Environmental benefits of planting fast-growing trees on eroding cropland in Java

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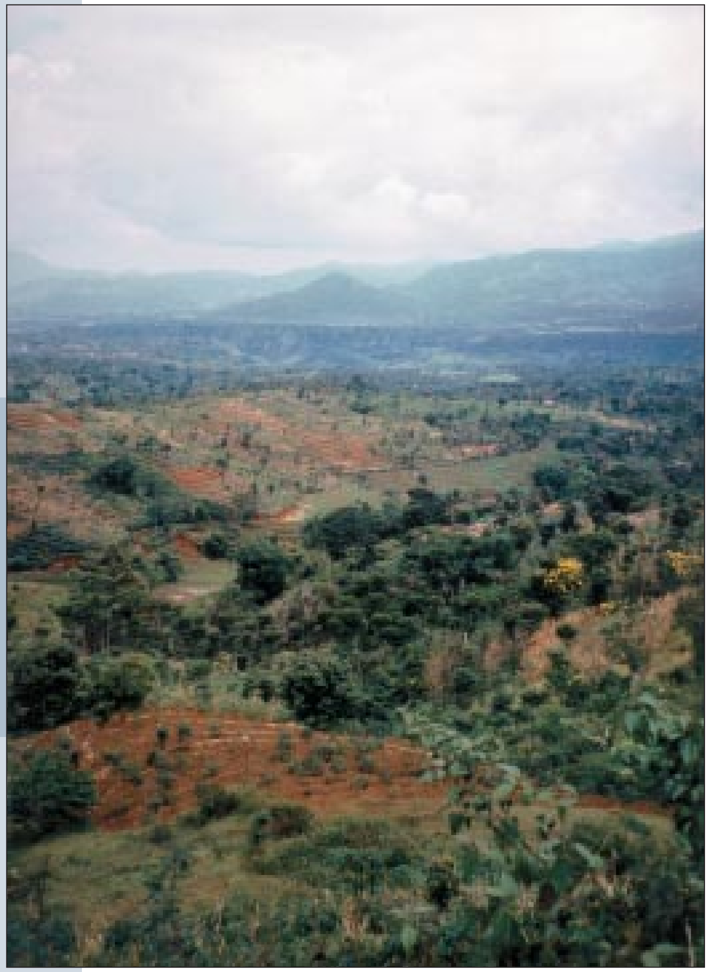

View from the upper part of the study area downwards showing bench terraces on the hillsides, paddy rice fields in the valley bottom and plantation forest (mainly *Paraserianthes falcataria*) in the centre of the photograph taken after maize harvest. Photo A.I.J.M. van Dijk.

Fast-growing albizia (*Paraserianthes falcataria*) trees are being planted to an increasing extent in the degraded uplands of Java. We studied biomass and carbon dynamics in these forests and on the bench-terraced cropland they replace. Carbon is lost from cropland through harvesting and eroded sediment, but the plantations appear to recycle carbon back into the soil at very high rates. Combined with beneficial effects on erosion and soil nitrogen content, albizia plantation forestry may offer considerable potential for soil improvement and carbon sequestration.

In recent years, there has been increasing interest in the potential of fast-growing tropical plantation trees as a basis for agroforestry, rehabilitation of degraded land, and wood products (Nambiar, Brown, 1997). Replacing low carbon sequestering forms of land use by fast-growing plantation forest may also help to reduce atmospheric carbon dioxide concentrations. Sound scientific evidence is still limited, however, especially with respect to humid tropical upland situations. The relationship between soil erosion and overall ecosystem carbon dynamics is also still poorly documented. We studied biomass development, carbon cycling and the role of erosion in this context for two contrasting ecosystems: a rainfed mixed cropping system with maize and cassava, and a 3 year old plantation forest of fast-growing albizia (*Paraserianthes falcataria*).

Measurements

Research setting

Research was conducted between 1998 and 2000 in a small upland catchment situated about 40 km east of Bandung, West Java, in the middle reaches of the Cimanuk Basin (7°03'S, 108°04'W, 560-740 m above sea level). Slopes in the area are fairly steep (15° on average) and mostly bench terraced. The soil consists of weathered volcanic tuffs. The humid tropical climate has a somewhat drier season extending from July until September and mean annual rainfall is ca. 2 650 mm.

The studied rainfed mixed cropping system was the dominant form of agricultural land use in the area. Maize was sown in November, a few weeks after the rainy season started, and some fertiliser and manure were applied at this stage. Cassava stem cuttings were planted two weeks later in alternating rows with the maize. The maize cobs were harvested in March, whereas the cassava tubers were harvested just before the land was hoed again in September-October before the next season.

Farmer reshaping and hoeing a bench terrace at the onset of the rainy season. This practice leaves the steep terrace riser unprotected from rainfall.
Photo B. van Eijk.

After one of the sample trees is felled, the leaves are collected to be weighed and analysed.
Photo M. Deelder.

Local farmers who can afford not to crop part of their land now often, and to an increasing extent, plant short rotations with fast-growing trees. A favoured species is albizia (*Paraserianthes falcataria* Nielsen, Leguminosae), originating from eastern Indonesia. The wood is not very durable but is useful for light construction work and pulp. Albizia, like other legumes, fixes nitrogen at its roots and can be used for enhanced fallowing and soil improvement (Duguma *et al.*, 1994; Binkley *et al.*, 1992).

Biomass development

Water and carbon fluxes associated with mixed cropping were measured on a bench terrace unit between 17 January 1999 and 17 January 2000 (i.e. spanning half of two cropping seasons). Crop height and density were monitored and combined with locally established allometric relationships to estimate crop component biomass development (Van Dijk, 2002; Van Dijk, Bruijnzeel, 2001). Sub-samples of crop components were analysed for carbon content by the dry combustion method.

The albizia plantation was established on former bench-terraced agricultural fields within 1 km of the mixed cropping site and on the same soil type. Trees were planted in September 1996 at a density of ca. 1 400 trees ha^{-1}; after three years the undergrowth was light. A 0.1-ha plot in the centre of the forest was selected where carbon and water dynamics were measured between 18 October 1999 and 18 October 2000. Tree girth and height were monitored on three occasions (n=20-72). Ten trees representing the observed range of sizes were cut in July 2000 to establish allometric relationships between tree size and tree component biomass; these were combined with the girth and height measurements to estimate standing biomass and increment. Tree root biomass was not measured but assumed to be 7.5% of above-ground biomass (Kumar *et al.*, 1998). Undergrowth and litter biomass were measured on seven occasions in four randomly selected 1-m^2 areas. Below-ground undergrowth biomass was assumed to be 10% of that above ground.

Dissolved carbon fluxes

A water budget was established for the two studied ecosystems using a soil-vegetation-atmosphere transfer (SVAT) model with a daily time step. The model was calibrated with measured micro-meteorology, rainfall interception, surface runoff, soil water suction and content, and soil hydraulic properties (see Van Dijk, Bruijnzeel, 2001 and Van Dijk, 2002 for details). Samples of rainfall, surface runoff and soil moisture (extracted by vacuum tube lysimeters) were analysed for dissolved carbon to estimate the associated fluxes.

Soil carbon build-up and litter dynamics

The carbon content of the top metre of soil was determined by sampling twelve boreholes spaced equally over a 50 m^2 area and determining carbon contents for three to six depth intervals by the dry combustion method. Samples were taken on seven occasions from the cropped bench terrace, on three occasions from the plantation forest and on one occasion from a cropped field directly adjacent to the forest. The data were analysed for trends; annual soil carbon build-up below the forest was estimated from the difference in soil carbon storage at the two sites. Litterfall was sampled daily from three roving 0.5-m^2 litter traps. Litter decomposition rates were estimated using the litter bag method. Sub-samples of tree, undergrowth and litter components were analysed for carbon.

Carbon losses in eroded sediment

Soil losses from a series of cropped rainfed bench terraces were measured between 1994 and 2002 at levels ranging from individual terraces to two 4-ha zero-order subcatchments and a 125 ha catchment (Van Dijk, 2002). Runoff and soil loss from a 0.3 ha section of bench-terraced hillslope was also measured before it was planted with albizia (1994-1996) and 3 years afterwards (1999–2001). Samples of suspended and coarse sediment were analysed for carbon to determine carbon losses in eroded sediment.

Setup to measure components of the forest carbon cycle (from front to back): vacuum tube lysimeters to sample soil moisture, a leaf litter trap, tensiometers to measure soil water suction, and researcher R.R.E. Vernimmen.
Photo A.I.J.M. van Dijk.

Table I.
Biomass and carbon budget (not including gaseous exchanges) for the mixed cropping site between 17 January 1999 and 17 January 2000.

	Flux or change	Carbon flux (tC ha^{-1})
Standing biomass change		-0.6
maize	-0.8 t ha^{-1}	-0.4
cassava	-0.3 t ha^{-1}	-0.2
Harvested material		-2.7
maize cobs	-2.6 t ha^{-1}	-1.1
cassava tubers	-1.4 t ha^{-1}	-0.6
maize residues	-1.9 t ha^{-1}	-0.8
cassava residues	-0.4 t ha^{-1}	-0.2
Manure	0.12 t ha^{-1}	0.03
Carbon fluxes in water		0.007
precipitation	2 650 mm	0.012
surface runoff	156 mm	-0.001
drainage	1 293 mm	-0.005
Lost in sediment	40 t ha^{-1}	-0.9
Net carbon budget		-4.1

Results

Mixed cropping

Total standing biomass on 17 January (2 months after planting) was estimated at 4.4 t ha^{-1} in 1999 and at 3.2 t ha^{-1} in 2000 (Table I). The difference was mainly due to differences in the planting density for maize. Total harvested biomass during the study period was 6.3 t ha^{-1} or 2.7 tC ha^{-1}, 64% (1.7 tC ha^{-1}) of which represented the marketable yield. The remainder was largely used for stable-fed livestock, while carbon returns to the soil via manuring amounted to only 0.03 tC ha^{-1}.

Pooling all measurements of soil loss from bench-terraced cropped hillsides between 1994 and 2001 have an estimated long-term soil loss of 40 t ha^{-1} yr^{-1} overall (range 20-70 t ha^{-1} yr^{-1}; Van Dijk, 2002). Associated average carbon losses were ca. 0.9 tC ha^{-1} yr^{-1}. Average surface runoff was ca. 5.9% of rainfall, but associated dissolved carbon losses were very low (Table I). Other dissolved carbon fluxes (e.g. in precipitation or percolating soil water) were also negligible (<0.01 tC ha^{-1} yr^{-1}).

The carbon pool in the top 100 cm of soil under cropping was 106 tC ha^{-1} (SD ±19 tC ha^{-1}). The cropped field adjoining the forest plantation had a similar carbon content of 112 tC ha^{-1}. Our limited measurements did not show a significant temporal decline in soil carbon during the year of study.

Paraserianthes falcataria plantation forest

Total above-ground tree biomass in the albizia plantation forest increased very rapidly after planting in September 1996, reaching 24 t ha^{-1} in March 1999 and 62 t ha^{-1} in July 2000 (Table II). Mean annual stem wood production was 12.4 t ha^{-1} or 54 m^3 ha^{-1}. Mean undergrowth biomass was 1.5 t ha^{-1}, corresponding to 0.6 tC ha^{-1}, with an additional 2.0 tC ha^{-1} stored in the litter layer. There were no significant trends with respect to undergrowth or litter biomass. For the entire (almost) 4-year period, mean annual carbon sequestration in trees and undergrowth biomass was estimated at 8.4 tC ha^{-1} yr^{-1}. Litter turnover was very rapid: production was high at 12.2 t ha^{-1} yr^{-1} (6.1 tC ha^{-1} yr^{-1}), but balanced by an equally high decomposition rate (95% of fresh litter decomposed within 146 days). Above-ground net primary production was 14.3 tC ha^{-1} yr when calculated as the sum of biomass increment and litterfall.

Runoff and soil loss were greatly reduced by reforestation. Runoff was only 0.8% of rainfall whereas soil loss was 0.72 t ha^{-1} for the 1-year period. Total carbon losses in drainage, runoff and eroded sediment combined were only 0.03 tC ha^{-1} yr^{-1}. The net carbon budget for the plantation forest was therefore highly positive.

Soil carbon content in the plantation forest was 195 (±20) tC ha^{-1}, almost double that of the cropped field. Moreover, a comparison of the two situations suggested an extremely high annual carbon accumulation of ca. 21 tC ha^{-1} over the first four years. By contrast, the differences in soil carbon content at the three times of sampling did not suggest any statistically significant trend.

Table II.
Biomass and carbon budget for the albizia (*Paraserianthes falcataria*) plantation forest site. Note: annual biomass and soil carbon content increases were estimated for the period September 1996–July 2000, while the water and sediment budgets and litterfall were measured for the period 17 January 1999–17 January 2000. Numbers in last column are best estimates for the first four years after plantation establishment.

	Standing biomass[a] (t ha^{-1})	Annual change (t ha^{-1})	Carbon pool[a] (tC ha^{-1})	Annual carbon flux (tC ha^{-1})
Standing biomass	74.1	17.3	34.7	8.4
albizia wood	60.7	15.6	29.0	7.4
leaves	1.7	0.4	0.8	0.2
below-ground	4.7	1.2	2.2	0.6
undergrowth [b]	1.6	ns	0.7	0.2
Litter and soil carbon				21.5
litter layer [b]		ns	2.0	0.5
soil (0-100 cm)		0.2 %C	195	21[c]
Carbon fluxes in water				0.001
precipitation		2 780 mm		0.014
surface runoff		21 mm		<0.001
drainage		1 372 mm		-0.010
Lost in sediment		0.72		-0.022
Net carbon budget			264	>>8

[a] On 7 July 2000.
[b] No significant trend during the study period, but an annual carbon flux was inferred from situation at the time of plantation and four years later.
[c] Not considered realistic; see text.

The studied *Paraserianthes* plantation forest with a runoff and sediment collecting basin in the foreground.
Photo A.I.J.M. van Dijk.

Discussion

Soil loss from the cropped bench terraces accounted for about 0.9 tC ha^{-1} yr^{-1} (or one-fifth) of the total measured carbon losses of 4.1 tC ha^{-1} yr^{-1}. Harvesting—for commercial and livestock feed purposes—was responsible for the main carbon losses. Manure inputs were very small. The difference in standing biomass between the start and end of the measurement period may well have been a transient phenomenon. Nevertheless, the probably low rates of crop litter and root turnover are unlikely to have balanced the carbon losses in sediment and any additional soil respiratory losses, and the overall carbon budget will therefore have remained negative (Table I).

The high annual stem wood and litter production from the albizia plantation agree closely with previously published data for albizia (6-21 t ha^{-1} yr^{-1} and 3.7-18 t ha^{-1} yr^{-1}, respectively; Binkley *et al.*, 1992; Matthew *et al.*, 1997; Kumar *et al.*, 1998; Resh *et al.*, 2002). The difference in soil carbon content between the cropped field and the nearly 4-year old forest suggested an unlikely high carbon accumulation rate of 21 tC ha^{-1} yr^{-1} (0.2 % yr^{-1} in the top 100-cm layer). A similar near-doubling was also observed for soil nitrogen contents (data not shown). It cannot be ruled out that the plantation soil was somewhat more fertile to begin with than the cropped soil four years on, or that it received some carbon through manuring at the time of planting. Alternatively, our soil samples may have been biased. However, it is unlikely that these factors could fully explain the very marked difference in soil carbon content between the cropped and forested land (>80 tC ha^{-1}). For Hawaiian albizia plantations, Binkley and Ryan (1992) documented a high below-ground primary production of ca. 7.5 tC ha^{-1} yr^{-1}. The associated high root turnover could partially explain the inferred high carbon accumulation rates. A similarly rapid 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). We conclude that the albizia trees assimilated soil carbon very rapidly, but longer-term measurements will be needed to determine the exact rate of accumulation.

Conclusions

The total rate of carbon sequestration in the studied albizia plantation was well over 8 tC ha^{-1} yr^{-1} and much higher than the net carbon losses from agricultural fields. Soil erosion contributed significantly (ca. 1 tC ha^{-1} yr^{-1}) to the latter losses but was negligible in the plantation. The bulk of carbon losses from the cropped fields was due to the imbalance between harvest outputs and returns by manuring. Alternative agricultural practices are needed to offset this negative balance of carbon (and other nutrients). Potential strategies should strive to increase the ratio of standing over harvested biomass or involve rotations with (fast-growing) plantation trees to increase soil productivity. Although perhaps inconclusive, our measurements indicate very high soil carbon (and nitrogen) accumulation rates below the albizia plantation. Other benefits of afforestation include a substantial reduction in surface runoff and soil loss. Possible negative side effects on the soil (acidification and depletion of nutrients such as P and Ca; Binkley, Giardina, 1997) and water resources (through high water use; Van Dijk, 2002) need to be further investigated, in addition to constraints imposed by the low socio-economic status of farmers and the possibility of albizia pests. Nonetheless, our results point to a potentially important future role of albizia plantations to enhance soil productivity in Java's eroding uplands.

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Carbon and nutrient losses through maize and cassava harvests are not balanced by manuring inputs.
Photo R. Mieremet.