Plantation agriculture in the tropics

Environmental issues

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Abstract: *Plantation agriculture is more than 400 years old and contributes to the regional and national economies in many tropical countries. This paper reviews some of the main environmental issues related to plantation agriculture with perennial crops, including soil erosion, soil fertility decline, pollution, carbon sequestration and biodiversity. Soil erosion and soil fertility decline are of concern in some areas, but in most plantations these are being checked by cover crops and inorganic fertilizer applications. Few studies have been conducted on the issue of carbon sequestration under perennial plantation cropping. Reductions in deforestation yield much greater benefits for a reduction in* CO_2 *emissions than expanding plantation agriculture. The biggest threat to biodiversity is the loss of habitat through expansion of the plantation area. Despite the environmental problems and concerns, this review has shown that crop yields of most perennial crops have increased over time due to improved crop husbandry including high-yielding cultivars and improved soil management. It is likely that more attention will be given to the environmental aspects of plantation cropping due to the increasing environmental awareness in tropical countries.*

Keywords: *plantation agriculture; soil erosion; soil fertility decline; biodiversity; environment; crop yield*

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Plantation agriculture started in the sixteenth century when the Portuguese settled in coastal parts of Brazil. The area lacked any known mineral wealth and settlers were involved in the cultivation of sugar cane, which would find a ready market in Portugal. Slaves were brought in from Portugal's Atlantic island colonies, and during the sixteenth century Brazil was the world's major supplier of sugar (Courtenay, 1980). This showed that large-scale agriculture in the tropics could be a successful business.

There are a number of definitions of plantation agriculture, but it is often referred to as a large-scale, mostly foreign-owned and specialized high-input/high-output farming system that is export-oriented (Courtenay, 1980; Goldthorpe, 1987 and 1994). Tiffen and Mortimore (1988) defined plantation agriculture as a farm of over 100 ha in size, with a specialized management team in charge of a labour force with specialized production techniques. A more recent definition was given by Stephens *et al* (1998):

> Plantations are defined as areas that are typically monocropped with perennials, producing tropical or subtropical products that commonly require prompt initial processing and for which there is an export market.

The term 'plantation' is also used in forestry: timber plantations, plantation forests or forest plantations (Evans, 1986; Parrotta, 1992; Sedjo and Botkin, 1997). Forest plantations are man-made forests where cultivation is generally less intensive. Forest plantations are defined as: 'a forest crop or stand raised artificially, either by sowing or planting' (Evans, 1992).

The world plantation belt runs from Central and South America across the equatorial regions of Africa to Asia, to the Far East and Queensland in Australia (Courtenay, 1980). The most important plantation crops are cocoa, coffee, tea, coconut, bananas, rubber, oil palm, jute, sisal and hemp (Burger, 1994). Other important plantation crops are sugar cane, tobacco, cinchona and pineapple. Oil palm is currently the most valuable plantation economy of the tropical world (Henderson and Osborne, 2000).

Agricultural plantations have a number of socioeconomic and ecological advantages and disadvantages when compared with smallholder agricultural systems. Large-scale production is in many cases more economic, and plantations offer labour and income for hundreds of thousands of people. In most situations plantation agriculture is a profitable business and earns foreign exchange. Disadvantages are the financial risks due to fluctuating world market prices, the dependence on cheap labour and often advanced technology, which requires imports and foreign exchange.

Despite the long-term history of plantation agriculture and its importance for many national economies, few studies have looked at the long-term environmental implications (Sawyer, 1993). The only plantation crop that has received a fair amount of attention is the oil palm (PORIM, 1994; Pushparajah, 1998). This paper reviews some of the major environmental issues related to plantation agriculture in tropical regions, and focuses on soil erosion, soil fertility decline, pollution, carbon sequestration and biodiversity. Research efforts as well as trends in crop yields are discussed.

Extent and importance

The exact extent of plantations in the tropics is not known, but several reports have indicated that the area under plantation agriculture has increased in the past decades. Estimates from the 1970s showed that about 4% of the farming areas in the tropics were plantations (Sanchez, 1976). Based on the cultivated area, the plantation area in the mid-1970s was about 20 million ha. Nair (1984) estimated that perennial plantation crops in 1984 occupied about 8% of the total arable area in the tropics, which suggests a considerable increase in area under plantations. Global statistics on the area under perennial cropping can be obtained from FAO databases, but no distinction is made between smallholders and plantations.

Large plantation areas occur in Malaysia where the extent of oil palm increased from about 150,000 ha in the early 1970s to 2.0 million ha in 1990 (Hardter *et al*, 1997) to 2.6 million ha in 1997 (Jalani, 1998) and over 3 million ha at the end of 1998. The increase occurred at the expense of the rainforest and rubber and cocoa (Pushparajah, 1998). The area under cocoa in Malaysia grew from 10,000 to 307,000 ha between 1970 and 1986 (Webster and Watson, 1988), but cocoa areas had declined to about 100,000 ha in 1998 because of labour shortages. It has been estimated that at least 0.8 million ha of new oil-palm plantings in Malaysia involved forest clearance (PORIM, 1994). The Malaysian government is actively promoting the cultivation of tree crops with a view to compensating for the loss of tree cover because of forest felling and to generate income for both the smallholder and plantation sectors. Another country where plantation tree crops are actively promoted is Côte d'Ivoire. Cocoa production in Côte d'Ivoire increased from 150 Mg (1 megagram = 1 tonne) in the 1960s to over 1,100 Mg in the mid-1990s, which reflects a large increase in the area under cocoa that occurred largely at the expense of the rainforest. Currently, Côte d'Ivoire is the largest cocoa producer, with a 95% increase in output over the 1980s, and it now supplies more than 40% of the world market (Hartemink, 2005).

An important plantation crop whose area has been substantially increased is sugar cane. In the 1960s, sugar production in the world was about 64 million Mg, half of which was produced in developing countries (FAO, 1996). By the mid-1990s, production had increased to 119 million Mg. Between the mid-1960s and 1990s the largest expansion of sugar production occurred in India (from 3 to 15 million Mg) and Brazil (from 5 to 10 million Mg). Part of the increase in sugar production has resulted from improved agronomic practices, but in many countries, increased production has resulted from a larger area under sugar cane.

Papua New Guinea is another country where the area under other plantation crops has expanded greatly and more than 80,000 ha has been planted with oil palm since the mid-1960s. Overall, plantation crops cover less than 4% of the total land under agriculture in Papua New Guinea (Hartemink and Bourke, 2000).

In some countries the area under plantation crops has declined. This applies, for example, to sisal in East Africa, especially in Tanzania. In the 1960s, sisal production in Tanzania equalled 234,000 Mg, or nearly one-third of the world's annual sisal fibre production, but in the mid-1980s, this had declined to about 30,000 Mg of fibre per year. In the Tanga region, there were more than 70 large sisal plantations in the 1960s, but in the late 1980s fewer than 20 were fully operational (Hartemink, 1995).

The plantation sector contributes substantially to the gross national product (GNP) and the wealth of several nations. In the 1980s, rubber exports contributed more than 10% to the GNP of Malaysia, whereas in Côte d'Ivoire a group of plantation crops produced 22% of GNP. As yields are usually higher on plantations, they may contribute more to GNP than the area they occupy, for example in Kenya tea plantations comprise 35% of the area under tea, but they produce more than 60% of the total output (Tiffen and Mortimore, 1988). In India, the major plantation crops, tea, coffee, rubber and cardamom covered less than 0.5% of the total cropped area in the mid-1980s, but accounted for over 10% of the added value in agriculture (Giriappa, 1989). In Ghana, cocoa export accounts for about 60% of the country's foreign earnings, whereas in Indonesia, the revenue of cocoa is over U$600 million per year (Hartemink, 2005).

Research on plantation crops

Agricultural research was greatly expanded in the 1920s and 1930s, and the research was mostly concentrated on the plantation industries and on crops that could be grown for sale (Hall, 1936). Until the outbreak of the Second World War, the Dutch in Indonesia were the leaders in research on most of the commodity crops, but Commonwealth countries became the major contributors

Table 1. Nutrient deficiencies reported in export tree crops and food crops in Papua New Guinea.

Crops		Macronutrients					Micronutrients				
		N	*P*	*K*	*Mg*	*S*	*B*	*Zn*	*Fe*	*Cu*	*Mn*
Export tree crops	Arabica coffee	2	3	1	2	2	1	1	1	4	4
	Robusta coffee	–	–	–	–	–	4	3	–	2	2
	Cocoa	1	–	–	–	–	4	2	2	3	3
	Coconuts	2	3	2	–	2	4	4	–	–	–
	Oil palm	2	–	–	2	–	–	–	–	–	–
	Rubber	–	–	–	–	4	4	–	4	4	3
	Tea	–	–	–	–	2	–	3	–	–	–
Food crops	Sweet potato	1	2	2	4	4	2	4	4	4	–
	Taro	1	3	2	–	4	–	–	–	–	–
	Irish potato	–	3	–	–	–	3	–	–	–	–
	Citrus spp.	–	–	–	–	–	–	1	–	–	3
	Maize	–	2	–	–	3	–	–	–	–	–
	Rice	–	–	–	–	2	–	3	–	–	–
	Peanuts	–	–	–	–	2	4	3	–	–	–
	Pyrethrum	–	–	–	–	–	3	–	–	–	–

1 = common in many parts of the country;
2 = locally;
3 = very locally;
4 = investigated but no deficiency present;
– = not investigated.
Source: Hartemink and Bourke, 2000.

after the Second World War. With considerable research effort in the 1950s and 1960s, plantation agriculture became more scientifically based and crop yields increased accordingly (Webster and Wilson, 1980). Up to the 1950s, there was more scientific research on plantation crops than on food crops. Research was conducted by different groups who had little interaction (Hartemink, 2003). For example, in Papua New Guinea at the experimental stations for export tree crops (plantation crops), agronomists and soil fertility experts investigated optimum inorganic fertilizer rates and nutrient deficiencies using field trials, greenhouse trials and on-farm experiments. The second group were pedologists and soil surveyors. Until the 1970s, agronomic and soil fertility research focused on plantation crops and no significant research on food crops took place. As a result much more is known about nutrient deficiencies in plantation crops than in food crops in Papua New Guinea (Table 1). Rubber is a fairly marginal crop in Papua New Guinea, but it has received more research than sago, which is the main staple for more than 10% of the people (Hartemink and Bourke, 2000).

The situation in Papua New Guinea is no exception, and throughout the tropical world, research in tree crops is fairly well advanced due to the long-term commitments of commercial research organizations. Examples of long-serving research institutes in the tropics are RRIM (rubber) in Malaysia, WAIFOR (oil palm) in West Africa, CRI (coffee) and the Kericho Tea Research Foundation (TRFK) in Kenya. These research organizations (some acronyms have changed) usually receive their funds through a levy on the export of the commercial produce. Fruits, nuts and spices have received less research attention by commercial organizations.

Research investments in plantation crops may be beneficial for smallholder farmers, although estimates of on-farm benefits from agricultural research are difficult and complex (Pannell, 1999). Research on tea plantations in Tanzania has proved to be of great benefit to smallholders, and the financial return on the research investment has been immense (Carr, 1999). Also Webster and Wilson (1980) noted that the crop productivity of smallholders can be more easily raised when improved planting materials and technological advances have been developed and tested on plantations.

It is difficult to distinguish between the real benefits of research on plantation crops and the fact that smallholders start to cultivate cash crops that generate financial returns. Studies in Indonesia have shown that the average net income of oil palm smallholders was seven times higher than that of their neighbours who were mainly involved in the subsistence production of food crops (Hardter *et al*, 1997). Despite difficulties in the assessment, it seems likely that research in plantation crops is useful to smallholders, provided sufficient interaction exists between plantation research centres and NGOs or government extension services.

International research organizations and NGOs are usually not interested in conducting research on plantation crops because their main focus is on resource-poor smallholders. Crops grown on plantations have been referred to as non-CGIAR crops (Smith, 2000). In the past decade, some Consultative Group on International Agricultural Research (CGIAR) centres have been established to conduct research in tree crops (eg the Centre for International Forestry Research (CIFOR) and the World Agroforestry Centre – ICRAF). Coconuts and bananas have also been included in some genetic database networks (Smith, 2000). Little has been done on the major plantation crops through the CGIAR centres, but much understanding on perennial crops has been gained by the agroforestry research conducted by the World

Agroforestry Centre – ICRAF, and Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) in Turrialba (Somarriba *et al*, 2001).

Soil erosion under perennial crops

The environmental impact factor that has probably received most research attention in the tropics is soil erosion, and there are excellent reviews available (eg El-Swaify, 1997; Hudson, 1986; Lal, 1990; Morgan, 1995). Overall, it is generally assumed that a perennial plant cover protects the soil better against erosion than an annual crop (Jacks and Whyte, 1939; Lal, 1990; Ruthenberg, 1972), although much depends on the soil, site factors (slope, rainfall, etc) and management practices. Most annual crops provide adequate cover within 30 to 45 days after planting and pastures within two to six months, but tree crops may require two to five years to close their canopy (Sanchez *et al*, 1985). Soil erosion can be considerable with inappropriate land-clearing methods and because of insufficient soil cover immediately after clearance.

Lal (1990) reviewed the literature on the effects of trees on soil erosion. He concluded that surface run-off from catchments with natural forest was generally low, but was higher with increasing annual rainfall. Soil erosion and sediment transport from the catchments with natural forests is minimal (<1 Mg ha^{-1} year^{-1}), but soil erosion increases when natural forest is changed to plantations. Erosion is greater during the initial stages of tree establishment than when the tree canopy is fully developed. A much-used solution to the problem of soil exposure during plantation establishment is to use a managed cover crop (Sanchez *et al*, 1985). New techniques used in plantation agriculture include underplanting, advanced planting material (very large plants) and high initial density followed by thinning.

Erosion under oil palm

Several erosion studies have been conducted on oil-palm plantations in Malaysia. The Palm Oil Research Institute of Malaysia (PORIM, now called MPOB – Malaysian Palm Oil Board) summarized the studies as follows: minimal soil erosion before forest clearing, five to seven times greater after clearance, and a subsequent decline to almost pre-clearance level when the crop is established (PORIM, 1994). Published data on soil erosion under oil palm in Malaysia are shown in Table 2.

Table 2 . Soil erosion losses under oil palm in Malaysia.

Soil order	Palm age (years)	Slope (%)	Condition	Soil erosion (Mg ha^{-1} year^{-1})
Tropeptic Hapludox (Oxisols)	2–4	2	With legume cover crop	18.8
		5	With legume cover crop	24.0
		9	With legume cover crop	35.4
		15	With legume cover crop	50.0
	12	<5	Uncovered	12.5
Typic Hapludox (Oxisols)	2–4	2	With legume cover crop	23.5
		5	With legume cover crop	38.8
		9	With legume cover crop	57.1
		15	With legume cover crop	77.6
Orthoxic Tropudult (Ultisols)	11	5	Harvesting path	14.9
			Palm row	7.4
			Beneath row	1.1
Typic Paleudult (Ultisols)	12–16	3–5	Uncovered	28.0
			Plots with fronds cut	19.7
			Plots with extra fronds cut	16.3

Note: Adapted from PORIM (1994), based on several studies conducted in peninsular Malaysia between 1979 and 1990.

Soil erosion from Oxisols ranged from 13 to 78 Mg ha^{-1} year^{-1} and depended on the slope of site. Soil erosion on Ultisols ranged from 1 to 28 Mg ha^{-1} year^{-1} and erosion was higher in harvesting paths. As the cover crop disappears after the closure of the palm canopy, harvest paths become exposed and compacted, which enhances run-off and soil erosion. Therefore, soil erosion may not necessarily decrease when the palms get older and the canopy is closed. The effect of erosion under oil palm is that the soil is removed from between the tertiary and quaternary feeding roots near the soil surface, in particular in the weeded circle. Exposed roots dry up and die, so that the water and nutrient-uptake capacity of the root system is reduced. Although no experimental evidence is available, it is obvious that oil palms growing under these conditions undergo water deficits and nutritional deficiencies (Ferwerda, 1977). Moreover, the nutrient use efficiency of applied fertilizers is reduced because of the lower uptake capacity of the roots. On oil-palm plantations, soil erosion is checked by early cover-crop establishment, strategic placement and treatment of pruned fronds and old palm trunks, with felling, terracing, construction of silt pits and mulching with empty fruit bunches (PORIM, 1994).

Erosion under coffee, cocoa and tea

Soil erosion losses can be considerable in coffee plantations that have no adequate shade or a low planting density with little natural mulch formed by litter. This is especially important for coffee grown in highlands on steep slopes and in new coffee plantations. Research in Colombia showed that annual soil N losses from unprotected areas exceeded the amount extracted by a good crop of coffee, but on well developed coffee plantations that were adequately shaded or with a high planting density, erosion could be reduced to less than 2% of the losses that occurred on unprotected plots (Bornemisza, 1982).

In Venezuela, where since the mid-1970s the government has actively promoted the removal of shade trees from coffee plantations, low erosion losses were found (Ataroff and Monasterio, 1997). Under shaded coffee, total erosion losses were very low – less than 2 Mg soil ha^{-1} year^{-1} – whereas under coffee without shade, erosion losses were 7 Mg soil ha^{-1} in the first year after the shade was removed. Erosion losses of unshaded coffee after two years were comparable with shaded coffee, whereas in general, run-off and soil loss are lower in shaded than in unshaded plantations (Beer *et al*, 1998). The research in Venezuela showed that soil erosion correlated positively with agricultural activities (ie harvesting, pruning, weeding) – more people in the field: more erosion.

Under monocropping cocoa in Malaysia, soil erosion losses were 11 Mg ha^{-1} $year^{-1}$, but losses were considerably lower when cover crops were planted (Hashim *et al*, 1995). When the cocoa was intercropped with banana and clean weeding with herbicide was practised, soil losses of up to 70 Mg soil ha^{-1} $year^{-1}$ were measured, which are high when based on a general rating of tolerable soil-erosion losses (Hudson, 1986).

Soil erosion can be a problem when plantations run down. This was found to occur in Sri Lanka where tea plantations had been neglected since the mid-1970s, causing serious soil erosion of vacant patches (Botschek *et al*, 1998). Othieno (1975) reported from Kericho, Kenya, erosion losses of up to 168 Mg soil ha^{-1} in the first year after the establishment of a tea plantation. In the second year, soil losses were up to 81 Mg ha^{-1} whereas in the third year losses were less than 7 Mg soil ha^{-1}. The severe erosion accounting for three-quarters of the total erosion over the three-year period, occurred between planting and the time when the canopy had developed to about 30%.

Erosion can considerably reduce the soil chemical fertility (Lal, 1997; Ruppenthal *et al*, 1997; Zobisch *et al*, 1995). Moberg (1972) compared the soil-fertility properties of Oxisols developed from sandstone in eroded and non-eroded coffee plots and in virgin land near Lake Victoria, Tanzania. Coffee gardens where erosion occurred were more acid and had lower levels of soil fertility than non-eroded soils with coffee, the levels of which were comparable with virgin land.

Soil fertility decline

Growing agricultural crops implies that nutrients are removed from the soil through the agricultural produce (food, fibre, wood) and crop residues. Nutrient removal may result in a decline of the soil fertility if replenishment with inorganic fertilizers or manure is inadequate. A decline in soil fertility implies a decline in the quality of the soil, and soil fertility decline is defined as: the decline in chemical soil fertility, or a decrease in the levels of soil organic C, pH, CEC and plant nutrients, and includes acidification (decline in pH and/or an increase in exchangeable Al).

In the 1990s, several studies were conducted that indicated that soil fertility decline was a problem in many tropical countries, and particularly in Sub-Saharan Africa (Henao and Baanante, 1999; Pieri, 1989; Stoorvogel and Smaling, 1990). Most of these studies used the nutrient balance to assess the rate of nutrient depletion. In a recent review of soil fertility decline under plantation cropping, Hartemink (2003) used standard soil chemical data (eg pH, organic C, total N, exchangeable cations). Two types of data were used: type I data in which soils were monitored over time, and type II data in which soils under plantation crops and adjacent natural vegetation were sampled. Both data types yield insights into the changes brought about by permanent cropping. Table 3 summarizes some of the changes in soil fertility under various plantation crops.

One of the first studies investigating long-term changes under oil palm was conducted by P.B.H. Tinker in West Africa. During the first five years of the plantation, there was a marked increase in soil fertility, but thereafter K and Mg levels and the pH decreased, whereas soil organic C levels remained constant (Kowal and Tinker, 1959; Tinker, 1963). Soil changes under oil palm have been well documented in Malaysia. PORIM (1994) summarized them as follows: levels of nutrients are found to increase in the early years under oil palm after forest because of the fertilizer applications and due to the N fixation by the leguminous cover crop. Longer-term trends are less well known, but it is likely that soil nutrients decline due to palm uptake and retention exceeding fertilizer applications.

On rubber plantations in Malaysia, it was found that soil organic C levels decreased, whereas the soil reaction increased slightly after clearing due to the addition of ash, slightly decreased thereafter and remained at the same level as the forest after 16 years (Sanchez *et al*, 1985). Duah-Yentumi *et al* (1998) found at Kade (Ghana) that soil under 40-year-old rubber had significantly lower C content when compared with soils under virgin forest or 20-year-old cocoa. The pH of the soils under virgin forest and rubber was about the same, whereas the pH of Ultisols under cocoa was about 0.5 unit higher. At CATIE in Turrialba, it was found that cocoa ecosystems were able to maintain soil organic C contents (Beer *et al*, 1990). On coffee plantations in Indonesia, topsoil organic C levels were less than half of those in the soils under forest. All exchangeable cations were lower under coffee than under forest. Several studies have been conducted in Nigeria investigating the effects of growing cocoa on soil chemical properties. These studies consistently show that soil organic C equilibrium data under cocoa settle below those of soils under natural forest (Hartemink, 2005).

In many cases it is found that soil fertility under plantation crops is lower than under forest. However, the rate of decline under plantation cropping is often much lower than under annual cropping because of the higher rates of nutrient inputs and possibly because of lower losses when compared with annual crops (Hartemink, 2003).

Pollution

Few pollution studies have been conducted in developing countries where both local industries and often foreign investment have shown a general lack of appreciation of the environment (Naidu, 1998). In developing countries, environmental ethics and laws have not kept pace with the increase in biocide use (Lal *et al*, 1988). Moreover, there is a shortage of data, and the expected increase in agricultural production in developing countries is likely to cause environmental damage (Tinker, 1997). Plantation crops are often grown with high levels of agrochemical inputs such as pesticides, herbicides and inorganic fertilizers. These inputs may pollute the environment when not used judiciously, and repeated use of agrochemicals could be a point of concern, particularly with regard to heavy metal input into the soil. In addition, smoke and milling by-products (effluent) may cause pollution in the oil-palm industry, although effluent

Table 3. Changes in soil chemical properties on perennial crop plantations in the tropics.

Data type[1] and soil order	Sampling depth (m)	Crop	Period[2] (years)	pH	C (g kg⁻¹)	N (g kg⁻¹)	P (mg kg⁻¹)	CEC and exchangeable cations (mmol$_c$ kg⁻¹)				Reference
								CEC	*Ca*	*Mg*	*K*	
TYPE I												
Ultisols	0–0.15	Oil palm	10	+0.4	+0.06	–0.04	nd	nd	+0.4	+0.8	–0.35	Tinker (1963)
Ultisols	0.15–0.45	Oil palm	10	+0.2	–0.04	–0.14	nd	nd	–4.6	–2.6	–0.57	Tinker (1963)
Ultisols	0–0.15	Rubber	16	+0.1	–8.00	–0.60	nd	nd	–3.5	–0.8	–0.40	Sanchez *et al* (1985)
TYPE II												
Alfisols	0–0.10	Cocoa	7	0.6	–10.5	0	–0.5	nd	–6.0	+1.0	–1.0	Ogunkunle and Eghaghara (1992)
Alfisols	0–0.10	Cocoa	13	–1.3	–14.0	–1.5	nd	–65.0	–48.9	–11.2	–2.4	Adejuwon and Ekanade (1988)
Alfisols	0–0.15	Cocoa	50	0.0	–2.3	nd	+0.7	–21.0	–16.0	–1.0	–1.0	Ekanade (1988)
Oxisols	0–0.10	Rubber	18	–0.9	+1.2	+0.8	nd	nd	–6.0	–5.0	–1.1	Aweto (1987)
Oxisols	0.10–0.30	Rubber	18	–0.4	–1.2	+0.1	nd	nd	–2.2	–2.4	–0.1	Aweto (1987)
Ultisols	0–0.15	Cocoa	20	+0.5	–2.6	–0.4	nd	nd	nd	nd	nd	Duah-Yentumi *et al* (1998)
Ultisols	0–0.20	Coffee	20	+0.5	–31.9	–3.2	–2.5	–318	–83.7	–1.7	–1.2	Lumbanraja *et al* (1998)
Ultisols	0.20–0.40	Coffee	20	+0.1	–14.9	–1.1	–0.5	–57.0	–22.5	–5.0	+0.7	Lumbanraja *et al* (1998)
Ultisols	0–0.15	Rubber	40	<–0.1	–11.7	–1.4	nd	nd	nd	nd	nd	Duah-Yentumi *et al* (1998)

[1] Type I data: same location sampled over time; Type II: soils sampled at the same time under different land use.
[2] Period between two soil samplings.
nd = no data.
Source: Modified from Hartemink (2003).

treatment is increasing (Basiron and Darus, 1996). In a review of environmental concerns about pesticides in soil and groundwater in Oceania, there were many examples from Australia and New Zealand, but hardly any from the tropical countries in Oceania – first because they were not available (Theng *et al*, 2000), but also because pesticide use in those countries is low when compared with Australia and New Zealand.

Wilcke *et al* (1998) sampled soils under coffee and forest near San José, Costa Rica, and analysed for heavy metals (Al, Cd, Cu, Fe, Mn, Pb and Zn). The soils under coffee are subject to heavy metal inputs as a result of the regular use of fungicides and inorganic fertilizers, and possibly because of atmospheric deposition originating from the densely populated and industrialized Valle Centre surrounding San José. Cadmium, Pb and Zn concentrations in all soils were low or comparable with background concentrations in temperate soils. Total Cu concentrations were high in soils under coffee, but were also high in soils under forest. It was concluded that the influence of the parent material on the metal concentrations in the soil was more pronounced than that of agrochemical inputs (Wilcke *et al*, 1998).

Although the Costa Rica study showed no marked increase in heavy metals in soils under coffee plantations, it is likely that the continuous use of agrochemicals will result in a build-up of heavy metals comparable with some of the problems encountered in soils under high-input temperate agriculture (Tinker, 1997). Some recent research on banana plantations in Costa Rica has shown that fungicides, nematicides and insecticides were present in surface waters and sediments near the plantation (Castillo *et al*, 2000). Also, research on tea plantations near Kyushu, Japan, showed that the heavy use of inorganic fertilizers on the plantations markedly increased nitrate and sulphate in neighbouring river waters (Ii *et al*, 1997). The rates of pesticide accumulation and nitrate leaching and their environmental impact are different in the humid tropics because of the longer growing season, higher temperatures, etc, which affect many soil processes.

Carbon sequestration

Many plantation crops are woody species such as rubber, cocoa and oil palm, and it has been suggested that such plantation crops, as opposed to annual crops, sequester carbon (Aweto, 1995; Pushparajah, 1998). In Malaysia it has been estimated that the net fixation of C by oil palm can be equivalent to that of a lowland rainforest. The total above-ground C stock of mature oil palm is about 100 Mg ha⁻¹, whereas the above-ground biomass of the rainforest is three to four times larger (Henson, 1999). However, at the end of the crop cycle most of the C in the oil-palm vegetation will be released when the trunks are burned or decomposing. Rubber is a slightly different story, as an increasing amount of rubber wood is used for industrial and other purposes so that the C fixed in the wood is not immediately released at the end of the crop cycle. So whether there is net C sequestration at plantations depends on the observational period: over one cropping cycle there may be net sequestration, but over more cropping cycles there may be little effect. Much depends on the amount of C stored in the soil, and on the previous land use. As mentioned, when perennial crop plantations are compared with rainforest, there is a loss of carbon, but when imperata grasslands, which are quite extensive in South-east Asia (Menz *et al*, 1998; Santoso *et al*, 1996), are planted with rubber or oil palm there is often net C sequestration.

In many parts of Malaysia, Sabah and Kalimantan, new oil-palm plantings are increasingly being made on peatland (Histosols). Tropical peatlands constitute one of the largest near-surface reserves of terrestrial organic C (Page *et al*, 2002). Clearing and draining peatland causes much subsidence (Wosten, 1997) and the decomposition of the peat emits large quantities of CO_2, which is considered a major greenhouse gas. Large areas of peatland have been cleared in South-east Asia, and it has been estimated that in some years up to 40% of the world annual C emission is due to peat and forest fires (Page *et al*, 2002).

It seems that C sequestration by agricultural plantations is an area with little hard data. Long-term data are needed that take into account changes in land use and many other factors that affect C storage in the soil and vegetation (Falloon and Smith, 2003; Hartemink, 2003). It has been suggested that a reduction in deforestation yields much greater benefits for a reduction in CO_2 emissions than expanding plantation silviculture, but deforestation reduction is much more uncertain (Fearnside, 2000).

Biodiversity

Crop monocultures are often regarded as unnatural, ecologically dysfunctional, and a threat to sustainable agriculture (Wood, 2000). In nature, however, there are also many productive monocultures, although they seem to occur in marginal or undisturbed conditions, one example being the large area of imperata grasslands in South-east Asia. A common objection to plantations, which are mostly crop monocultures, is that they contain a low diversity of wildlife as compared with natural forests (Cannell, 1999). Monoculture systems restrict habitat and favour only a very restricted number of co-habiting species. Biodiversity receives increasing public and political concern (Gowdy and McDaniel, 1995; Morin, 2000) and in many cropping systems biodiversity has been reduced, whereas productivity has remained high (Anderson, 1994).

Research conducted in Malaysia showed that 75 species of mammals were found in primary forest, but fewer than 20 species were found in oil-palm or rubber plantations (PORIM, 1994). Biodiversity conservation at the expense of agricultural development and poverty alleviation is a difficult discussion. The biggest threat to biodiversity is, however, the loss of habitat through the expansion of the plantation area (Tinker, 1997). Currently, South-east Asian farmers and companies are exploiting the oil palm to the limit by converting forests, with all their biodiversity, to plantations for profit. The smoke clouds from the burning rainforests are the downside of a successful industry (Henderson and Osborne, 2000).

Trends in crop yields

Productivity on many of the older plantations was low because of low-yielding planting material, erosion resulting from clean weeding, little or no use of inorganic fertilizers, and poor crop-husbandry practices. Moreover, many of the rubber and oil-palm plantations in, for example, Nigeria are situated on poor soils because no soil surveys were conducted before the land was planted (Saylor and Eicher, 1970). There are several examples of historical failures in plantation development. The failure of Danish plantations in the former Gold Coast Colony of Ghana was largely due to the unsuitable climate and soil conditions (Breuning-Madsen *et al*, 2002).

Table 4. Perennial crop yields (kg ha^{-1} $year^{-1}$) for the 1930s and 1980s under good management and conditions on plantations.

Crop	1930s	1980s	% change 1930s–80s
Rubber (dry rubber)	500	2,000	+300
Palm oil (oil)	2,000	5,500	+175
Coconut (copra)	1,500	3,000	+100
Cocoa (dry beans)	900	2,200	+144
Coffee (dry, clean beans)	1,000	2,200	+120
Tea (dry leaf)	1,000	3,000	+200

Source: data from Webster and Watson (1988).

Webster and Watson (1988) have compiled plantation yields for perennial crops (Table 4). Yields of coffee, cocoa and tea tripled between the 1930s and 1980s. The main technical advances that have contributed to these higher yields are improved planting material and nursery techniques, improved pest and disease control, soil-conservation measures and leguminous ground covers, chemical weed control, improved diagnosis of crop nutrient requirements by leaf and soil analysis, and field experiments leading to better use of inorganic fertilizers. The yield data in Table 4 are from plantations under good management and conditions. Not all plantations achieve the yields given in the table, partly because they are not fully replanted with modern planting material (Webster and Watson, 1988).

Yields for the major perennial crops between the 1950s and 1990s are shown in Table 5. Yield data were calculated as total annual production divided by the area under the crop from FAO databases, and the table shows 10-year averages. Yield increases were considerable for tea, coffee, cocoa and the oil palm in Africa, but the most spectacular yield increase occurred in the oil palm in Asia.

Yield differences with smallholders

A growing proportion of perennial crop cultivation is in the hands of smallholders, and the firm distinction between plantation and smallholder agriculture formed

Table 5. Perennial crop yields (kg ha^{-1} $year^{-1}$) for different periods.

	Tea	Coffee	Cocoa	Oil palm	
Period				*Africa*	*Asia*
1949–59	640	384	229	932	236
1960–69	769	451	307	1,135	391
1970–79	768	493	343	1,245	1,718
1980–89	867	524	373	1,466	5,519
1990–96	1,072	549	439	1,782	11,095
% change, 1950s–90s	+68	+43	+92	+91	+4,601

Source: based on FAO data provided by W. Stephens (Cranfield University, personal communication, 2000). Annual yield data were averaged for periods of 10 years (Hartemink, 2003).

Table 6. Plantation and smallholder yields (kg ha^{-1} $year^{-1}$) in various countries.

Country	Crop	Plantation	Smallholding	% difference
Côte d'Ivoire	Oil palm (fresh fruit)	10,200	5,800	76
Kenya	Coffee	1,078	633	70
	Tea	2,000–3,500	1,000–1,400	43–250
Tanzania	Tea	3,000	500	500
Sri Lanka	Rubber	1,000	450	122
	Tea	900	700	29
Malaysia	Rubber	1,300–1,600	800–900	44–100
	Cocoa	1,080	850	27
	Copra	2,000	900	122
	Oil palm (fresh fruit)	24,100	15,700	54
Indonesia	Rubber	1,190	530	125
	Coconuts	960	960	0
	Cocoa	580	160	263
	Coffee	580	380	53
	Tea	1,410	480	194
	Oil palm	3,940	1,180	234
Papua New Guinea	Rubber	500–600	200–600	0–200
	Coconut	900	500	80
	Cocoa	440	330	33
	Coffee	2,000	700	186
	Oil palm (fresh fruit)	21,500	11,900	81

Source: compiled from data in Goldthorpe (1985), Barlow and Tomich (1991) and Stephens *et al* (1998). Yield data were mostly from the 1980s and could be substantially higher nowadays (Hartemink, 2003).

during the colonial period has disintegrated (Tiffen and Mortimore, 1988). Crops are grown as monocrops or incorporated in mixed-cropped homegardens. Examples of smallholder perennial crops are the cultivation of cocoa and oil palm in West Africa, tea in Kenya, rubber in Indonesia, Malaysia, Thailand and Sri Lanka, and cashew in Tanzania (Ruthenberg, 1972; Watson, 1990; Webster and Wilson, 1980).

For most crops and in most countries, yields on plantations are twice as high as on smallholder fields, but differences between plantation and smallholder yields can be as high as 500%. They are generally smaller if proper extension and training is given to smallholders in the cultivation of perennial (plantation) crops. In many areas, smallholders' stands of perennial tree crops consist of old stands of inherently low-yielding unselected seedlings (Webster and Wilson, 1980). At establishment there was poor crop husbandry (no weeding; no fertilizer use; erosion), and after the trees reached maturity, lack of equipment, inputs or skill was another important cause of low yields. Cash crops may be neglected at certain seasons when priority is given to food crops, and the young people may have migrated to towns, leaving only those too old to work effectively (Webster and Watson, 1988). Another reason for the yield gap might be that plantations are situated on better soils compared with the surrounding smallholders, and that more inorganic fertilizers and other inputs are being used.

There are exceptions to this pattern, such as the smallholder sugar growers of Cuba, whose yields are reported to be higher than those of the government-owned estates. In Malaysia, high oil-palm and rubber yields, comparable with the yields obtained on plantations, are obtained by trained and supervised smallholders. There has also been evidence that smallholders produce at least as much or more output per hectare than large plantation farms, and this lower productivity of plantations is due to underuse of the land (Tiffen and Mortimore, 1988). See Table 6 for plantation and smallholder yields.

Discussion

This paper reviewed some of the major environmental issues related to plantation agriculture in the tropics. Hard data on soil erosion losses collected over many seasons and in different regions are scarce. Most papers reiterate that soil erosion under perennial crops is relatively low, provided the crops are well managed. Measured data show that erosion could be high in oil palm (PORIM, 1994), cocoa (Hashim *et al*, 1995) and tea (Othieno, 1975) – particularly during establishment. However, soil erosion under tree-crop systems is often a fraction of the erosion under annual crops. Agroforestry research has accumulated considerable evidence confirming lower erosion in land-use systems with tree crops than research with perennial plantation crops (Sanchez, 1995; Young, 1997). Under the same agro-ecological conditions, land-use systems with perennial crops form better protection against soil erosion than annual crops, simply because they cover the soil the whole year through. Erosion is lower under mature crops than in young plantings because of the complete ground cover, but harvesting paths and open patches in mature plantations may result in high soil erosion losses.

Changes in soil chemical properties under perennial crops were found to be different for different crops. This is related to the fact that soils, crops and climates were different. Nevertheless, a slight decline was found in most soil chemical properties and in most soils. Various studies indicated that the original C and N levels under natural forest are not attained again in perennial cropping systems, although levels of P and exchangeable cations, in particular K, may be much higher in soils under perennial crops due to the use of inorganic fertilizers. The change in soil chemical properties may reflect the decrease in nutrient stocks of the soil, but it also reflects immobilization of nutrients in the biomass. Therefore it is more difficult to assess soil fertility decline and its causes in perennial crops than in annual cropping systems. Again, rates of soil fertility decline under annual cropping systems are often much higher than under perennial crops (Hartemink, 2003). This is related to the fact that leaching losses under perennial plantation crops are consistently smaller than under annual crops. Tree crops grow the whole year, whereas in annual cropping there may be periods when there is no crop or the crop is either too young or old to take up nutrients from the soil solution. Tree crops generally provide a 'safety net', but an adequate supply of all nutrients for a dense root mat is essential to reduce nutrient leaching and to enable deep uptake of leached nutrients (van Noordwijk and Cadisch, 2002).

In Western Europe, North America and Australia there is public concern over the environmental impact of agriculture. But environmental awareness is also on the increase in many developing nations. This review has shown that plantation cropping has environmental effects, and in some cases the environmental quality has been lowered. Amongst other factors, this will sooner or later affect production and thus reduce the export and income of a country, because plantation agriculture is a major contributor to the income of many countries in the tropics and provides hundreds of thousands of people with labour and income (Hartemink, 2003). Sustaining and improving the production capacity of agricultural plantations is therefore important, and maintenance of the soil resources is a key issue for sustainable production.

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