with longer rotation lengths, projected C stock levels of homegarden will increase over that in Example 1. Table 6 provides two examples of projected time-averaged C stocks for homegardens under these two assumptions, namely a higher current above-ground C stock (59.0 Mg ha^{-1}) and species with longer rotations. These examples estimate time-averaged above-ground C stocks of 122.5 and 104.4 Mg C ha^{-1}, that are 120.3 Mg (54.7 times) and 102.2 Mg (46.5 times) greater than the time-averaged C stock of *Imperata*-cassava systems. We feel that these projections are fair estimations, as they are similar to above-ground C stock levels of 60–year-old community forests, 114–123 Mg C ha^{-1}, assuming above-ground C is 65–70% of total C (Tomich et al., 1998). To achieve high C stocks, the smallholders should develop systems that maintain high tree density, contain species with long rotation lengths and manage the system for long rotations. It would also be beneficial to limit the number of low-biomass species such as coconuts and bananas. This last consideration must be balanced with the livelihood and market objectives of the smallholders' management plan, but clear opportunities exist for smallholders to select management practices that favor increased C stocks. However, smallholders are not going to select these management practices solely to provide society with C sequestration services. Incentive mechanisms need to be developed to assure that smallholders will benefit from selecting management practices that favor higher C stocks.

Recent studies indicate there are over 220,000 ha of *Imperata* land in Lampung, 8.5 million across Indonesia, and 35 million throughout Asia (Garrity et al., 1997). These ecosystems are prone to burn and generally underutilized, both biologically and economically. They represent a vast underutilized land resource, part of which could be used to establish tree-farming systems to meet smallholder's household and income needs (Tomich et al., 1997), while also making a significant contribution to the regional C budget. In conversations with the authors, smallholders in Pakuan Ratu show a clear interest in expanding their tree-farming activities, particularly on fallow agricultural land, which is quickly invaded by *Imperata*. Farmers are interested in tree farming for the following reasons: (1) to diversify and intensify their farming systems and income streams; (2) to develop private tree resources to meet household and market demand; and (3) to make better use of their limited labor and financial capital (Roshetko and Purnomosidhi, 1998). However, despite their experience with homegardens and interest in tree farming, most smallholders have little to no experience with intensive tree planting or management systems. Although the activities of individual farmers have been successful, many local tree-farming activities suffer from poor species selection and the use of inferior germplasm. This is evident in the species composition recorded during this study. Sengon putih (*Paraserianthes falcataria*) and rambutan (*Nephelium lappaceum*) account for 21% of the trees, both living and dead, in the homegardens. However, both species appear to be poorly adapted to Pakuan Ratu. Twenty-five percent of the rambutan surveyed were dead, a result of their sensitivity to drought; this is 33% of the total dead trees surveyed. Sengon putih shows inconsistent performance both biophysically and economically. The preference for these species results from farmers' experience with the species on other sites in Lampung and Java, or their promotion by government programs. Farmers in the study area are quick to adapt technology that serves their needs; however, they lack reliable technical input regarding species selection, germplasm quality, tree propagation, tree-farm management and markets for tree products. Additionally, farmers' initiatives to plant trees may be stifled by government regulations that are perceived to limit farmers' tree utilization rights. A team of socio-economic, forestry, horticultural and livestock specialists visiting the study area determined that smallholders' keen interest in tree farming and the productivity of those tree systems would benefit greatly from assistance in the form of technical information, resources and consultation (Gintings et al., 1996).

Smallholder agroforestry systems are not, at present, a common C sequestration project type, because working with a large number of independent smallholder farmers presents many unique challenges for C investment. However, there are large

Table 6. Projection of time-averaged above-ground carbon stock for homegardens, assuming a current above-ground carbon stock level of 59.0 Mg C ha^{-1} and species components with longer rotation lengths.

Species component	% of HGS[1]	Current C above-ground stock (Mg ha^{-1})	Maximum / current age (years)	Maximum C above-ground stock (Mg ha^{-1})	Time-averaged above-ground C stock (Mg ha^{-1})
Example 4					
Long-lived NWPS[2] species	80	47.2	60 / 13	217.9	108.9
Medium-lived NWPS species	20	11.8	30 / 13	27.2	13.6
Total	100	59.0	–	245.1	122.5
Example 5					
Long-lived NWPS species	60	35.4	60 / 13	163.4	81.7
Medium-lived NWPS species	20	11.8	30 / 13	27.2	13.6
Timber species	20	11.8	20 / 13	18.2	9.1
Total	100	59.0	–	208.8	104.4

[1] HGS, homegarden systems.
[2] NWPS, non-wood forest products and services species.

numbers of smallholder farmers in the tropics and vast areas of degraded land in need of rehabilitation. Agroforestation of these areas would sequester C and could prevent further deforestation by providing on-farm sources of trees (Sanchez, 1994; Schroeder, 1994). Simultaneously, the development of smallholder tree-farming systems would improve the livelihood of farm families. The CDM of the Kyoto Protocol will provide opportunity for the development of projects that have the dual objectives of C sequestration and sustainable social development. The structure of CDM projects might be unilateral (activities undertaken by a single entity who would then sell the CERs on the international market), bilateral or multilateral. The multilateral approach is likely to be the most effective for involving communities of smallholder farmers and having a strong focus on sustainable development (CIFOR, 2001). Projects that involve numerous smallholders will have higher transaction costs, justified as the added costs required to achieve more equity distribution of project benefits. The design and implementation of carbon sequestration projects that target smallholder agroforestry systems for sustainable development are just beginning to be addressed. Research issues related to smallholder systems as CDM projects were identified at a recent international workshop hosted by the Center for International Forestry Research (CIFOR) in Bogor, Indonesia (CIFOR, 2001). Some of the key questions identified include: How can C sequestration projects involving smallholders be made more attractive to investors? How can the transfer payments be disbursed efficiently and equitably to large numbers of households? What combination of financial and non-financial payments are appropriate? How can contractual agreements with communities for carbon (and other environmental) services be created, enforced and verified in a cost-effective way? What type of institutional arrangements and enabling regulatory environment are needed to facilitate transfer payments to communities? These questions are the focus of a new project being implemented by the International Fund for Agricultural Development (IFAD) and the International Centre for Research in Agroforestry (ICRAF), with collaboration from Winrock International, the World Resources Institute and CIFOR (ICRAF, 2000). The project seeks to develop models for rewarding rural communities for the environmental services they provide to society. The resulting models will help develop guidelines for the design and implementation of smallholder-focused C sequestration projects.

In the case of Lampung, a C sequestration project could provide farmers with financial incentive as well as the technical information, inputs and expert consultation required to convert *Imperata* or other underutilized lands to productive tree-farming systems. Such a project would be a wise investment in social, political, economic and environmental terms. Questions of 'leakage'lthe loss of C, primarily as woody biomass, in outside areas due to changes in land-use practices resulting from C investment activities at a project sitelwe would expect to be minimal or non-existent. The conversion of some *Imperata* lands is not likely to greatly alter local land-use practices that would result in losses of C elsewhere, particularly when abundant *Imperata* lands remain. Nor are negative market impacts expected to result from an increased supply of smallholder-produced tree products, because the current demand for both timber and fruit in Lampung exceeds local production (Suparman, 2000; Yuliyanti, 2000). More problematic is the question of 'additionality'lassuring that C credits accrued to a C sequestration project are 'additional' to those that would occur without the project. As previously stated, the initiative of farmers to expand tree-farming systems is hampered by technical problems and other issues. However, some farmers do plant trees. Determining accurately the amount of 'additional' carbon sequestered by project incentives will rely on the establishment of quantifiable baseline data. However, the development of baseline data in smallholder communities could be difficult because of the plethora of landowners, their objectives, land-use systems and other factors. The development of guidelines for the establishment of quantifiable baseline data is an important issue that has not yet been addressed.

Although at this point there are more questions than answers concerning the implementation of smallholder-focused C sequestration projects, we believe such projects are highly desirable from both a C investment and sustainable development point of view. Agroforestation of *Imperata*, or other low-biomass lands, would increase a region's C budget and provide many socio-economic benefits to the people living in the region. Mechanisms should be explored that facilitate the implementation of smallholder-focused projects.

Conclusion

Individual smallholder agroforestry systems are of limited size and by themselves store small amounts of C. However, on a per area basis, homegardens and other smallholder agroforestry systems accumulate significant amounts of C, equaling the amount of C stored in other tree-based systemslincluding primary or secondary forestslover similar time periods. However, smallholder systems greatly exceed the amount of C stored by *Imperata* grasslands or agricultural fallow land, which are extensive in many parts of Indonesia and of low productivity. Thus, aggregate smallholder systems offer the potential for increased C sequestration via tree establishment on *Imperata* and other degraded lands. These systems could be established by farmers to meet both their household production and income generation needs, and simultaneously contribute to the reduction of greenhouse gases. Governments are generally supportive of tree-planting efforts, as a means of achieving conservation, reforestation and watershed protection objectives, as well as improving the livelihoods of smallholder farm families. We suggest that it is timely and appropriate to explore the CDM and other mechanisms by which communities or consortia of smallholder farmers can access international C investment funds to convert low-biomass lands, such as *Imperata*-cassava lands, to productive tree-based systems which contain much higher C stocks.

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