CHANGES IN CARBON AND INORGANIC NUTRIENTS AFTER CLEAR FELLING A RAINFOREST IN MALAYSIA AND PLANTING WITH *ACACIA MANGIUM*

N Nykvist[1,*] & BL Sim[2]

[1]*Skogsstigen 1, SE 14462 Ronninge, Sweden*
[2]*7-17, Bk M4, Mewah View Apartment, Mewah Ria 2/10, Bukit Mewah, Johor Bahru, Malaysia*

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NYKVIST N & SIM BL. 2009. Changes in carbon and inorganic nutrients after clear felling a rainforest in Malaysia and planting with *Acacia mangium*. The amounts of organic C, and N, P, K, Ca and Mg in the biomass and soils were investigated in two catchments in Sabah, Malaysia, that had formerly supported a dipterocarp rainforest before it was clear felled and planted with *Acacia mangium*. Trees in one catchment (W4) were manually felled and extracted. Trees in the other (W5), were also manually felled but extracted with crawler tractors. The slash was burnt in W5 before planting, which is the normal practice in this area. During the 10-year rotation period of the plantations, 95 Mg of organic carbon ha^{-1} were lost from the soil in both W4 and W5, corresponding to about 80% of the soil carbon at planting. About 1390 and 1190 kg N ha^{-1} were lost from the soil in W4 and W5 during this period, corresponding to 26 and 22% respectively of the initial amounts of nitrogen in the soil before planting. The amounts of plant-available P and Mg in W4 and W5, and Ca in W5 increased in the soil, in spite of the high amounts of nutrients taken up by plants. The content of plant-available K declined, probably due to leaching.

Keywords: Burnt and unburnt catchments, losses of nutrients, 10-year-old plantations

NYKVIST N & SIM BL. 2009. Perubahan kandungan karbon dan nutrien bukan organik satu hutan hujan di Malaysia selepas tebangan habis dan penanaman dengan *Acacia mangium*. Kandungan C organik dan N, P, K, Ca serta Mg dalam biojisim dan tanah diselidiki di dua kawasan tadahan di Sabah, Malaysia yang dahulunya menampung hutan hujan dipterokarpa. Pokok-pokok di sini ditebang habis dan kemudiannya ditanam dengan *Acacia mangium*. Pokok-pokok di kawasan tadahan W4 ditebang secara manual dan dikeluarkan. Di W5, pokok-pokoknya juga ditebang secara manual tetapi balaknya dikeluarkan dengan traktor perangkak. Serpihan kayu di W5 dibakar sebelum penanaman. Ini merupakan amalan yang biasa di kawasan ini. Pada pusingan 10 tahun ladang ini, 95 Mg ha^{-1} karbon organik hilang daripada tanah di W4 dan W5. Nilai ini bersamaan dengan lebih kurang 80% karbon tanah semasa penanaman. Sejumlah 1390 kg N ha^{-1} dan 1190 kg N ha^{-1} juga hilang daripada tanah di W4 dan W5 pada masa ini, yang bersamaan dengan masing-masing 26% dan 22% daripada kandungan nitrogen tanah permulaan sebelum penanaman. Kandungan P dan Mg yang terdapat untuk pokok di W4 dan W5 serta kandungan Ca di W5 bertambah dalam tanah walaupun kandungan nutrien yang tinggi diserap oleh tumbuh-tumbuhan. Kandungan K yang terdapat untuk pokok merosot mungkin kerana penjerapan.

INTRODUCTION

When the first integrated pulp and paper mill was proposed in Malaysia, the Malaysian government requested for an environmental impact assessment, examining not only the air and water pollution it could cause, but also the ecological consequences of the associated forest operations. The objective of this investigation was to study water and nutrient budgets after clear felling a tropical rainforest and replanting differently-treated parts of the clear felled area with *Acacia mangium*, the most commonly planted forest tree species in the region at the time of the study.

The biomass and nutrient levels in the rainforest that was clear felled before planting with *A. mangium* had been thoroughly described by Sim and Nykvist (1991), Nykvist *et al.* (1994), and Nykvist (1997). The biomass and nutrient contents of the *Acacia* plantations after 1.5 and 3.8 years had been described by Sim and Nykvist

* *E-mail: nils.nykvist@telia.com*

(1991), and Nykvist *et al.* (1996) respectively. In addition, the losses of nutrients through leaching during the 33 months following clear felling of the rainforest were investigated by Malmer and Grip (1994).

In this paper, we describe the biomass and nutrient contents of the soil and *Acacia* plantations when they were harvested 10 years after planting, and assess changes in the soil nutrient status.

MATERIALS AND METHODS

Research area

Two adjacent catchments were identified for the impact assessment in a lowland hill dipterocarp forest which was selectively logged six years before the forest was clear felled at the end of 1987. At clear felling there were about 145 trees with girths exceeding 60 cm [about 19 cm diameter at breast height (dbh)] per ha, the largest measured girth being 330 cm (about 105 cm dbh).

The rainforest was situated near the Mendolong nursery about 35 km from the mill at Sipitang in south-western Sabah. The slopes of the catchments are gentle to moderate (< 40%) and the average annual rainfall was 3352 mm from 1985 till 1990 (Malmer 1992). The bedrock consists of sandstones and siltstones with interbedded shale. The soils in the two catchments are predominantly Acrisols, with Gleyic Podzols occasionally found in the lower parts of the catchments where sand has been deposited. The soil texture is loam, with varying proportions of sand depending on the underlying type of bedrock. No significant difference in soil type was found between the two catchments.

Plantation establishment

After clear felling the rainforest with chain saws, the logs were extracted with crawler tractors in one of the catchments, named W5, and the slash was burnt before planting the whole catchment with *A. mangium*. In the other catchment, designated W4, the logs were pulled on wooden sleighs according to the old 'Kuda-Kuda' method (Brown 1955) and transported out of the catchment. The logging residue was left in the catchment but removed in rows where *A. mangium* was planted, across the whole catchment.

Acacia mangium plants to be planted were grown in 450 cm^3 pots in a nursery at Mendolong, each filled with soil mixed with 6 g CIRP (Christmas Island rock phosphate) during potting. TSP (triple super phosphate, 1 g) was subsequently applied to each pot on the second week after transplanting, and 1–2 g NPK (15 + 15 + 6 + 4 MgO) every fortnight until the third month. For 1089 pots ha^{-1}, the fertilization corresponded to an application of approximately 1.5 kg N, 2.6 kg P, 0.6 kg K, 2.2 kg Ca and 0.2 kg Mg ha^{-1}. The plants were not fertilized in the field.

The *A. mangium* spacing was 3 × 3 m in the catchments (about 1089 trees ha^{-1}). Circle weeding and inter-row slashing were carried out once every three months until the plants were one-and-a-half years old. All logging and silvicultural treatments in this study were carried out by a regular contractor and by personnel involved in commercial forest plantations from surrounding areas.

Biomass sampling

An inventory recording the species and diameter of all trees with a girth exceeding 60 cm in the rainforest was compiled before they were felled. Sample trees were selected from 10 of 28 girth classes in each catchment by randomly selecting positions along numbered grid lines and then choosing (and felling) the nearest tree of the selected girth class. The lengths of the stems in each diameter class were measured, and the biomass of their trunks, leaves and branches was weighed.

Stumps and coarse roots representing different diameter classes of trees were also sampled from six of the 20 sample trees from the two catchments. Ground vegetation and trees smaller than 60 cm girth were harvested at random from five 10 × 10 m sample plots in each catchment. Volumes of dead stems and large branches, in varying degrees of decomposition, were estimated in the same 10 × 10 m sample plots and the dry weights of samples were determined. Roots were randomly sampled from each 10 cm layer of the mineral soil down to 50 cm depth in seven 50 × 50 cm plots. The sample plots were randomly placed at least 3 m from the centre of stems of large trees. A detailed description of the rainforest and the biomass sampling is given in Sim and Nykvist (1991).

Inventories of the *A. mangium* plantations were compiled before clear felling the 10-year-old plantations in 1997. A total of eight *A. mangium* trees were sampled from diameter classes 5–10 cm to 35–40 cm in W4 and nine from diameter classes 5–10 cm to 45–50 cm in W5 and the weights of their aboveground biomass components (leaves; branches < 2 cm, 2–5 and 5–20 cm thick; dead branches; bark and wood) were determined. The trees were randomly selected along sampling lines that did not coincide with planting lines.

In each catchment, the aboveground biomass of plants other than *A. mangium*, was sampled from five 10 × 10 m plots, situated at fixed positions (10 m) along sampling lines relative to the randomly sampled trees. Roots were sampled to a depth of 50 cm in five 50 × 50 cm sample plots, situated 30 m from the nearest sampled trees along sampling lines. If a sample plot coincided with a tree, it was displaced 50 cm along the line from the centre of the tree.

Small subsamples were taken immediately after weighing the biomass and stored in plastic bags which were transported to the laboratory where oven-dried weights of the biomass were determined. From the dry weights of the different parts of the sample trees representing different diameter classes and the number of trees per ha in the respective classes, the dry weights of the standing crop per ha were calculated.

Soil sampling

From the randomized plots where roots had been sampled, duplicate samples of the soil were taken using cylinders (diameter 7.2 cm, height 5 cm) from the humus layer and from each 5 cm layer of the mineral soil down to 50 cm depth. The samples were sealed in plastic bags and deep-frozen on the same day. These samples were stored in a freezer (-18 °C) until they were transported to the laboratory, still deep-frozen, where they were thawed overnight and chemically analysed.

Chemical analyses

Following digestion with nitric and perchloric acids, the biomass and humus samples were analysed using inductively coupled plasma emission-electrospray mass spectrometry (ICP-EMS). Concentrations of exchangeable cations in the soil were determined by ICP-EMS after extraction with 1 M ammonium acetate at pH 7 and subsequent filtration of the solution. Plant-available phosphorus (P) was analysed using the Sibbesen method and total P, after digestion with perchloric and hydrofluoric acids. Total nitrogen (N) and carbon (C) were determined by elemental analysis. A detailed description of the methods used can be found in Emteryd (1989). The samples were analysed at the Mendolong and Sipitang laboratories in Sabah, Malaysia.

RESULTS

Biomass production in the *Acacia* plantations

The tree biomass was higher in the less disturbed, unburnt catchment (W4) than in the more heavily disturbed and burnt catchment (W5) at both ages (Table 1). When the plantations were 3.8 years old, the trees were larger on average in W4 than in W5. When they were 10 years old, there were twice as many trees per ha in W4 than in W5. However, a few trees were found in W5 with diameters exceeding 40 cm, larger than any tree recorded in W4 (Figure 1). The differences in stem-wood biomass between the two catchments were 10.7 Mg ha^{-1} in the 3.8-year-old plantations and 20.5 Mg ha^{-1} in the 10-year-old plantations (Table 1). The greatest aboveground biomass in the 10-year-old plantations was in the 20–25 cm diameter class (Figure 1).

In the first few years after planting *A. mangium*, the catchments were dominated by the grasses *Paspalum conjugatum* and *Imperata cylindrica*, the herb *Eupatorium odoratum*, and the bush *Melastoma malabatricum* (Table 2). These plants had disappeared 3.8 years after planting. However, *P. conjugatum* was found in the 10-year-old plantations. The biomass of the fern *Nephrolepis biserrata* had increased 3.8 years after planting. It had the greatest biomass among all understorey plants in both catchments. This fern was still found in the 10-year-old plantations at W5.

After 10 years, most of the plants other than *Acacia* in the plantations were members of various small tree species. Members of *Shorea* species, belonging to the plant family Dipterocarpaceae, which dominated the rainforest before clear-felling, were also found in the 10-year-old *Acacia* plantations.

Table 1 Biomass dry weight (Mg ha^{-1}) of components of 3.8- and 10-year-old plantations of *Acacia mangium* in the Mendolong research area in Sabah, Malaysia

Biomass compartment		3.8 years[a]		10 years	
		W4	W5	W4	W5
Aboveground parts of trees					
Leaves		2.4	1.6	1.5	1.6
Branches	< 20 mm	5.2	4.7	3.5	2.1
	20–50 mm	2.7	0.3	4.0	1.2
	50–200 mm			2.1	1.2
Dead		4.3	0.7	6.2	0.6
Stem bark		7.2	2.8	5.4	3.4
Stem wood		22.7	12.0	55.0	34.5
Total tree biomass above ground		44.5	22.1	77.7	44.6
Understorey and climbers		5.4	8.3	16.5	16.3
Stumps and roots					
Stumps and root crowns		7.4	3.1	4.0	2.3
Roots 20–50 mm		0.1	0.2	10.0	4.6
Roots 5–20 mm		1.0	1.0	0.2	0.1
Roots < 5 mm		2.8	4.2	3.8[b]	4.1[b]
Total stumps and roots		11.3	8.5	18.0	11.1
Total biomass		61.2	38.9	112.2	72.0

[a] Nykvist *et al.* (1996)
[b] Lindquist (1998)

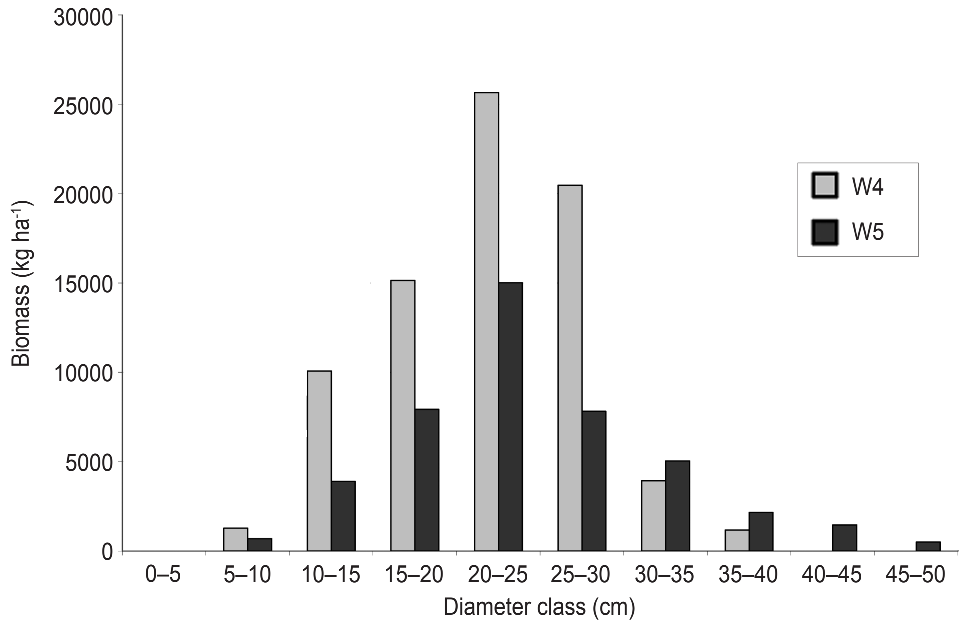

Figure 1 Aboveground dry weight biomass for different diameter classes of *Acacia mangium* in Mendolong 1997

Table 2 The aboveground biomass of some common plants in the understorey of the 1.5-, 3.8- and 10-year-old *Acacia* plantations in Mendolong (kg ha^{-1})

Plant species	1.5 years[a]		3.8 years[b]		10 years	
	W4	W5	W4	W5	W4	W5
Paspalum conjugatum	241	571	–	–	24	22
Imperata cylindrica	15	92	–	–	–	–
Eupatorium oderatum	19	–	–	–	–	–
Melastoma malabatricum	6	225	–	–	–	–
Nephrolepis biserrata (fern)	–	–	766	1587	–	22
Ficus spp.	–	97	204	554	538	2199
Macaranga spp.	37	–	–	227	1983	578
Bamboo spp.	–	–	639	113	1683	2294
Zingiber spp. (ginger)	–	–	180	137	171	61
Musa spp. (banana)	–	–	209	223	4	442
Dicranopteris linearis (fern)	–	–	385	870	–	53
Eugenia spp.	–	–	–	–	1148	539
Mallotus spp.	–	–	–	–	1076	13
Shorea spp.	–	–	–	–	875	128
Rattan spp.	–	–	–	–	763	303
Litsea spp.	–	–	–	–	902	698
Geunsia pentandra	–	–	–	–	623	2644
Beresmia spp.	–	–	–	–	129	1950
Mikania cordata (vine)	–	–	–	–	455	742
Glochidion spp.	76	–	–	–	–	97

[a] Sim and Nykvist (1991)
[b] Nykvist *et al.* (1996)

Carbon and nutrient amounts in the biomass of the *Acacia* plantations

No statistically significant differences were found between the nutrient concentrations related to either tree age or treatment in either catchment. Thus, differences in the amounts of plant nutrients in tree biomass between plots generally followed the trends observed for tree biomass.

The nutrients were taken up very quickly in the *Acacia* plantations. After 3.8 years, the amounts of N, P, K, Ca and Mg stored in the biomass of the fastest growing plantation (W4) were equivalent to 64, 70, 125, 66 and 70% of the amounts stored in the biomass of the plantation 6.2 years later (Table 3). The amount of carbon incorporated in the biomass of the 3.8-year-old W4 plantation was equivalent to 57% of the carbon in the 10-year-old plantation.

Amounts of organic carbon and nitrogen in the soil to 50 cm depth

Losses of carbon in the soil during the period from planting to harvesting *Acacia* trees amounted to *ca.* 95 Mg ha^{-1} in both W4 and W5, corresponding to about 80% of the amount of soil carbon at planting (Table 4).

During the same period about 53 and 34 Mg of carbon accumulated per ha in the above- and belowground biomass of the *Acacia* trees in W4 and W5 (Table 5). The losses of carbon due to harvesting the stems of the *Acacia* trees amounted to about 28 and 18 Mg ha^{-1} in W4 and W5 respectively (Table 5). Thus, the accumulations of carbon in the biomass after harvesting the *Acacia* stems were 25 Mg per ha for W4 and 16 Mg for W5, which can be compared with the loss of 95 Mg of soil carbon during the same period (Table 5).

Table 3 Contents of organic carbon and plant nutrients in leaf, branch, stem wood, stem bark, undergrowth (including creepers), stump and root to 50 cm depth in the *Acacia mangium* plantations at the Mendolong research area in Sabah, Malaysia

Content	Age (years)	Catch-ment	Leaf	Branch	Wood	Bark	Under-growth	Stump + root	Total
Carbon	3.8	W4	1171	5863	10668	3305	2572	6736	30315
		W5	795	2836	5621	1290	3926	6341	20809
	10	W4	700	7500	5900	2500	7800	8500	52900
		W5	800	2500	16200	1600	7700	5200	34000
N	3.8	W4	77	67	57	89	82	67	439
		W5	49	38	30	35	111	77	340
	10	W4	31	97	261	43	156	93	681
		W5	37	33	115	38	166	39	428
P	3.8	W4	3.1	2.0	1.8	2.4	4.7	1.6	15.6
		W5	2.2	1.3	1.0	0.5	6.5	2.4	13.9
	10	W4	1.5	3.3	8.1	0.8	6.7	1.9	22.3
		W5	1.1	1.0	4.1	0.6	5.4	1.6	13.8
K	3.8	W4	40	61	66	47	103	37	354
		W5	24	31	30	11	123	37	256
	10	W4	18	47	45	15	135	23	283
		W5	15	12	79	5	153	15	279
Ca	3.8	W4	11	47	13	59	22	25	177
		W5	6	24	10	28	47	21	136
	10	W4	4	84	41	35	83	22	269
		W5	4	21	62	12	104	15	218
Mg	3.8	W4	2.9	8.1	5.4	6.0	9.8	6.1	38.3
		W5	1.8	2.9	3.5	1.8	15.8	5.7	31.5
	10	W4	1.4	13.7	7.6	2.7	25.0	4.5	54.9
		W5	1.8	2.8	8.4	0.9	25.2	1.6	40.7

The contents are given in kg ha^{-1}. Figures for the 3.8-year-old plantations are taken from Nykvist *et al.* (1996).

During the rotation period of 10 years, the soil in the *Acacia* plantations lost 1390 and 1190 kg N ha^{-1} in the W4 and W5 catchments respectively (Table 5). During the same period 680 and 430 kg N ha^{-1} were accumulated in the above- and belowground biomass of W4 and W5 respectively (Table 5). About 300 and 150 kg N ha^{-1} of this accumulated nitrogen were lost when the *Acacia* stems were harvested, reducing the accumulation of nitrogen in the above and belowground biomass of W4 and W5 to 380 and 280 kg N ha^{-1}. In spite of the fact that *A. mangium* is a nitrogen-fixing tree, the W4 ecosystem lost 1010 kg N ha^{-1} (1390 – 380) and the W5 ecosystem, 910 kg N ha^{-1} (1190 – 280) (Table 5).

The amounts of plant-available phosphorus, potassium, calcium and magnesium in the soil to 50 cm depth

The most commonly assayed parameters in attempts to describe the status of nutrients in the soil are their ‘plant-available’ levels. Such analyses are very important in agriculture for

Table 4 Amounts (kg ha^{-1}) of organic carbon and total nitrogen in the soil to 50 cm depth when *Acacia mangium* was planted and when it was clear felled after 10 years

	Organic carbon		Total nitrogen	
	W4	W5	W4	W5
At planting				
Humus layer	22 000 ± 4900		793 ± 172	
Mineral soil				
0–10	58 600 ± 46000		2834 ± 1762	
10–20	18 200 ± 10300		974 ± 604	
20–30	9800 ± 5900		491 ± 314	
30–40	4700 ± 1700		264 ± 226	
40–50	2900 ± 600		78 ± 29	
Total	116 200		5434	
At clear felling				
Humus layer	2518 ± 1831	4104 ± 1572	420 ± 255	581 ± 198
Mineral soil				
0–10	6430 ± 2098	6895 ± 1704	1225 ± 249	1243 ± 365
10–20	3669 ± 1550	3825 ± 973	911 ± 291	665 ± 160
20–30	3350 ± 1197	2601 ± 880	545 ± 175	637 ± 255
30–40	3515 ± 2670	2199 ± 536	506 ± 51	583 ± 179
40–50	1988 ± 364	1973 ± 758	440 ± 95	534 ± 145
Total	21470	21597	4047	4243
Total loss after 10 years	94730	94603	1390	1190

Table 5 Losses and accumulations of organic carbon and total nitrogen in 10-year-old plantations of *Acacia mangium*

	Carbon (Mg ha^{-1})		Total nitrogen (kg ha^{-1})	
	W4	W5	W4	W5
Losses in the soil to 50 cm depth	94.7	94.6	1390	1190
Accumulated in the biomass	52.9	34.0	680	430
Losses when harvesting the stems	28.4	17.8	300	150
Total losses	70.2	78.4	1010	910

determining the amounts and type of fertilizers that should be applied to the soil to ensure that yields are not limited by nutrient deficiencies. A prerequisite for such analyses is that the soil should be sampled before or after harvest when the soil is bare and no nutrients are fixed in vegetation.

Analyses of plant-available nutrients have also been the most widely used methods to assess the amounts of nutrients in forest soils. The amounts of plant-available phosphorus, exchangeable potassium, calcium and magnesium in the soil of *Acacia* plantations at planting and at 3.8 and 10 years of age are shown in Table 6. Compared with analyses of agricultural soils sampled from bare soils, the analyses of plant-available nutrients in forest soils usually give very low nutrient content levels because large amounts are fixed in biomass or in plant residues from earlier wood harvests. The importance of plant residues left after harvesting wood for plant growth is illustrated in Table 7. In spite of the high amounts of nutrients taken up by the plants in the *Acacia* plantations, the amounts of plant-available P and Mg in the soil were higher in the 10-year-old W4 and W5 plantations than they were after felling the rainforest (Table 7). This also applies to Ca in the most slow-growing catchment, W5. The only monitored nutrient that decreased in both W4 and W5 during this period was K.

Table 6 Amounts of plant-available phosphorus (P), exchangeable potassium (K), calcium (Ca) and magnesium (Mg) in the litter, humus layer and mineral soil layers down to 50 cm at planting, and in both the 3.8- and 10-year-old *Acacia* plantations. Average figures in kg ha^{-1} are shown with 95% confidence intervals.

			Litter and humus	Mineral soil depth (cm) 0–10	10–20	20–30	30–40	40–50	Total
	At planting		3.2 ± 0.8	9.1 ± 2.6	3.8 ± 2.2	1.7 ± 1.4	0.6 ± 0.1	0.2 ± 0.1	18.6
P-	3.8 years	W4	0.7 ± 0.4	5.0 ± 1.4	3.7 ± 1.0	1.7 ± 1.0	0.7 ± 0.6	0. 3 ± 0.3	12.1
avail.		W5	0.7 ± 0.7	3.5 ± 1.6	4.0 ± 1.6	1.8 ± 1.3	1.0 ± 0.6	0.8 ± 0.4	11.8
	10 years	W4	2.0 ± 0.7	8.1 ± 1.1	4.9 ± 0.7	2.8 ± 0.9	1.6 ± 0.3	1.0 ± 0.4	20.4
		W5	2.2 ± 1.4	8.9 ± 2.0	6.4 ± 1.9	3.2 ± 1.2	2.2 ± 1.2	1.5 ± 1.0	24.4
	At planting		39 ± 11	94 ± 54	30 ± 30	13 ± 11	6 ± 2	6 ± 2	188
K-	3.8 years	W4	31 ± 4	61 ± 24	35 ± 15	28 ± 5	27 ± 5	23 ± 3	205
exch.		W5	25 ± 4	53 ± 13	37 ± 21	22 ± 13	26 ± 22	27 ± 22	190
	10 years	W4	6 ± 2	29 ± 10	16 ± 7	9 ± 3	10 ± 7	13 ± 8	83
		W5	14 ± 8	35 ± 8	24 ± 9	17 ± 8	12 ± 6	8 ± 5	110
	At planting		66 ± 36	25 ± 20	5 ± 2	3 ± 2	2 ± 0.1	2 ± 0.1	103
Ca-	3.8 years	W4	91 ± 15	45 ± 3	9 ± 6	7 ± 4	7 ± 5	3 ± 2	162
exch.		W5	104 ± 23	132 ± 71	30 ± 24	4 ± 2	2 ± 1	2 ± 1	274
	10 year	W4	10 ± 3	30 ± 13	23 ± 24	13 ± 10	12 ± 11	8 ± 4	96
		W5	21 ± 4	111 ± 66	32 ± 22	22 ± 14	12 ± 4	11 ± 3	209
	At planting		28 ± 11	37 ± 18	10 ± 5	4 ± 3	2 ± 1	2 ± 1	83
Mg-	3.8 years	W4	19 ± 3	52 ± 31	24 ± 11	19 ± 8	16 ± 7	4 ± 11	144
exch.		W5	23 ± 4	41 ± 21	21 ± 16	9 ± 7	5 ± 2	4 ± 1	103
	10 years	W4	3 ± 1	26 ± 11	24 ± 8	23 ± 8	21 ± 5	16 ± 5	113
		W5	8 ± 3	39 ± 12	25 ± 11	19 ± 11	17 ± 9	13 ± 8	121

The data at planting are from Nykvist (1997).

Table 7 Amounts of nutrients in kg ha^{-1} taken up by the plants and stored in the above and belowground biomass of the 10-year-old *Acacia* plantations compared with the amounts of plant-available nutrients in the soil to 50 cm depth before planting and 10 years later in the *Acacia mangium* plantations

		P		K		Ca		Mg	
		W4	W5	W4	W5	W4	W5	W4	W5
Nutrients taken up and stored in plant biomass		22.3	13.8	283	279	269	218	55	41
Plant-available nutrients in the soil	Before planting	18.6	18.6	188	188	103	103	83	83
	After 10 years	20.4	24.4	83	110	96	209	113	121
	Increase/decrease	+1.8	+5.8	-105	-78	-7	+106	+30	+38

Changes of pH in the soil

The pH of the soil in W4 and W5 decreased with the age of the *Acacia* plantations and the differences were significant at the 95% confidence level between the 3.8- and 10-year-old plantations (Figure 2). There were no significant difference at the 5% probability level between W4 and W5 in this respect, except that the pH of the litter layer was significantly lower in the fastest-growing *Acacia* plantation, W4.

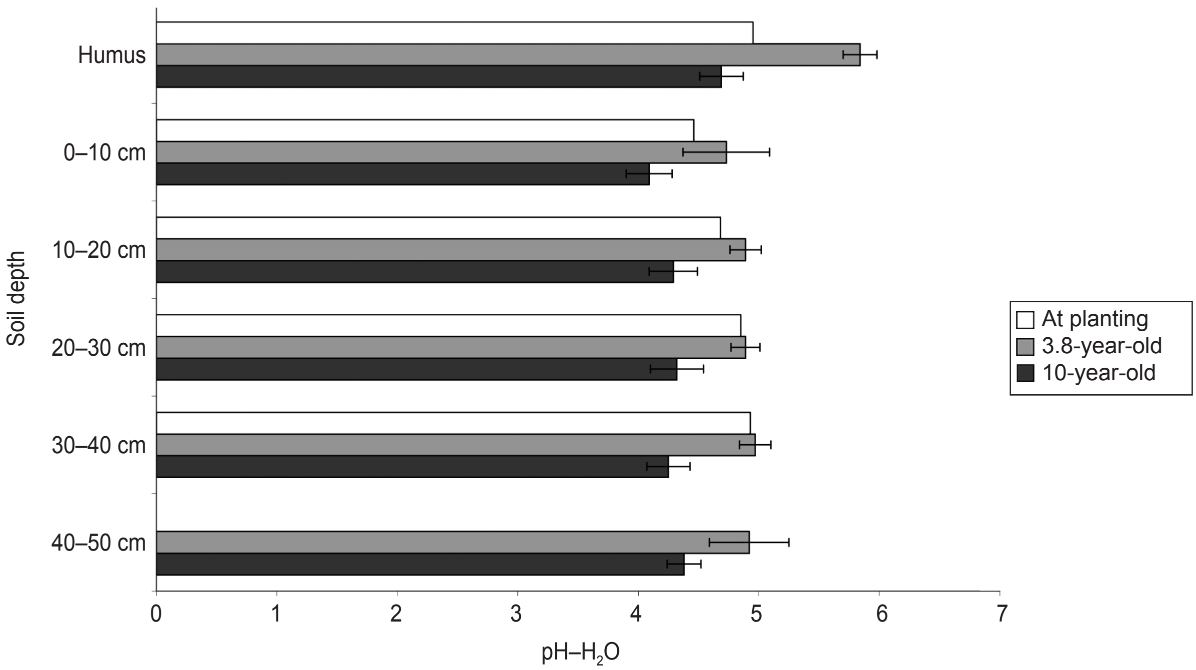

Figure 2 The pH of the humus and each 10 cm layer down to 50 cm soil depth before planting and in the 3.8- and 10-year-old *Acacia* plantations respectively in catchment W4. Mean figures with 95% confidence levels.

DISCUSSION

Biomass production

Ten years after clear felling the rainforest, the total aboveground biomass values in the *A. mangium* plantations in W4 and W5 were equivalent to approximately 34 and 25% respectively of the total aboveground biomass in the rainforest covering the catchments before it was clear felled, respectively (cf. Table 1, and Sim and Nykvist 1991). Compared with increments reported in other studies, the mean annual aboveground tree biomass increment (MABI) of the Mendolong plantations was low (Table 8).

The biomass of stem wood and stem bark in the 10-year-old *Acacia* plantations in W4 and W5 amounted to 60.4 and 37.9 Mg ha^{-1} (Table 1). With a basic density of 420 kg m^{-3} for *A. mangium*, these figures correspond to annual increments of approximately 14 and 9 m^3 ha^{-1} $year^{-1}$ respectively. The lower annual increment in W5 compared with W4 was probably due to soil compaction by tractor logging and the greater losses of carbon and inorganic nutrients due to burning the slash in W5. The annual increments in plantations of *A. mangium* over 8–10 years usually range from 20 to 40 m^3 ha^{-1} $year^{-1}$ (Binkley & Giardina 1997), but can exceed 45 m^3 ha^{-1} $year^{-1}$ under ideal conditions (Whitmore 1998). The very low annual increments in our experimental area may be ascribed to the nutrient-poor sandstones, siltstones and shales forming the bedrock.

In spite of the lower annual increment in W5, a few trees were larger in W5 than in W4 (Figure 1). The main reason for this is probably the heterogeneity of the soil caused by the tractor logging in W5, in which nutrient-rich topsoil was scraped away in some places and deposited in others.

The increase in aboveground biomass of the trees between 3.8 and 10 years of age was mainly due to an increase in stem-wood biomass. The biomass of leaves and smaller branches was even smaller in the 10-year-old plantations than in the 3.8-year-old plantations. The dry weight of dead branches was greater in W4 than in W5, for both the 3.8- and 10-year-old plantations, indicating that there was more self-pruning in the more productive plantation.

Table 8 Mean annual increment of aboveground biomass (MABI) for some *Acacia mangium* plantations in the humid tropics

Age (years)	MABI ($Mg\ ha^{-1}\ year^{-1}$) Mendolong study W4	W5	Other studies	Source
0.7			0.3	Kurosaki (1988)
1.6	6.5	3.9		Sim & Nykvist (1991)
3.5			15.5	Lim & Mohd. Basri (1985)
3.5			18.3[a]	Lim (1985)
3.8	11.8	6.3		Nykvist *et al.* (1996)
4.0			21.0	Lim (1988)
4.0			12.0[b]	Yantasath *et al.* (1992)
4.0			32.0[b, c]	Yantasath *et al.* (1992)
4.6			18.2[c, d]	Lim (1986)
5.0			12.8	Ruhiyat (1989)
6.8			18.1	Halenda (1989)
10.0	7.8	4.5		Present study

[a]Projected for plantation conditions
[b]Converted from fresh weight data by multiplying by 0.4
[c]10 000 stems per ha
[d]Regular fertilization of cocoa planted between the trees

A carbon budget for the clear felling of rainforest at Mendolong and growing *Acacia mangium* in a 10-year rotation

Following recent concerns about increases in atmospheric levels of carbon dioxide and their effects on global warming, great interest has been focused on the large amounts of organic C in forest ecosystems and the effects of different forest management strategies on carbon dioxide release. Dixon *et al.* (1994) estimated that forest ecosystems contain approximately 1146 Pg C (10^{15} g C) and that two-thirds of these are present in forest soils.

Several investigations have indicated that forest ecosystems can act as significant sinks or sources of C, depending on conditions. However, most of these studies have only considered the aboveground biomass of forests. Although the soil organic C content may be similar to, or greater than the amount found in above-ground biomass, little information is available on changes in the C contents of forest soils and the existing literature is contradictory (Johnson 1992). Paul *et al.* (2002) reviewed available global data on soil C contents following afforestation on agricultural land. Average figures indicate that there tends to be an initial decline in soil C following afforestation and then a gradual increase, so after approximately 30 years the C content is often greater than in the previous agricultural soil. On former pasture sites, the soil C tends to decrease after afforestation, whereas on former cropping sites it increases. In addition, Johnson and Curtis (2001) have reviewed the effects of forest management on soil organic C and N. Their 'harvest effects database' contains observations regarding 73 sites from 26 publications, mostly in temperate forests. Compared with control or pre-treatment values, forest harvesting generally appears to have little effect on soil C and N contents, with sawlog harvesting causing significant increases in soil C and N, and whole-tree harvesting causing slight decreases. Observed increases in soil C and N following sawlog harvesting have generally followed the felling of coniferous stands.

Prior to the planting of *A. mangium* at the Mendolong research area, the rainforest was clear felled and harvested. The biomass of wood and bark in stems larger than 20 cm dbh in the rainforest amounted to 167 and 163 $Mg\ ha^{-1}$ in the W4 and W5 catchments respectively (Sim

& Nykvist 1991). However, many trees were crooked, hollow, broken or 'oversized', so only 61% of the stem biomass in W4 and 50% in W5 was extracted from the catchments (Nykvist *et al.* 1994). Furthermore, during the mechanized logging in W5, most bark was scraped off the logs, so mainly stem wood was extracted from this catchment. Thus, the losses of biomass when harvesting the rainforest in the W4 and W5 catchments amounted to 102 and 73 Mg ha^{-1} (Sim & Nykvist 1991). The carbon content in the biomass was 47% and the losses of carbon when harvesting the rainforest were 48 Mg ha^{-1} in W4 and 34 Mg ha^{-1} in W5.

The logging residues started to decompose rapidly in the warm, humid climate. After 10 years, before the *Acacia* plantations were clear felled, only the stems and largest branches left after harvesting the rainforest could be seen on the soil surface. If all above and belowground biomass components from the rainforest given in Sim and Nykvist (1991) with diameters smaller than 5 cm decomposed during the 10-year rotation period, or were present in varying degrees of decomposition in the sampled soil layers, adjusted losses of carbon amounted to 46 Mg C ha^{-1} in W4, while in W5, where the logging residues were burnt, 53 Mg C ha^{-1} were lost.

A summary of the carbon losses from the time when the rainforest was clear felled and harvested until the *Acacia* stems were harvested and removed from the site is presented in Table 9. Total estimated losses amount to 165 Mg C ha^{-1} each for both W4 and W5, corresponding to about 44% of the carbon content in the rainforest ecosystem before clear felling (cf. Nykvist 1997).

The main reason for the large losses of organic C when the rainforest was harvested and the clear-felled area was planted with *A. mangium* was the decrease in soil organic C. The losses of C in the ecosystems were probably somewhat greater than the presented data suggest because the budgets were based on the assumption that branches and roots thicker than 5 cm had not decomposed at all during the experimental period.

Greater losses of organic C were found in our study than in the studies by Johnson and Curtis (2001) in a review of the effects of forest management on soil organic carbon, probably because in our study the same areas were examined before and after clear felling. In the studies reviewed by Johnson and Curtis (2001), the amounts of C in the soil after harvesting were compared with controls in unharvested forests. The increases in soil C after sawlog harvesting found in many investigations may be due to harvest residues being incorporated into the soil (Johnson & Curtis 2001).

A reduction in the soil organic matter content has more negative impact on the fertility of

Table 9 Changes in carbon and total nitrogen amounts when the rainforest was harvested and the clear felled area planted with *Acacia mangium* which was harvested after 10 years

	Carbon (Mg ha^{-1})		Total nitrogen (kg ha^{-1})	
	W4	W5	W4	W5
Carbon and nitrogen amounts in the soil to 50 cm depth				
In the rainforest before clear felling	116.2		5430	
In the *Acacia* plantations before clear felling	21.5	21.6	4050	4240
Decreases	94.7	94.6	1380	1190
Decreases of carbon and nitrogen in biomass				
Harvesting of the rainforest	48.2	34	150	80
Decomposition of plant remnants < 5 cm diameter	46.2	52.6	490	580
Harvesting of *Acacia* trees	28.4	17.8	300	150
Total	122.8	104.4	940	810
Increases of carbon and nitrogen in biomass				
Plant production in the *Acacia* plantations	52.9	34	680	430
Decreases minus increases	69.9	70.4	260	380
Decreases of carbon and nitrogen in soil and biomass	164.6	165	1640	1570

Figures for the rainforest ecosystem are from Sim and Nykvist (1991), and Nykvist *et al.* (1994).

tropical than temperate soils because the types of clay minerals formed in tropical soils have much lower cation exchange capacities. At our study sites, the contents of organic carbon and plant-available nutrients decreased with depth but the clay content increased, indicating that nutrients are mainly tied up in organic substances or adsorbed to them. Sanchez (1976) stated that in many highly-weathered tropical soils, the cation exchange capacity is related to the organic matter content. Accordingly, Fölster *et al.* (2001) found that the cation exchange capacity in soils in Venezuelan Guyana is almost completely dependent on soil organic matter, and that few cations are adsorbed to clay particles in them. Krishnaswamy and Richter (2002) have also found a significant relationship between the organic C contents and cation exchange capacity of old weathered soils in Costa Rica.

A nitrogen budget for the clear felling of the rainforest at Mendolong and growing with *Acacia mangium* in a 10-year rotation

After growing *A. mangium* in a 10-year rotation, substantial losses of nitrogen had occurred relative to the amounts present in the rainforest. The losses of N in soil and biomass after harvesting the *Acacia* stems amounted to 1640 kg N ha^{-1} in W4 and 1570 kg N ha^{-1} in W5 (Table 9). As percentages of the original amounts of nitrogen in the rainforest ecosystem before clear felling, the total losses after harvesting the *Acacia* stems amounted to 24% in the manually-harvested catchment W4 and 23 % in the tractor-logged, burnt catchment W5 (cf. Nykvist 1997).

The large losses of N in the plantation were unexpected, since *A. mangium* is a nitrogen-fixing tree that can fix 100–300 kg N ha^{-1} $year^{-1}$ from atmospheric N_2 in an alley cropping system (Sanginga *et al.* 1995). However, the high N concentrations in the stems of the fastest-growing plantation (W4) resulted in higher losses of N when all the stems in the 10-year-old *Acacia* plantation were harvested than when all stems were harvested in the rainforest (cf. Nykvist 1997).

Losses of dissolved N in stream water from the W4 and W5 catchments during the first 33 months after starting to clear-fell the rainforest amounted to 27 and 40 kg N ha^{-1} respectively (Malmer 1992). We estimated the losses during the remaining 87-month period up to the clear felling of the 10-year-old *Acacia* plantations by extrapolating leaching losses measured between 24 and 33 months after clear felling the rainforest, giving estimated leaching losses of N in the *Acacia* plantations at the W4 and W5 catchments of 106 and 167 kg ha^{-1} respectively. Since the annual input from wet deposition at the Mendolong research station was about 6 kg N ha^{-1} $year^{-1}$ (Grip *et al.* 1994), our overall estimated losses of N in the streams amounted to *ca.* 46 kg ha^{-1} and 107 kg ha^{-1} at W4 and W5 during the 10-year *Acacia* rotation period.

Losses of plant nutrients after harvesting the rainforest and the 10-year-old plantations of *Acacia mangium*

The losses and inputs of P, K, Ca and Mg from and to the W4 and W5 catchments after harvesting the clear felled rainforest, planting *A. mangium* and harvesting it 10 years later are summarized in Table 10. Harvesting the *Acacia* stems caused the greatest losses of P, but the greatest losses of Ca occurred when the rainforest trees were harvested. Leaching was the most serious cause of losses for K. The effects of soil erosion were relatively minor.

Overall, the net losses of some nutrients (K and Ca), but not others (P and Mg) exceeded the amounts of plant-available nutrients in the soil to 50 cm depth in the 10-year-old *Acacia* plantations (Table 6). However, in relation to the total amounts of P, K, Ca and Mg in the soil to 50 cm depth (cf. Nykvist 1997), the losses were comparatively small, especially for P and Mg for which the total amounts in the soil were more than 100 times greater than the losses, while the total amounts of K and Ca were about 40 and 3 times greater than the losses respectively.

The very low figures for calcium are uncommon and are a result of the very Ca-poor soil and bedrock in the research area of Mendolong. Despite this, foliar analysis has not revealed any deficiency of Ca in the two investigated catchments (Table 11), nor in two adjacent *Acacia* plantations with similar bedrock (Comstedt 2001, Björck 2002). However, the Ca-values in the leaves from the adjacent plantations seemed to decrease with time.

The implications for sustainable forest management of the low amount of total Ca in the soil (1082 kg ha^{-1}), relative to the amounts in stem

Table 10 Losses and inputs (kg ha^{-1}) of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) when the rainforest at Mendolong was logged and the clear felled area was planted with *Acacia mangium*, which was harvested after 10 years

		P		K		Ca		Mg		Reference
		W4	W5	W4	W5	W4	W5	W4	W5	
Losses	Clear felling rainforest	3.4	1.8	125	57	248	112	47	32	a
	Burning	–	2.3	–	33	–	26	–	8	b
	Soil erosion	0.2	0.4	4	8	1	1	2	3	c
	Leaching	0.8	1.6	290	411	35	27	18	35	d
	Clear felling *Acacia*	8.9	4.7	60	84	76	74	10	9	e
	Total losses	13.3	10.8	479	593	360	240	77	87	
Supply	Fertilization	2.6	2.6	0.6	0.6	2.2	2.2	0.2	0.2	f
	Input from rain	6.5	6.5	18	18	16	16	4	4	g
	Total supply	9.1	9.1	19	19	18	18	4	4	
Losses minus supply		4.2	1.7	460	574	342	222	73	83	

a. Nykvist *et al.* (1994). The logs were extracted manually in W4 and mechanically in W5.
b. The losses by burning have been estimated from investigations by Mackensen *et al.* (1996) from burning logging residues in the Amazon. If the lowest figures for burning losses of different plant nutrients given by Mackensen *et al.* (1996) are assumed to be relevant for W5, the logging residues in the catchment W5 would have lost approximately 220 kg N, 2.3 kg P, 33 kg K, 26 kg Ca and 8 kg Mg ha^{-1}.
c. The soil erosion caused by clear felling during the first 18 months was 1.75 and 3.45 tonnes per hectare for W4 and W5 respectively (Malmer 1996a). After 18 months the erosion was considered to be minor and was disregarded. The soil losses have been multiplied by the concentration of nutrients in the top soil given by Nykvist (1997).
d. The losses by leaching were investigated by Malmer and Grip (1994) for the first 33 months after clear felling of the rainforest. For the remaining period up to the clear felling of the *Acacia* plantation, the losses have been estimated from leaching losses between 33 and 24 months after clear felling of the rainforest. The amounts of suspended particulate phosphorus have been estimated from Malmer (1996b).
e. Present study
f. Present study
g. Ten times the figure for annual supply of K, Ca and Mg given by Grip *et al.* (1994). The annual supply of P was not investigated at Mendolong, but was estimated from Galloway *et al.* (1982).

wood and stem bark in the old rainforest (398 kg ha^{-1}), have been discussed by Nykvist (1997, 1998, 2000). Low total Ca contents in mineral soils have also been found outside the research area in Mendolong. In a surrounding area, covering approximately 46 000 ha, the total Ca content in the mineral soil to 100 cm depth amounted to 790 ± 440 kg Ca ha^{-1}. Lower total Ca contents than in the Mendolong research area have also been found in areas of Colombia, Brazil, Zambia, Indonesia, Ivory Coast, Costa Rica, Thailand and Cuba, according to estimates of total Ca derived from concentrations of exchangeable Ca in soil profiles described in the FAO-Unesco 'Soil map of the world' and country reports published by the International Soil Reference and Information Centre (Nykvist 2002). Thus, low Ca levels appear to be features of soils in many tropical areas.

CONCLUSIONS

In recent decades intense interest has been focused on the gains and losses of carbon in forest ecosystems, but most investigations have only dealt with the carbon contents in above-ground biomass, partly because they are easy to evaluate. However, our studies at the Mendolong research area (in which changes in both biomass and soil have been investigated) showed that 44% of the total carbon was lost when a rainforest was harvested, the clear felled area was planted with *A. mangium* and the *Acacia* stems were harvested 10 years later, and that *ca.* 57% of these carbon losses were from the soil.

Furthermore, although *A. mangium* can fix considerable amounts of nitrogen, about 23% of the total amount of N present before clear

Table 11 Foliar analysis of *Acacia mangium* and rainforest trees

Species	Age	Plot	n	N	P	K	Ca	Mg	Reference
A. mangium	3.8	W4	5	3.19	0.11	1.64	0.42	0.11	a
				± 0.07	± 0.08	± 0.10	± 0.09	± 0.04	
	3.8	W5	5	3.12	0.14	1.55	0.41	0.12	a
				± 0.14	± 0.01	± 0.39	± 0.10	± 0.02	
	10	W4	15	2.05	0.11	1.15	0.35	0.11	b
				± 0.26	± 0.02	± 0.12	± 0.12	± 0.03	
	10	W5	16	2.29	0.09	0.99	0.32	0.10	b
				± 0.18	± 0.02	± 0.11	± 0.07	± 0.02	
	5–7		14	2.51	0.16	2.17	0.60	0.21	c
				± 0.49	± 0.01	± 0.29	± 0.26	± 0.04	
	6		20	2.3	0.06	0.53	0.40	0.19	d
	Critical value			–	< 0.13	< 0.6	< 0.2	< 0.1	e
Rainforest			10	1.23	0.062	0.78	0.62	0.23	f
				± 0.13	± 0.008	± 0.28	± 0.31	± 0.093	

Mean figures are shown with 95% confidence levels for the percentages of biomass dry weight.

a. Nykvist *et al.* (1996)
b. Present study
c. Ruhiyat (1989)
d. Amir & Wan (1994)
e. Srivastava (1993)
f. Sim & Nykvist (1991)

felling the rainforest was lost after harvesting the rainforest trees and (10 years later) the *Acacia* stems. Most of the losses occurred from the soil.

The variables most commonly determined in assessments of soil fertility in agricultural systems and forest ecosystems are plant-available phosphorus, potassium, calcium and magnesium levels. However, such analyses can give misleading results if the amounts of nutrients in biomass and logging residues are not taken into account. In the *Acacia* plantations at Mendolong the amounts of plant-available P and Mg and for Ca in the most slow-growing catchment, W5, increased in the soil despite the strong uptake of nutrients by the *Acacia* trees.

When the rainforest at Mendolong was converted to plantations of *A. mangium,* the harvesting of *Acacia* stems caused the greatest losses of P and harvesting the rainforest trees, the greatest losses of Ca and Mg. Leaching was the most serious cause of losses of K. The effect of soil erosion was relatively small.

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