Carbon cycling and erosion losses in two contrasting man-made ecosystems in upland west Java, Indonesia

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Abstract

Replacing low carbon sequestering land use forms in humid tropical uplands by fast-growing plantation forest may help reduce atmospheric CO_2 concentrations. Sound scientific evidence is still limited, however, while the importance of soil erosion in landscape carbon dynamics also remains unclear. We compared erosion and carbon cycling in two contrasting ecosystems in West Java, Indonesia, i.e. a rain-fed mixed cropping system with maize and cassava, and a 3-year old pure stand of fast-growing albizia (*Paraserianthes falcataria*) trees. Soil loss from a hillslope was measured both before and after mixed crops were replaced by plantation forest. Sediment outputs from other agricultural fields and micro-catchments were also measured, and sediment and soil samples analysed for carbon. Crop biomass and tree growth were monitored for one year, whereas tree litter cycling was also studied. Dissolved carbon concentrations in various water budget components were analysed to estimate the corresponding carbon fluxes. The average annual soil loss from cropped bench-terraced hillsides (40 t/ha/yr) was much greater than from plantation forest (0.7 t/ha/yr), despite considerable inter-annual and spatial variability. Sediment lost from cropped bench terraces contributed 21% (0.9 tC/ha/yr) to gross carbon losses. Most carbon was lost in harvested maize (1.9 tC/ha/yr) and cassava (0.8 tC/ha/yr). Because these losses were not compensated by manure (0.03 tC/ha/yr) and atmospheric inputs (0.01 tC/ha/yr), a negative carbon budget of 4.1 tC/ha/yr resulted. By contrast, the plantation forest showed a strongly positive carbon budget, with an above-ground net primary production of 14.3 tC/ha/yr. Litter production was very high (12.2 t/h/yr or 6.1 tC/ha/yr), while leaf litter decomposed rapidly (>95% within 5 months). Almost four years after afforestation, the total carbon pool (including the top one metre of soil) had already reached 264 tC/ha, compared with 110 tC/ha for agricultural fields.

Keywords: carbon sequestration, *Paraserianthes*, plantation forest, mixed cropping, soil erosion, humid tropics

Résumé

CYCLE DE CARBONE ET PERTES D'ÉROSION DANS DEUX ÉCOSYSTÈMES CRÉES PAR LES HOMMES EN HAUTE JAVA OCCIDENTALE, EN INDONÉSIE.

Ce serait peut-être possible de réduire les concentrations atmosphériques de CO_2 en remplaçant les méthodes avec peu de séquestration de carbone des terres tropicales humides en altitude par la plantation des arbres qui poussent rapidement. Les preuves scientifiques solides sont pourtant encore limitées et l'importance de l'érosion du sol dans la dynamique de carbone de la terre n'est pas très claire. Nous avons fait la comparaison de l'érosion et du cycle de carbone dans deux écosystèmes contrastés en Java occidentale, en Indonésie, c.-à-d.: un système de récoltes mixtes avec du maïs et du manioc, et un système à un endroit, où n'y a que des arbres Albizia (*Paraserianthes falcataria*) de 3 ans, qui poussent rapidement. La perte de sol du versant de la colline a été mesurée aussi bien avant qu'après que les cultures mixtes avaient été remplacées par la forêt plantée. La quantité des sédiments d'autres champs agricoles et des micro-captages a aussi été mesurée, et des échantillons de sédiment et de la terre ont été analysés pour le carbone. La biomasse des récoltes et la croissance des arbres ont été observées pendant une année, en même temps que le cycle des résidus des arbres. Les concentrations en carbone dissous dans les différents types d'eau ont été analysées, afin de pouvoir estimer les flux de carbone correspondants.

La perte moyenne de terrasses cultivées (40 t/ha/an) a été beaucoup plus grande que celle de la forêt plantée. (0.7 t/ha/an), malgré une variabilité inter-annuelle et spatiale considérable. Les sédiments perdus sur les terrasses cultivées ont contribué pour 21% (0.9 tC/ha/an) des pertes brutes du carbone. La majorité du carbone a été perdue dans les récoltes du maïs (1.9 tC/ha/an) et du manioc (0.8 tC/ha/an). Parce que ces pertes n'ont pas été compensées par des entrées de carbone par de l'engrais (0.03 tC/ha/an) et par l'atmosphère (0.01 tC/ha/an), le résultat est un bilan négatif de carbone de 4.1 tC/ha/an. Par contraste, la forêt plantée a montré un bilan de carbone fort positif, avec une production primaire de carbone au-dessus du sol de 14.3 tC/ha/an. La production de résidus a aussi été tres haute (12.2 t/ha/an ou 6.1 tC/ha/an) ; les feuilles ont été décomposées rapidement (>95% en 5 mois). Presque 4 années après le boisement le poids total de carbone (la terre jusqu'au 1 mètre inclus) avait déjà atteint 264 tC/ha, en comparaison avec 110 tC/ha pour des champs agricoles.

Mots clé: Séquestration du carbone, *Paraserianthes*, Jachère forestière plantée, Erosion, Tropiques humides, Java.

Introduction

Recent years have seen an increasing interest in the potential of fast growing tropical plantation trees for providing wood products, as a basis for agroforestry and for restoring or rehabilitating degraded land (Nambiar and Brown, 1997). Moreover, it has been widely suggested that replacement of low carbon sequestering forms of land use by fast-growing plantation forest can play an important role in reducing atmospheric carbon dioxide concentrations. Yet sound scientific evidence for this contention is still limited, particularly with respect to humid tropical upland situations. Also, the importance of soil erosion in relation to overall ecosystem carbon dynamics is still poorly documented. A preliminary study of erosion and carbon cycling was conducted in the volcanic uplands of West Java, Indonesia, in two contrasting ecosystems: (i) an agricultural system of rain-fed mixed cropping of maize and cassava; and (ii) a 3-year old plantation forest of fast-growing albizia (*Paraserianthes falcataria*). We addressed three major issues:

1. The net carbon budget for these two ecosystems;
2. The importance of soil erosion in carbon losses from both ecosystems;
3. The possibility for improved fallowing with albizzia plantations to restore soil fertility on degraded agricultural fields.

To determine the carbon budget, fluxes of carbon associated with biomass increment, litterfall and soil carbon build-up were determined for both ecosystems. A water budget was constructed and combined with carbon concentration measurements in precipitation and soil moisture to estimate the associated fluxes. Soil loss was measured for six years from plots of a range of sizes and combined with measured carbon contents to determine loss of carbon through erosion.

Environment

Research was conducted within the 1 km^2 upper catchment of the Cikumutuk river, situated about 40 km East of Bandung, West Java, in the middle reaches of the Cimanuk basin at an altitude of 560 to 740 m asl. (7E03'S, 108E04'W). Slopes are generally fairly steep at about 15E. The soil consists of Quaternary volcanic tuffs that have weathered to kaolinitic Oxisols with several decimetres of permeable, well-aggregated soil on top of a less permeable, massive subsoil. The area experiences a humid tropical climate with a drier season (average monthly rainfall less than 60 mm) generally extending from July until September and a mean annual rainfall of about 2650 mm. Bench terraces were constructed on most hillsides as part of a major soil conservation programme in the 1980s. More details about the research area and the project framework may be found in Van Dijk (2002) and on the internet (*http://www.geo.vu.nl/~trendy/AIJMvanDijk-PhD.html*).

Fig. 1. A bench-terrace with inter-cropped maize and cassava located immediately next to the nutrient study plot, and from which runoff and sediment loss were measured in the collecting basin seen at the bottom. Photograph taken at the height of canopy development, in January 1999.

The water and carbon fluxes of a mixed cropping system were studied within a 0.4 ha terraced field on the lower part of the south-west facing slope of the catchment, at an altitude of 590 m a.s.l. (Fig. 1). The original, now terraced slope had a gradient of 19% at this point. The cultural practice during the measuring season can be considered typical for rain-fed agriculture in the study area and is described in Van Dijk (2002). Maize (cultivar Pioneer P5) was sown at density of 41,000 plants/ha on 17 November 1998, some weeks after the rainy season had started. Upland rice was also sown but failed to germinate. Cassava stem cuttings were planted two weeks later in alternating rows with the maize, at a density of 11,000 plants/ha. The maize flowered after around 10 January 1999 and the cobs started to develop a week later. Maize senescence occurred after 7 February and the cobs were harvested on 23 March 1999. Cassava started to form tubers after about three months and were harvested just before the land was hoed again and sown in with maize (at 29,000 plants/ha) and cassava (at 11,000 plants/ha) on 27 October 1999. At this time the crops received 120 kg/ha goat manure as well as NPK fertiliser.

The carbon budget of a pure albizia (*Paraserianthes falcataria* Nielsen syn. *Albizia f.* Fosberg, Fam. *Leguminoceae*) plantation forest was also studied (Fig. 2). With reported growth rates of up to one metre per month, albizia or Moluccan sengon often outgrows other fast growing species such as *Gmelina arborea*, *Eucalyptus deglupta* and *Acacia mangium* (Duguma et al., 1994; Sato and Dalmacio, 1991). The wood is light and not very durable but relatively strong and useful for pulp production. As other legumes, albizia assimilates nitrogen at its roots with the aid of *Rhizobium* bacteria and as such has potential for improved fallowing and soil improvement (Duguma et al., 1994; Binkley et al., 1992). The studied 0.7 ha albizia forest was established on bench-terraced former agricultural fields, within a kilometre of the mixed cropping site and on the same soil. The trees were planted in September 1996, resulting in a tree density of about 1400 trees/ha without substantial thinning during the first four years. The forest had an undergrowth that was dominated by ferns and Siam weed (*Chromolaena odorata*).

Methods

Biomass development

Between 17 January 1999 and 17 January 2000 measurements were made at the mixed cropping site on a ca. 140 m^2 plot encompassing a terrace bed and a riser with a terrace drain in between (Fig. 1). Above-ground and below-ground biomass of the maize and cassava crop was estimated using allometric relationships between crop height and biomass. These relationships were determined destructively: after plant height was measured, the different organs (including roots) were sampled and their dry mass determined. Crop development and height were monitored and at different stages during the cropping cycle. These measurements were used combined with planting density to estimate biomass accumulation over the course of the cropping cycle (see Van Dijk, 2002 for details). Because the terrace bed and riser were weeded regularly, no attempts were undertaken to estimate weed biomass. All sampled crop parts were pulverised and analysed for carbon at the Vrije Universiteit laboratory. This was also done for the manure that was applied.

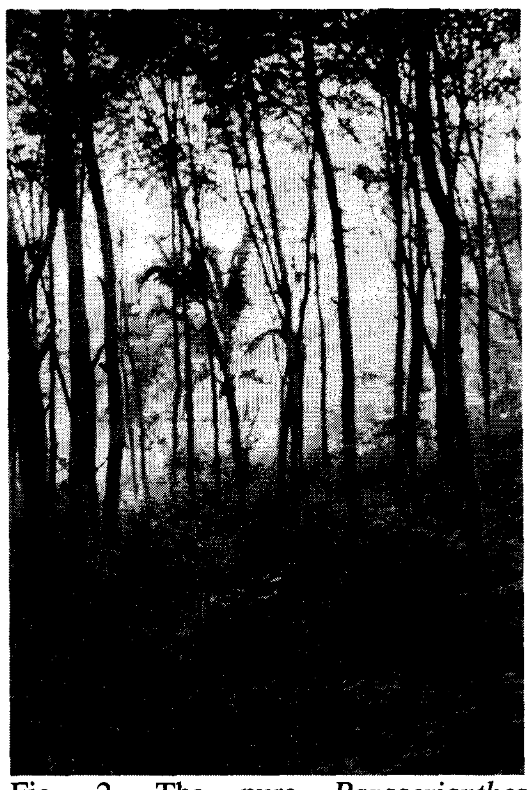

Fig. 2. The pure *Paraserianthes falcataria* plantation forest in January 1999.

In the plantation forest a subplot of ca. 900 m^2 was selected for studies of biomass development, litter dynamics and water and nutrient fluxes that were made from 18 October 1999 to 18 October 2000 (Fig. 2). In the albizia plantation forest tree girth and height were surveyed on 6 March 1999 (n=40), 18 November 1999 (n=72) and 21 July 2000 (n=20). Ten trees of known diameter and height, covering the occurring range of sizes, were cut on 21 July 2000 after which the different tree parts were weighed. Sub-samples were taken to find conversion factors between field-moist and oven-dry weight and for chemical analysis. Allometric relationships between tree size and biomass partitioning were established and used to estimate standing biomass from the surveys. Tree root biomass was not measured but assumed to be 7.5% of aboveground biomass (cf. Kumar et al., 1998). Undergrowth and litter biomass were measured on 4 square 1-m^2 areas on seven occasions between 8 October 1999 and 15 February 2001. All biomass was sampled and sorted by species, after which the litter was also sampled. Below-ground undergrowth biomass was not sampled, but assumed to be 10% of above-ground biomass. To study the internal cycling of carbon, litterfall in the forest was measured from 18 October 1999 until 20 April 2001 using 3 roving 0.5-m^2 litter traps that were sampled daily. Litter decomposition rates were measured using 25 nylon 1-mm mesh litterbags sized 20x15 cm. The litterbags were placed in clusters of five throughout the forest. After 4, 8, 12, 16 and 26 weeks respectively, a litterbag was taken from each cluster and the contents oven-dried and weighed. Again, the different tree, undergrowth and litter components were sampled and analysed for carbon.

Carbon content of the top metre of soil was determined seven times between December 1998 and October 1999 at the mixed cropping site, and three times in the plantation forest. Soil was sampled from twelve boreholes spaced equally over a ca. 50 m^2 area and bulked for three to six depth intervals before taking a sub-sample. For comparison, on one occasion the soil of a field with maize and cassava adjacent to the forest was also sampled. All samples were analysed for carbon at the Vrije Universiteit laboratory. Soil carbon content below the plantation forest was compared to that below mixed cropping to estimate annual carbon accumulation in the soil. In principle, the change in the amount of carbon stored in the vegetation and soil represents the net carbon sequestration, i.e. gross productivity *minus* respiration. Direct eddy covariance measurements of surface-atmosphere CO_2 exchange could have provided an independent check on the derived uptake figure, but were not available.

Carbon fluxes in water and sediment

A water budget was established for the mixed crops for the year-long study period by combining micro-meteorological and hydrological measurements with a soil-vegetation-atmosphere transfer (SVAT) model operating at daily time steps. Evapotranspiration was modelled using the Penman-Monteith equation that was calibrated using micro-meteorological measurements. Interception was modelled using a version of the analytical interception model that was adapted for use in a vegetation of changing density and calibrated using measurements of throughfall and stemflow (Van Dijk and Bruijnzeel, 2001ab). The SVAT model was further calibrated and tested using measurements of soil hydraulic properties and time series of surface runoff, soil suction and water contents. The model yielded amounts of evapotranspiration (ET), runoff, change in soil water storage and percolation. Full details about the followed procedure and model components can be found in Van Dijk (2002). Micro-meteorological measurements were not made above the plantation forest and therefore the Penman-Monteith equation parameters needed to be based on literature (details are available from the author upon request). Interception was again modelled using the adapted analytical interception model, which was calibrated with throughfall and stemflow measurements (Vernimmen, 2001). The same SVAT model was used to estimate the components of the water budget.

Rainfall was sampled after every storm and bulked every two weeks for chemical analysis. Lysimeters with a 5-cm diameter ceramic suction cup were installed at both sites to sample soil moisture at depths of 10, 30 and 60 cm. A vacuum of about 500 mbar was created in the lysimeters and the collected soil water sampled weekly. Rainfall and soil moisture samples were analysed for carbon at the Vrije Universiteit laboratory, and the concentrations multiplied with the corresponding water budget components. Carbon concentrations in surface runoff were not measured routinely, but analysis of selected samples suggested that its quality was very similar to that of rainfall; therefore these values were used as substitute.

Runoff and soil loss from a 0.31 ha hydrologically defined section of a steep, bench-terraced hillslope was measured during two seasons of rain-fed cropping before its afforestation with albizzia in September 1996. In addition, sediment outputs from cropped rain-fed bench terraces were measured between 1994 and 2002 at levels varying from individual terraces to two 4-ha zero-order sub-catchments and a 125 ha catchment dominated by rain-fed cropping (see Van Dijk, 2002). Runoff and soil loss from the now forested 0.31 ha hillslope were measured again for one-and-a-half year between 11 December 1999 and 23 April 2001. Samples of coarse and suspended sediment were analysed for carbon to enable the calculation of carbon losses associated with these sediment losses.

Water and sediment budget	Mixed crops	Plantation forest
Period from	17 Jan 1999/2000	18 Oct 1999/2000
Rainfall (mm)	2650	2780
Total evapotranspiration (mm)	1228	1425 (1260-1600)
Interception losses (mm)	181	307
Evapotranspiration (mm)	1047	1118 (950-1290)
Soil water storage change (mm)	-28	-38
Surface runoff (mm)	156*	21
runoff coefficient	5.9 (3-12) %*	0.8%
Percolation (mm)	1294	1372
Soil loss (t/ha)	40 (20-70)*	0.72
Average sed. conc. (g/l)	25*	3.6
Fraction coarse sediment	29 (16-51) %*	76 %

* based on longer-term measurements (Van Dijk, 2002)

Table 1. Approximate annual water and sediment budget for the two studied ecosystems.

Results

Water and sediment budget

The water budget for the mixed cropping system is listed in Table 1. Rainfall during the period of study (2650 mm) was equal to the longer term average. The estimated total evapotranspiration (ET) for the period is also equal to the 1228 mm estimated for a nearby crop stand, despite minor differences in planting density (see Van Dijk, 2002). The period of study in the plantation forest was somewhat wetter (2780 mm). Forest water use could not be modelled accurately, mainly because of uncertainties with regard to canopy conductance. It is probably close to open water evaporation in the area (ca. 1400 mm) and somewhat more than crop water use.

Total soil loss from the 0.31 ha hillslope during the rainy seasons of 1994/1995 and 1995/1996, when it was still used for rain-fed cropping, amounted to 34 and 261 t/ha, respectively. By comparison, soil loss from the 4 ha sub-catchment surrounding the mixed cropping study site was much less: 11 t/ha in 1998/1999 and 17 t/ha in 1999/2000. Combining all scales of measurement between 1994 and 2001, Van Dijk (2002) estimated the average soil loss for bench-terraced hillsides to be 20 to 70 t/ha/yr, with a longer-term average of 40 t/ha/yr for this period. Of this sediment, 29% was transported as bed load. The fraction of rainfall running off superficially was also found to vary between years, from 3% to 12%, with a 6-year average of 5.9%. For the study year this yields a runoff of 156 mm. Runoff and soil loss from plantation forest were measured on one hillslope only and for a shorter period, but were clearly much smaller than on cropped land: runoff amounted to no more than 0.8% of rainfall and soil loss for the one-year period was 0.72 t/ha. At 76%, the fraction of coarse sediment was much larger. The carbon contents of coarse and fine sediment from the cropped terraces was 1.5% and 2.4%, respectively, which is somewhat

Annual biomass and carbon budget for mixed cropping site	Flux or change	Carbon content	Carbon flux (tC/ha)
Inputs			
Atmosphere	2650 mm	0.50 mg/l	0.01
Manure	0.12 t/ha	20.5%	0.03
Biomass change			
Standing biomass			**-0.6**
maize	-0.8 t/ha	43.6%	-0.4
cassava	-0.3 t/ha	45.9%	-0.2
Harvested			**-2.7**
maize pellets	-2.6 t/ha	43.0%	-1.1
cassava tubers	-1.4 t/ha	42.6%	-0.6
maize residue	-1.9 t/ha	44.4%	-0.8
cassava residue	-0.4 t/ha	44.5%	-0.2
Losses			
In solution			**-0.006**
surface runoff	156 mm	0.50 mg/l	-0.001
percolated	1293 mm	0.40 mg/l	-0.005
Soil loss	40 t/ha	2.2%	**-0.9**
fine sediment	28 t/ha	2.4%	-0.7
coarse sediment	12 t/ha	1.5%	-0.2
Net carbon budget			**-4.1**

Table 2. Biomass and carbon budget for the mixed cropping site for the period of 17 January 1999 to 17 January 2000.

higher than the 1.4% measured for the top 5 cm. The carbon content of coarse sediment produced in the plantation forest was 2.7%, versus 2.6% for the topsoil. The carbon contents of suspended sediment from the forest was not measured, but a comparison of figures for the cropped fields suggests that this may have been about 4.4%.

Biomass development and carbon budget

Standing biomass of maize and cassava on 17 January 1999 (two months after planting) was estimated at 3.7 and 0.7 t/ha, respectively, whereas a year later these numbers were 2.9 and 0.3 t/ha. the difference was attributed mainly to the lower planting density of maize in the 1999/2000 season. The resulting difference in standing biomass between the two dates is 1.2 t/ha or 0.6 tC/ha (Table 2). Harvested biomass in 1999 amounted to 6.3 t/ha or 2.7 tC/ha. Of this amount, 64% or 1.7 tC/ha consisted of marketable yield, while the remaining 1.0 tC/ha was used mainly for stable-fed livestock. Carbon returns in manure were small, amounting to only 0.03 tC/ha in the study period. Carbon inputs from the atmosphere and outputs in surface runoff and percolating water were all very minor (<0.01 tC/ha/yr). Combining the estimated long-term soil loss figure (40 t/ha/yr) and relative coarse and fine sediment fractions with their carbon contents suggests carbon losses in sediment to amount to 0.9 tC/ha/yr. As a result of these fluxes, the overall carbon budget for the mixed crops was negative, amounting to a loss of 4.1 tC/ha over the studied year-long period. The carbon pool in the top 100-cm of soil was determined at 106 ±19 tC/ha or 1.1%. The limited data did not suggest a decline of soil carbon over time. The cropped field adjoining the forest plantation had a similar carbon content of 112 tC/ha.

Biomass and carbon budget for the albizzia plantation forest

	Annual change	standing biomass (20/7/2000)	carbon content	carbon pool (tC/ha) (20/7/2000)	Annual carbon flux tC/ha
Atmopsheric inputs	2780 mm		0.50 mg/l		**0.014**
Biomass	**17.3 t/ha**	**74.1 t/ha**		**34.7**	**8.2**
albizia wood	15.6 t/ha	60.7 t/ha	47.7%	29.0	7.4
albizia leaves	0.4 t/ha	1.7 t/ha	48.7%	0.8	0.2
albizia roots	1.2 t/ha	4.7 t/ha	47.7%	2.2	0.6
undergrowth	-*	1.5 t/ha	42.9%	0.6	-*
undergrowth roots	-*	0.1 t/ha	42.9%	0.1	-*
litter layer	-*	5.4 t/ha	36.8%	2.0	-*
Soil carbon accumulation					
soil (0-100 cm)	0.30 %C		2.0%	**195**	**30**
litterfall	12.2 t/ha		50.2%		**6.1**
Losses					
in solution					**-0.01**
surface runoff	21 mm		0.50 mg/l		~0
percolated	1372 mm		0.95 mg/l		-0.01
soil loss	0.72 t/ha		3.1%		**-0.022**
fine sediment	0.17 t/ha		4.4%		-0.008
coarse sediment	0.54 t/ha		2.7%		-0.014
Net carbon budget				264	**8-38**

* assumed to be constant by lack of a clear trend (see text for explanation).

Table 3. Approximate annual biomass and carbon budget for the albizzia (*Paraserianthes falcataria*) plantation forest site. Note that the annual biomass and soil carbon content increases were estimated for the period of September 1996 to July 2000, while the water and sediment budget and litterfall were measured for the period of 17 January 1999 to 17 January 2000.

Based on the surveys of tree girth and height and allometric relationships, the total above-ground tree biomass in the albizia plantation forest appeared to increase very rapidly since its establishment in September 1996: to 24 t/ha in March 99, 51 t/ha in November 1999 and 62 t/ha in July 2000. Of all above-ground tree biomass, stem wood made out 77%, amounting to an annual stem wood production of 12.4 t/ha (Table 3). Combining this with the stem wood density (0.23 t/m^3) yields an annual wood production of 54 m^3/ha. Undergrowth biomass varied between 0.8 and 1.6 t/ha, with an average of 1.5 t/ha. The corresponding carbon pool was 0.6 tC/ha, with an additional 2.0 tC/ha residing in the litter layer. The measurements did not suggest a trend in the amount of undergrowth and litter. For the entire, almost four year period the annual biomass increment in trees and undergrowth was estimated at 17.3 t/ha/yr or 8.2 tC/ha/yr. Litter turnover appeared to be very intensive. Litter production was very high at 12.2 t/ha/yr or 6.1 tC/ha/yr, but was balanced by an equally high decomposition rate: the half-life of fresh litter was 34 days, with 95% being decomposed within 146 days. Aboveground net primary production (ANPP), calculated as the sum of biomass increment and litterfall, was 29.5 t/ha/yr or 14.3 tC/ha yr. The soil carbon content in the plantation forest was 195±20 tC/ha or 2.0%. Comparing this to the soil carbon content below mixed crops suggests an unlikely high annual carbon accumulation of ca. 30 tC/ha, i.e. an increase of carbon content in the top metre of 0.30%/yr. Carbon losses associated with surface runoff, percolation and soil loss were all minor (<0.02 tC/ha/yr). As a result, the net carbon budget for the plantation forest was strongly positive, amounting to well over 8 tC/ha/yr.

Discussion

Mixed cropping

The measurements suggest that soil loss from bench terraces contributes in the order of 0.9 tC/ha/yr to carbon losses from the mixed cropping system. During the year of study this constituted 21% of total carbon losses. The main carbon losses occurred through harvesting, however, both commercial (1.7 tC/ha/yr) and to feed livestock (1.0 tC/ha/yr). Because livestock manure was not, or hardly, returned to the rain-fed fields the non-marketable harvest also constitutes a loss to the carbon budget. Carbon inputs via manure were higher a year earlier (0.4 tC/ha; Van Verseveld, 2000), but still modest compared to exports. Net carbon loss from the mixed cropping system was estimated at 4.1 t/ha/yr. If the decrease in standing biomass is dismissed as a non-permanent phenomenon and manure inputs are assumed to be generally higher this still leaves a loss of more than 3 tC/ha/yr.

Plantation forest

The annual stem wood production (12.4 t/ha/yr) for the almost four-year old albizia plantation forest is within the 6-21 t/ha/yr reported in literature (Binkley et al., 1992; Kumar et al., 1998; Resh et al., 2002). At 12.2 t/ha/yr, the measured litter production rate is at the upper end of published values, but less than the 18 t/ha/yr measured in a pure albizia stand in Hawaii (Binkley et al., 1992). Canopy biomass amounted to only 1.7 t/ha, which together with the measured litter production rate would imply a leaf life span of only around 52 days if all litter were leaves. This is at the lower extreme of published values, but comparable with values found for early successional rainforest species (Shukla and Ramakrishnan, 1984). For a 4-year old *Acacia auriculiformis* plantation elsewhere in West Java, a litter production rate of 10.7 t/ha/yr was found, although this stand had more leaf biomass (6-7 t/ha; Team Vegetation and Erosion, 1979). Assuming that the litter layer was indeed close to a steady state, as suggested by the lack of a clear trend, this is consistent with the combination of high litter production and decomposition rates. Both are much higher than values found in Indian albizia plantations: Matthew et al. (1997) report a litter production of 3.7-4.1 t/ha/yr, while Sankaran (1993) found the half-life of albizia litter to be 5 months. The difference may be partly ascribed to the more seasonal rainfall regime in India. For Hawaiian albizia plantations, Binkley and Ryan (1998) reported an annual aboveground biomass increment of ca. 14 t/ha/yr between ages 14 and 16, compared with 16 t/ha/yr in this study. They found considerably higher ANPP values of ca. 40 t/ha/yr at age 6-16, however (versus 29.5 t/ha/yr in this study). The main reason is the high below-ground primary production of 15 t/ha/yr inferred by these authors, compared to the 1.2 t/ha/yr estimated by us. The high root turnover that may be associated with these high below-ground production rates offers some support to the very high carbon accumulation rates in the top 100-cm (30 tC/ha/yr or 0.30%/yr) suggested by the soil carbon measurements. A similarly soil carbon accumulation of 0.2-0.3% per year was observed in the top 60 cm of a 3-6 year old albizia plantation in India (Matthew et al., 1997). Although it cannot be entirely ruled out that the plantation soil was somewhat more fertile to begin with or received manure at the time of tree planting, the albizia trees must have assimilated carbon very rapidly nonetheless.

Conclusions

At well over 8 tC/ha/yr, the rate of net carbon gain by the studied albizia plantation forest is much higher than the ca. 4 tC/ha carbon lost annually from the agricultural fields. Soil erosion appeared to contribute to ca. 21% of these latter losses, but the bulk occurred through harvesting. For a reversal of this negative balance of carbon (and other nutrients) alternative agricultural practices are needed, which may involve a greater ratio of standing over harvested biomass or rotation with (fast-growing) plantation trees. Although somewhat inconclusive, the current measurements indicate very high soil carbon accumulation rates below the albizia plantation forest. Measurements not discussed here indicated similarly high accumulations of nitrogen (Van Verseveld, 2000; Vernimmen, 2001), although possible soil acidification and depletion of other nutrients (notably P and Ca) below albizzia calls for some restraint in promoting albizia afforestation (Binkley and Giardina, 1997). Both increasing the amount of crop biomass left on the terraces and crop-forest rotation are likely to result in a considerable reduction of soil losses. Unfortunately, any development towards improved land husbandry is currently restricted by the adverse social and economical situation prevailing in Java's uplands, which favours short-term profits over longer-term investments.

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