AN ASSESSMENT OF CHANGES IN BIOMASS CARBON STOCKS IN TREE CROPS AND FORESTS IN MALAYSIA

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Received December 2003

HENSON, I. E. 2005. An assessment of changes in biomass carbon stocks in tree crops and forests in Malaysia. This study assesses changes in the biomass carbon stocks of forests and tree crops in Malaysia during the period 1981 to 2000; a time of rapid expansion in oil palm cultivation. Peninsular Malaysia and the East Malaysian states of Sabah and Sarawak are considered separately. Changes in the planted areas of oil palm, other tree crops (rubber, cocoa, coconut) and forests are presented, as are changes in the total biomass of each vegetation type as estimated from the product of area and biomass density. Although oil palm area increased progressively in all three regions, total forest plus tree crop area was reduced in 2000 compared with 1980 by 0.87 million ha, thus perpetuating a historical trend. The decline was gradual in Peninsular Malaysia but more erratic in the East Malaysian states. The effect of various assumptions on the outcomes of the analysis and the implications for carbon emissions and total carbon balance are discussed, and the contribution of oil palm in reducing potential carbon emissions is evaluated.

Key words: Oil palm – rubber – coconut – cocoa – forest – carbon emission

HENSON, I. E. 2005. Penilaian perubahan stok karbon biojisim dalam pokok tanaman dan hutan di Malaysia. Kajian ini menilai perubahan stok karbon biojisim dalam hutan dan pokok tanaman di Malaysia dari tahun 1981 hingga tahun 2000 yang merupakan tempoh perkembangan pesat penanaman kelapa sawit. Semenanjung Malaysia dan Sabah serta Sarawak di Malaysia Timur dikaji secara berasingan. Perubahan di kawasan yang ditanam kelapa sawit, pokok tanaman lain (getah, koko dan kelapa) dan hutan diberi dalam kertas kerja ini. Begitu juga dengan data jumlah biojisim setiap jenis tanaman seperti yang dianggarkan daripada hasil darab luas kawasan dan ketumpatan biojisim. Walaupun kawasan kelapa sawit meningkat secara berperingkat-peringkat di ketiga-ketiga kawasan, jumlah kawasan hutan dan tanaman pokok berkurangan sebanyak 0.87 juta ha pada tahun 2000 berbanding tahun 1980. Penurunan ini beransur-ansur di Semenanjung Malaysia tetapi lebih tidak menentu di Malaysia Timur. Kesan pelbagai tanggapan terhadap hasil analisis dan implikasi untuk pelepasan karbon serta imbangan jumlah karbon dibincangkan. Selain itu, sumbangan kelapa sawit dalam mengurangkan pelepasan karbon dinilai.

Introduction

The area occupied by oil palm (*Elaeis guineensis*) in Malaysia has expanded rapidly such that in the year 2000 about 10% of the country was covered by the crop, representing 56% of the agricultural land area, thus dominating any other single agricultural activity (MPI 2001). In the early years of plantation development large areas of forest were cleared to establish plantations, e.g. especially in the west coast

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of the peninsula, this being the most fertile and productive area. More recently, oil palm has been planted extensively in parts of East Malaysia on newly cleared forest land. Generally, recent oil palm planting has replaced logged, degraded and secondary forests. Further oil palm expansion has occurred by the replacement of other tree crops such as rubber (*Hevea brasiliensis*), coconut (*Cocos nucifera*) and cocoa (*Theobroma cacao*), as these have become less profitable than oil palm.

Changes in landuse have implications for carbon cycling through emission of CO_2, a major greenhouse gas, to the atmosphere. Worldwide, forest denudation is seen as an important contributor to the rise in atmospheric CO_2 levels. Primary rain forests have gradually accumulated carbon over centuries in both the vegetation and the soil. Much of this has been released following clearance or disturbance by logging or slash and burn agriculture (Anderson & Spencer 1991, Tinker *et al.* 1996, FAO 2000). The quantities of carbon contained in primary forests in Southeast Asia have been itemised in detail for relatively few sites (e.g. Anderson & Spencer 1991, Okuda *et al.* 2003), but the total carbon stocks can be substantial, not only in the vegetation but also in the soil (Chan 1982).

This paper examines the likely changes over the past two decades in total biomass, and hence carbon storage, of Malaysian forests and the major tree crops grown in Malaysia. In this time the oil palm planted area has expanded from 1.02 million ha to over 3.38 million ha while forested areas and areas of rubber and other tree crops have, in general, declined. As there are some differences in the area changes between Peninsular Malaysia and the East Malaysian states of Sabah and Sarawak, each of these was treated separately.

The study does not deal with all vegetation types to be found in the country. However, other agricultural crops and non-forest natural vegetation have a much lower biomass density than the 'tree' crops while changes in their areas will be relatively small.

Materials and methods

Areas

Data on areas planted with oil palm were obtained from MPOB (2001) while the areas of rubber and coconuts were obtained from MPI (2001 and earlier editions) or DOS (1999 and earlier editions). Areas for cocoa were as given on the April 2002 website of the Malaysian Cocoa Board (Malaysian Cocoa Board 2002).

The forest areas were taken from four sources, namely, MPI (2001 and earlier editions), DOS (2000 and earlier editions), Molofsky *et al.* (1986) and the FAO website (FAO 2002). Data from FAO (2002) were available only for certain years and were used for verification only. An FAO estimate quoted by Molofsky *et al.* (1986) was used for the 1980 forest area in Sabah (see Discussion). Otherwise, where available, DOS data were used in preference to MPI data since the former were more precise (the forest areas in MPI are generally given to the nearest 10 000 ha only). A further reason for the use of DOS rather than MPI data was the occurrence of some inconsistent values in the MPI datasets for Sarawak.

Standing biomass

The total biomass of each vegetation type was estimated from the product of area and biomass density where the density includes provision for both roots and shoot. For oil palm, the biomass density was derived as described previously (Henson 2003) with mean biomass densities being calculated for each year based on the age distribution, with separate calculations for Peninsular Malaysia, Sabah and Sarawak.

For rubber, the mean biomass of mature stands obtained by Yew (2000) was used. This was taken to represent the biomass at clearing. Biomass prior to this was not required for the calculations as only the changes in biomass since 1980 were considered and the area of rubber has been declining since this time. Any possible replanting of rubber or its replacement prior to it reaching 'maturity' (i.e. normal age for clearing) was ignored.

For cocoa and coconut, the biomass estimated for mature stands was also used. Assessing biomass for these crops was more problematic, especially for cocoa, as the area of this crop both increased and decreased over the period. Furthermore, there were few available data on biomass. For cocoa, the biomass at seven years was calculated from the data of Thong and Ng (1980) and doubled for stands at clearance. For coconut, a value of 80 tonnes ha^{-1} was adopted. Due to these assumptions the calculated changes in biomass for these two crops are indicative only. However, the overall results are little affected as the estimated maximum contribution to changes in the total biomass of tree crops and forest was less than 4.6% for cocoa and less than 2.7% for coconut.

Estimates of Malaysian forest biomass have been made in several publications. In this study the changes in mean biomass density were calculated by extrapolating the long-term trend in biomass carbon density presented by Richards and Flint (1994). Their value for 1980 of 239 tonnes ha^{-1} is very close to the mean density estimated for the same year for Malaysian logged forest by Hall and Uhlig (1991). Similar estimates of 223 tonnes ha^{-1} and 250 tonnes ha^{-1} were deduced for Peninsular Malaysia by Brown *et al.* (1991, 1993). Effects of the reduction of density over time using the Richard and Flint (1994) trend were compared with both the use of a slower rate of density decline and with the effect of assuming a constant density.

Although the soil can contain as much or even more carbon than the vegetation (Chan 1982, Brown *et al.* 1993), changes in the soil and soil surface organic carbon were not assessed as insufficient local data were available to determine the long- term impacts of landuse change on these components.

Allowance for harvested biomass

Loss of standing biomass may be offset by long-term carbon storage, either as harvested material or carbon sequestered in soil organic matter. The main products of relevance here are harvested logs from forests and rubber plantations. The biomass conserved in the form of rubber-wood logs was estimated as 56% of the biomass at clearance (24–30 years after planting) (Yew 2000). Biomass conserved as forest logs was calculated from the log production volume data (MPI 2001 and earlier) assuming a specific density of 0.57 (Chan 1982). Other forms of harvested biomass, such as oil palm fruit bunches, are likely to have only a limited lifetime and were not included in the analysis.

Calculation of carbon sequestration and emission

The balance between carbon gains and losses (given in Mt $year^{-1}$) was calculated assuming a mean carbon content of biomass of 45% (Chan 1982, Yew 2000).

Results

Area and biomass changes

Peninsular Malaysia

Changes in the areas of oil palm, other tree crops and forest are shown in Figure 1. While the area occupied by oil palm increased considerably over the 20-year period, other tree areas, with the exception of cocoa, showed consistent reductions. However, the area of cocoa also declined in the later years.

The increase in oil palm area was initially greater than the recorded declines in areas of other tree crops and forest, implying that other categories of land must have been utilised. However, from 1996 onward the increased oil palm area balanced that released due to clearance of forest and other tree crops.

The biomass changes are shown in Figure 2, from which it is apparent that there has been an overall loss of biomass even after allowing for stable product biomass (forest logs and rubber wood), as losses, mainly in forest biomass, outweighed gains due to oil palm. Biomass loss was slow during the first decade but accelerated in the second decade with the decline in forest biomass density contributing substantially to the overall loss.

Sabah

The changes in the areas of oil palm, other tree crops and forest are shown in Figure 3. A different pattern is evident from that of Peninsular Malaysia. None of the tree crops show any substantial reduction in area over the period while cocoa showed appreciable gains in the late '1980's. Only forest showed a substantial decline and most of this was accounted for by the high starting value in 1980. (The decline would have been even greater had the MPI area for 1980 been used instead of the FAO estimate; see Discussion.) There was also a steady decline in area of forest from 1987 to 1995.

In Figure 3(b) it can be seen that initially, there was no shortage of land available for oil palm as a consequence of the large initial decline in forest area, despite increases in the other tree crops. However, from 1998 onwards there was an apparent shortage as indicated by the positive 'difference' values. Assuming the area data to be correct, oil palm would have had to be planted on other land such as land released by forest clearance in earlier years but not utilised for tree crops. The biomass changes are shown in Figure 4. In Sabah, the changes in forest biomass

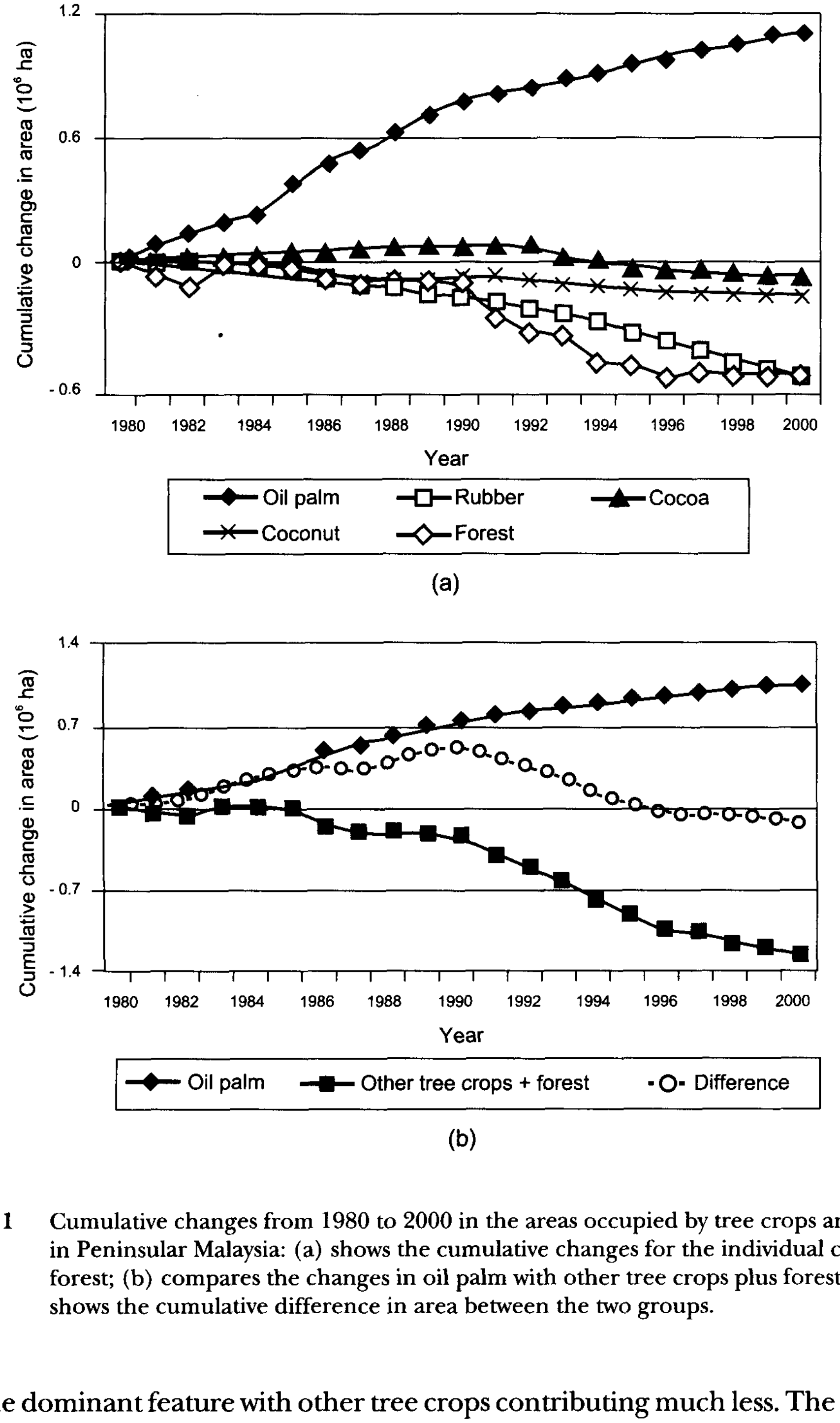
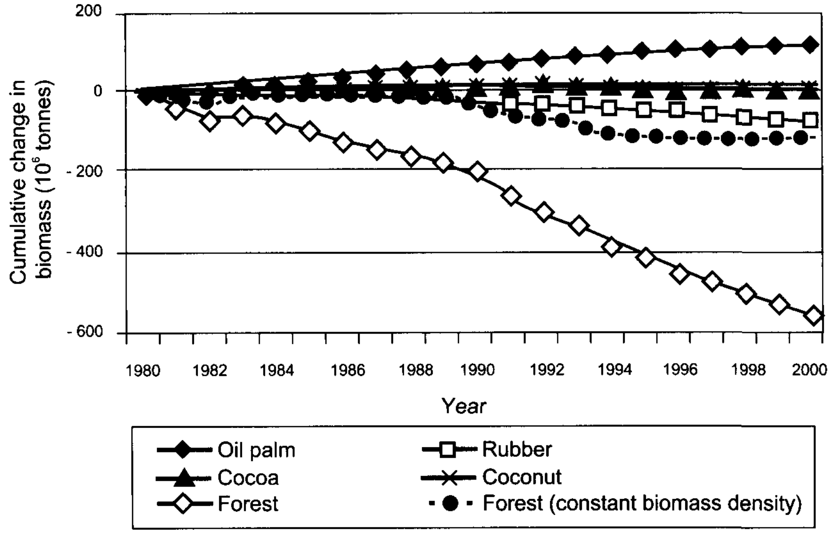


Figure 1 Cumulative changes from 1980 to 2000 in the areas occupied by tree crops and forest in Peninsular Malaysia: (a) shows the cumulative changes for the individual crops and forest; (b) compares the changes in oil palm with other tree crops plus forest and also shows the cumulative difference in area between the two groups.

were the dominant feature with other tree crops contributing much less. The pattern of biomass loss is largely governed by the area changes so the initial rapid fall is heavily dependant on the initial starting value.

Sarawak

The changes in the areas of oil palm, other tree crops and forest are shown in Figure 5. As for Sabah, but unlike Peninsular Malaysia, none of the tree crops showed any substantial reductions in area over the period while the small cocoa area increased in the late 1980's prior to a fall. Forest showed an abrupt decline between 1989 and 1990. However, it is probable that this sudden 'decline' was a result of the preceding area data being overestimates. Nevertheless, the long-term (20 years) trend indicated a substantial decline that has yet to be filled by planting tree crops.



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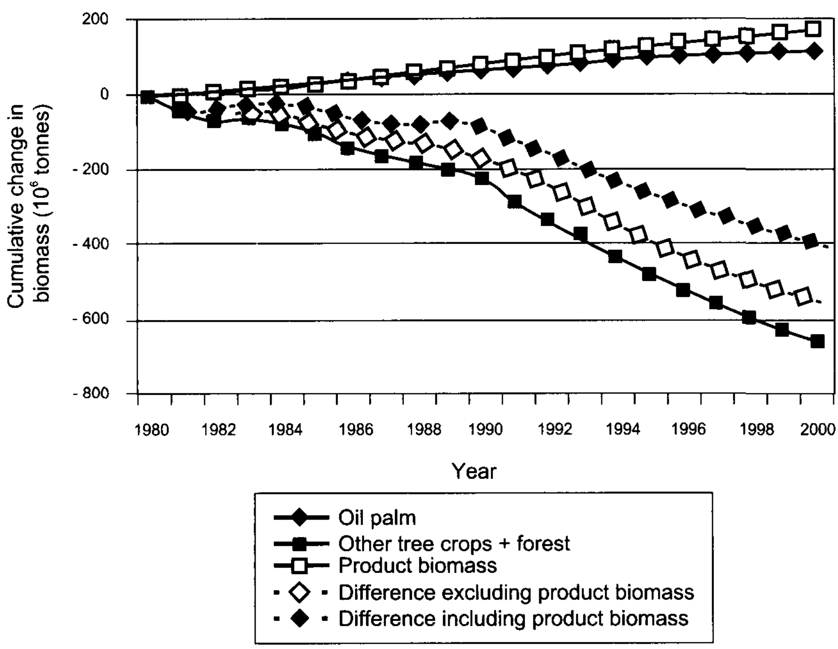

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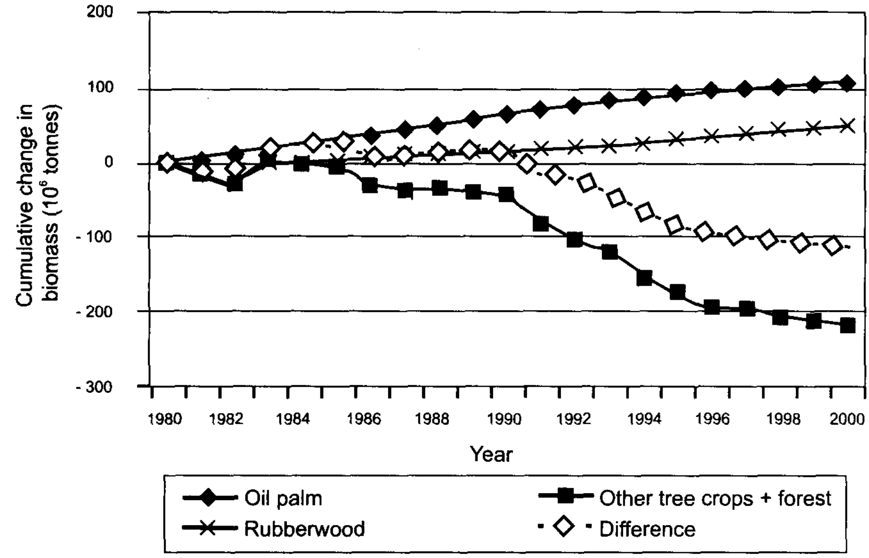


(c)

Figure 2 Cumulative changes from 1980 to 2000 in estimated biomass of tree crops and forest in Peninsular Malaysia: (a) shows the cumulative changes for individual crops and forest with and without allowance for a change in biomass density; (b) compares the cumulative changes in oil palm and product biomass with the cumulative biomass changes of other tree crops plus forest and also shows the difference between the positive and negative changes with and without allowance for the product biomass; (c) compares the cumulative biomass changes in oil palm and other tree crops plus forest assuming no change in forest biomass density (and hence no allowance made for biomass retention in logs) together with the yield of rubberwood and the difference between cumulative biomass gains and losses.

The biomass changes in Sarawak are shown in Figure 6. As with Sabah, the biomass changes in Sarawak were dominated by forest and showed the effect of the abrupt change in area in 1990 referred to above. However, there was no such abrupt change in the curve for log production (Figure 6b).

Total biomass changes and carbon release

Figure 7 shows the total loss of biomass carbon over the two decades arising from changes in tree biomass (tree crops plus forest). These data were calculated with allowance for changes in both the forest biomass density, as described above, and the carbon storage in product biomass (the 'standard case'). Calculations were also performed assuming either a reduced rate of change or no change in forest biomass density and for Sabah, the effect of using differing starting values of forest area was also assessed. The results are summarised in Tables 1 and 2.

Using the 'standard case' assumptions, a mean carbon emission of 33.4 Mt year^{-1} was calculated for Malaysia as a whole between 1981 and 2000. This figure is, however, highly dependent on the assumed rate of forest biomass density reduction and, in the absence of any change in the biomass density, the emissions are reduced to about a third of this value.

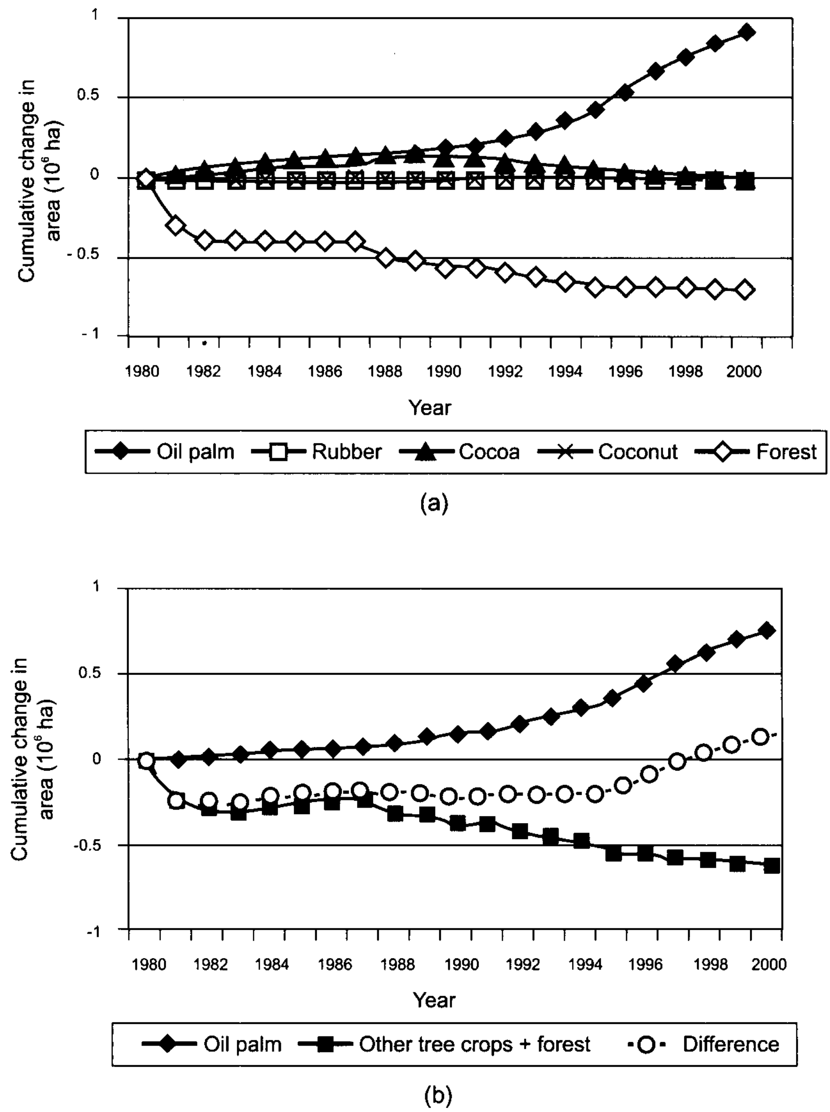
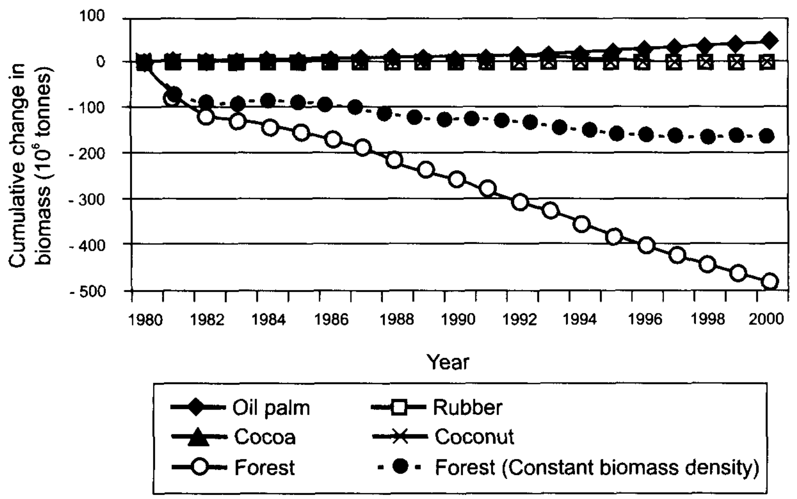


Figure 3 Cumulative changes from 1980 to 2000 in areas occupied by tree crops and forest in Sabah: (a) shows the cumulative changes for the individual crops and forest; (b) compares the cumulative changes in oil palm with other tree crops plus forest and also shows the difference in area between the two groups.

Except in the case of zero biomass change, the emissions showed an accelerating trend, being greater in the second than in the first 10-year period. Of the three regions, Sarawak contributed most to the emissions. In Peninsular Malaysia, positive values representing the sequestration of carbon were obtained during the first decade, by assuming modest or zero rates of change in forest biomass density.

Effect of oil palm planting on carbon release

To assess the impact on carbon release of replacing forest with oil palm as opposed to no replacement crop, carbon stocks in oil palm were discounted when calculating total emissions in the latter case. The effect was also examined of replacing oil palm with a relatively low biomass annual crop. The results of the first exercise, given in Table 3, show an overall reduction due to oil palm in average annual carbon emissions of almost 10% over the 20-year period. By contrast, substitution of oil palm by an annual crop, with an assumed mean standing biomass of 10 tonnes ha^{-1}, resulted in an overall reduction in total carbon emissions of less than 1%.



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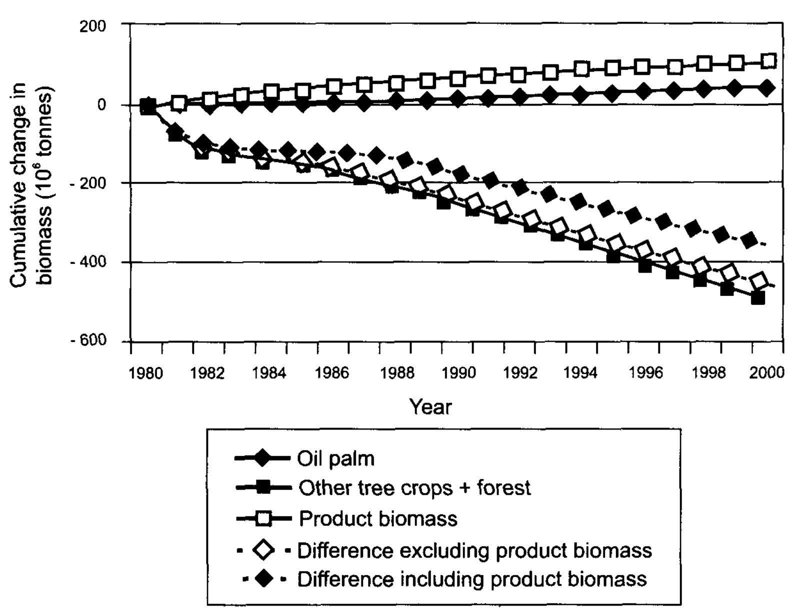

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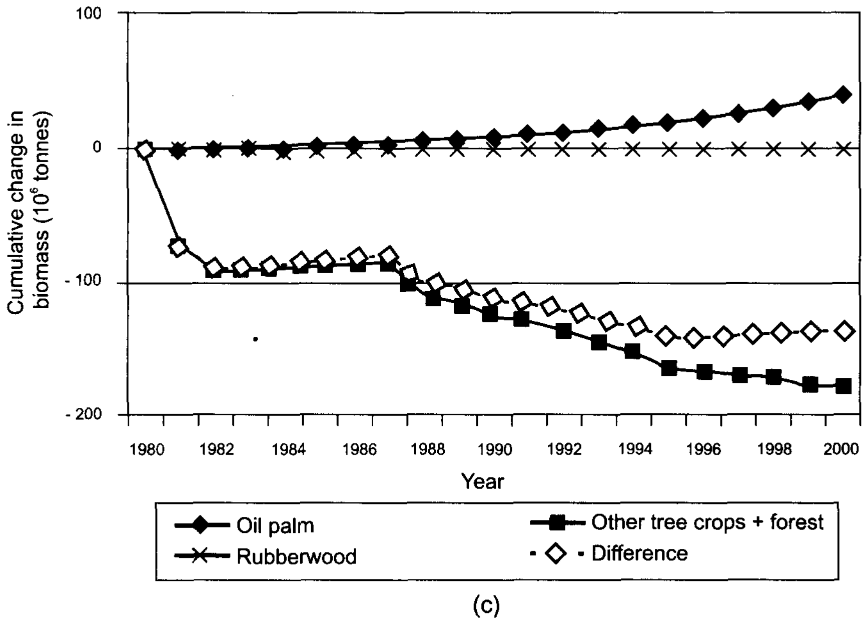


Figure 4 Cumulative changes from 1980 to 2000 in estimated biomass of tree crops and forest in Sabah: (a) shows the cumulative changes for the individual crops and forest with and without allowance for a change in biomass density; (b) compares the cumulative changes in oil palm and product biomass with biomass changes in other tree crops plus forest and also shows the difference between the positive and negative changes with and without allowance for product biomass; (c) compares the cumulative biomass changes in oil palm with other tree crops plus forest assuming no change in forest biomass density (hence no allowance for biomass retention in logs) together with the yield of rubber wood and the difference between biomass gains and losses.

Discussion

This study represents only an initial attempt to assess the recent impacts on carbon stocks and release from biomass which has taken place in association with a phase of rapid expansion of the oil palm area in Malaysia. The results can only be considered tentative in view of uncertainties concerning certain of the input data, especially for forest areas and biomass. Nevertheless it was felt that the effort was justified in order to provide a first approximation and to indicate where improvements in information can lead to a more accurate picture. The following discussion will focus on the main areas of contention.

Vegetation types

The study has mainly dealt only with forest and tree crop biomass while other forms of vegetation have been ignored. However, forests and tree crops continue to occupy about 75% of the land surface area in Malaysia and in 2000, tree crops (oil palm, rubber, cocoa, coconuts together with very minor contributions from tea and coffee) constituted about 87% of the area occupied by major agricultural

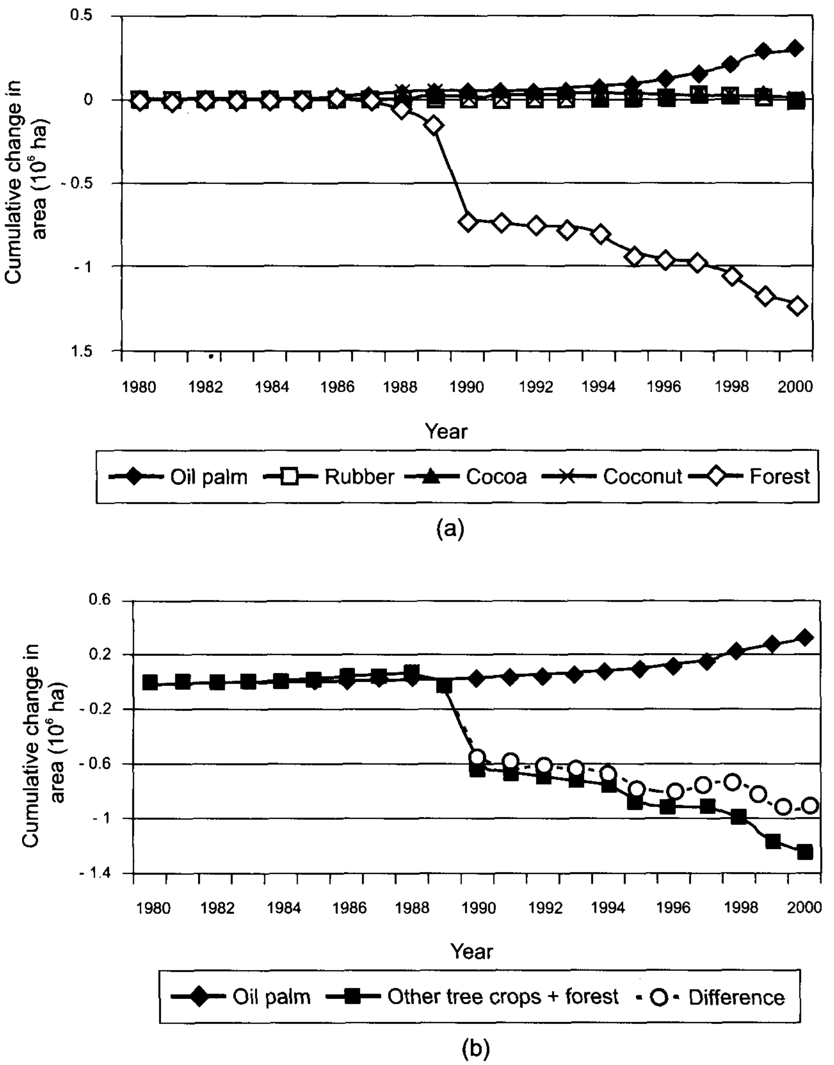


Figure 5 Cumulative changes from 1980 to 2000 in the areas occupied by tree crops and forest in Sarawak: (a) shows the cumulative changes for the individual crops and forest; (b) compares the cumulative changes in oil palm area with the area of other tree crops plus forest and also shows the difference in area between the two groups.

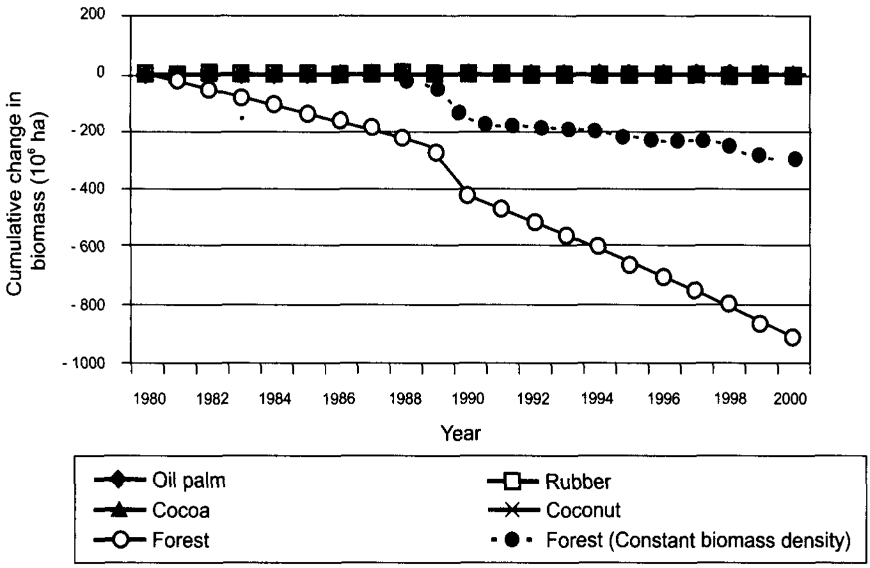
crops; the only other crop of significance being rice. In terms of biomass, forests and tree crops would be even more dominant, given their high biomass densities in comparison with values likely for non-arborescent vegetation.

Area data

There is inevitably some uncertainty in the area estimates used for the calculations. This was particularly so for forest in East Malaysia with even the local official sources differing in the data presented. It is likely that this situation could be remedied in future by the use of satellite images but there will still be doubt concerning the historical trends.

Biomass

Assumptions were necessary with regard to biomass densities. Oil palm biomass density was calculated using a detailed model as described by Henson (2003), which took account of the changes in the oil palm age profile. However, insufficient



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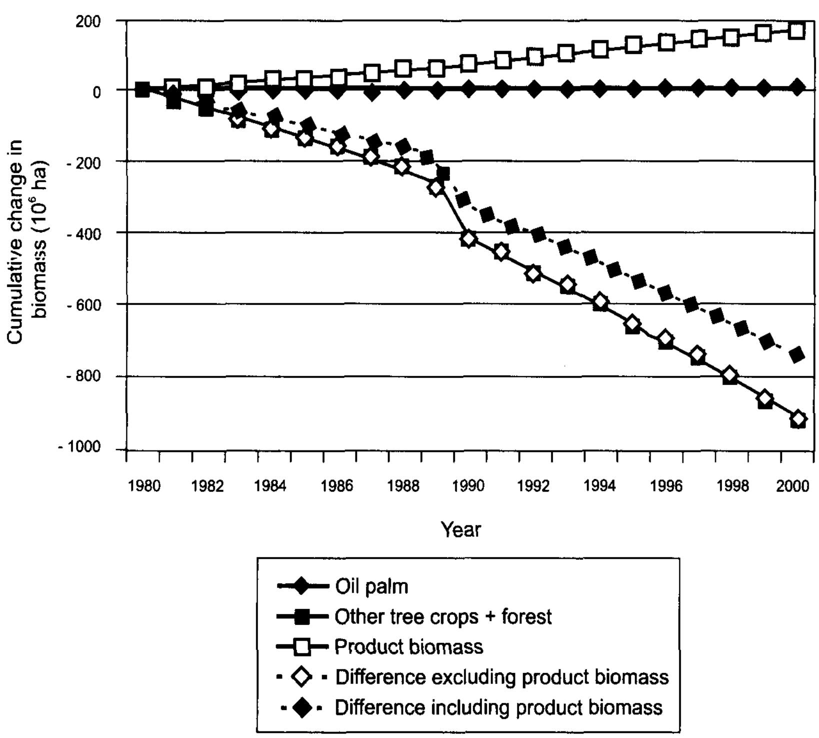

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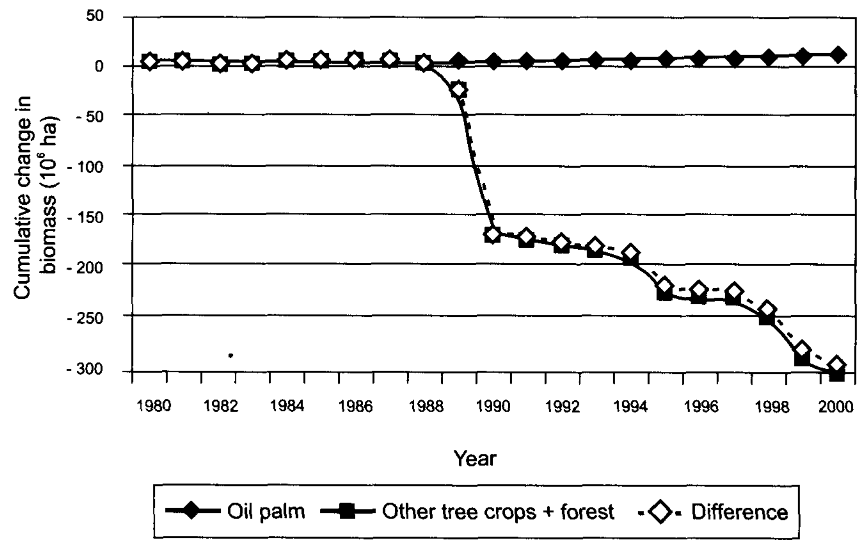

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Figure 6 Cumulative changes from 1980 to 2000 in the estimated biomass or tree crops and forest in Sarawak: (a) shows the cumulative change for individual crops and forest with and without allowance for changes in the biomass density; (b) compares the cumulative changes in oil palm and product biomass with the biomass changes of other tree crops plus forest and also shows the difference between the positive and negative changes with and without allowance for product biomass; (c) compares the cumulative biomass changes in oil palm and other tree crops plus forest assuming no change in the forest biomass density (and hence no allowance has been made for biomass retention in logs) together with the difference between biomass gains and losses. N.B. There was no appreciable rubberwood production in Sarawak.

data were available to allow this approach to be used with the other crops. For rubber in Peninsular Malaysia, it was sufficient to use a final biomass estimate at clearance since the rubber area has declined steadily and it was reasonable to assume that these reductions largely comprised mature plantings at the end of their economic life, which were being cleared for other crops such as oil palm. A similar assumption would be valid for the declines in cocoa and coconut areas. However, the cocoa and coconut areas increased transiently in Sabah and Sarawak in the late 1980's so that their biomass density was probably overestimated due to new plantings. In general, however, this had little overall impact due to the relatively small areas involved. Thus, a reduction in estimated cocoa biomass density by 50% reduced the mean carbon emissions by less than 1% (results not presented).

Forest biomass is difficult to assess both due to the different types of forest and the varying factors affecting their mean biomass density. There is, however, a general consensus that the biomass density of most forests in the world has undergone a progressive decline over the past century due to human interference. Population density is one factor used in current biomass models (e. g. Brown *et al.* 1993). In the present study, the standard case scenario used the long-term data for Malaysian

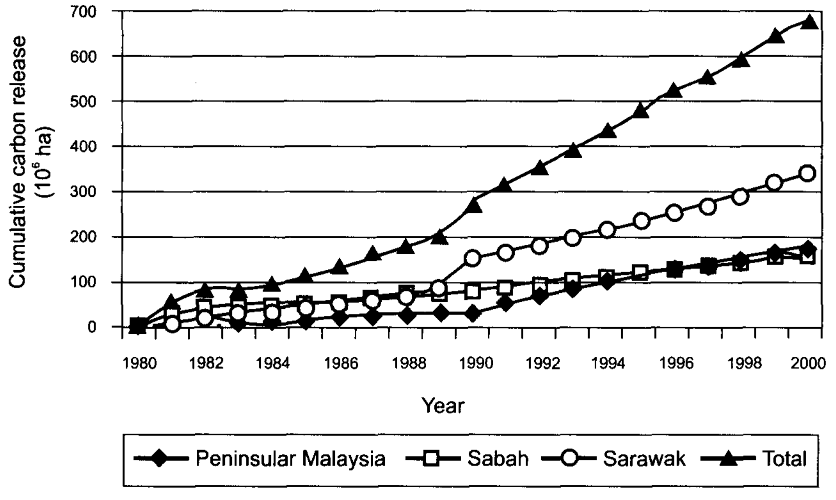

Figure 7 Estimated cumulative carbon release due to changes in tree biomass in Malaysia between 1980 and 2000 using 'standard case' assumptions

Table 1 Carbon release or sequestration due to changes in tree biomass in Malaysia between 1981 and 2000 using 'standard case' and alternative assumptions. Sequestration of carbon is indicated by negative figures in bold.

Assumptions	Period	Carbon release/sequestration (Mt year^{-1})			
		Peninsular Malaysia	Sabah	Sarawak	Total
Standard case [1]	1981–1990	3.64	8.15	15.10	26.89
	1991–2000	14.40	7.56	18.01	39.97
	1981–2000	9.02	7.86	16.55	33.43
Half rate of forest	1981–1990	**- 0.31**	5.36	9.61	14.66
biomass density	1991–2000	8.49	3.09	9.65	21.23
decline [2]	1981–2000	4.09	4.23	9.93	17.95
Constant forest	1981–1990	**- 1.50**	5.34	7.43	11.27
biomass density [3]	1991–2000	4.85	0.38	5.51	10.74
	1981–2000	1.67	2.86	6.47	11.00

Notes:

1) Data calculated using standard rate of forest biomass density decline with allowance for carbon storage in forest logs and rubberwood

2) Data calculated using half the standard rate of forest biomass density decline with allowance for carbon storage in forest logs and rubberwood

3) Data calculated assuming no decline in forest biomass density with allowance for carbon storage in rubberwood but not in forest logs

forests of Richards and Flint (1994) to calculate the forest biomass changes over the study period. The values for 1981 given by Brown *et al.* (1991) for Peninsular Malaysia (223 tonnes ha^{-1}) are close to the 1980 (239 tonnes ha^{-1}) value calculated from the data of Richards and Flint (1994). Brown *et al.* (1993) give a similar figure

Table 2 Carbon release due to changes in tree biomass in Sabah between 1981 and 1990 using alternative assumptions and different initial forest area estimates

	Carbon release/sequestration (Mt year^{-1})	
Source of initial forest area	FAO	MPI
Standard case [1)]	8.15	12.03
Half rate of forest biomass density decline [2)]	5.36	9.24
Constant forest biomass density [3)]	5.34	9.21

Note: [1)-3)] Details as for Table 1

Table 3 Mean annual carbon release between 1981 and 2000 using 'standard case' assumptions due to changes in tree biomass in Malaysia, either: (a) in the absence of either oil palm or a replacement crop or (b) with oil palm replaced by an arable annual crop with an assumed mean standing biomass of 10 tonnes ha^{-1}

Case		Period	Peninsular Malaysia	Sabah	Sarawak	Total
(a) Oil palm absent and no replacement crop	Carbon emissions (Mt year^{-1})	1981 - 1990	6.55	8.65	15.22	30.32
		1991 - 2000	16.19	8.90	18.37	43.46
		1981 - 2000	11.37	8.78	16.79	36.93
	Carbon emissions with an oil palm crop as a % of emissions without a crop	1981 - 1990	55.6	94.3	99.2	88.7
		1991 - 2000	88.9	85.0	98.0	92.0
		1981 - 2000	79.3	89.5	98.6	90.5
(b) Oil palm absent but replaced with an annual crop	Carbon emissions (Mt year^{-1})	1981 - 1990	6.19	8.64	15.21	30.04
		1991 - 2000	16.03	8.89	18.37	43.29
		1981 - 2000	11.11	8.76	16.79	36.66
	Carbon emissions with an oil palm crop as a % of emissions without a crop	1981 - 1990	94.6	99.9	99.9	99.1
		1991 - 2000	99.0	99.8	99.9	99.6
		1981 - 2000	97.8	99.9	99.9	99.3

for Peninsular Malaysia but proposed a higher biomass density in East Malaysian forests. Were this value used, the carbon emissions, even in the absence of density decline, would be substantially higher than those presented in Table 1. Starting forest biomass density is, therefore, an important parameter influencing the emission estimates.

Carbon retention in biomass products

Logging is the likely main cause of biomass degradation in Malaysian forests. It can be argued, however, that timber products constitute a form of carbon retention. Recorded log production was, therefore, used to offset forest biomass losses, as was potential carbon storage in rubberwood.

The proportion of usable timber that is 'exported' from the forest and effectively conserved from immediate decomposition (i.e. incorporated into semi-permanent features such as furniture or buildings) is difficult to estimate with any degree of precision. Much timber is nowadays used in chipboard or paper manufacture, which is less durable than cured unprocessed timber. The amount of rubberwood assumed probably represents an upper limit, and official data on rubberwood production (MPI 2001) falls much below the present estimates.

Carbon emission

To place the current emission estimates in perspective, the present data are compared in Table 4 with other estimates of carbon loss from tropical ecosystems in Malaysia and the Southeast Asian and south Asian regions.

Houghton (1991), using the data of Brown *et al.* (1991), calculated the carbon loss for Peninsular Malaysia between 1971 and 1981 to be 26.8 Mt year^{-1}. This is considerably larger than the present mean estimate for the period 1981 to 2000 of 9.02 Mt year^{-1} using the standard case (Table 1). Using data from FAO, Hall and Uhlig (1991) estimated the carbon emission in 1990 in response to landuse change

Table 4 Comparisons of estimates of carbon emissions due to vegetational change in different regions

Region	Period	Vegetation	Carbon emission (range) Mt year^{-1}	Reference
Peninsular Malaysia	1972	All	20 – 50	Chan (1982)
	1971-1981	Forest	26.8	Houghton (1991)
Malaysia	1980-2000	Forest/tree crops	1.7 – 9.0	This paper
	1980	Forest	6.4 – 9.9	Hall and Uhlig (1991)
	1990	Forest	16.1 – 25.2	
Southeast Asia [1)]	1981-1990	Forest/tree crops	11.3 – 26.9	This paper
South Asia [2)]	1980	All	150 – 430	Palm *et al.* (1986)
	1970-1980	All	562	Richards and Flint (1994)

Notes: [1)] Includes Indonesia, The Philippines, Malaysia, Thailand, Cambodia, Laos, Burma, Vietnam.
[2)] Includes the above plus India, Bangladesh, Sri Lanka.

for the whole of Malaysia to be 25.2 Mt. This is very similar to our mean estimate for 1981–1990 based on the standard case scenario (26.89 Mt $year^{-1}$). The same authors gave data in graphical form for Sabah from which an emission of around 6.4 Mt carbon may be deduced for 1990. This compares with 7.9 Mt $year^{-1}$ in Table 1 for 1981–2000.

Carbon emissions would have been greater were annual crops grown in place of oil palm (Table 3). Planting oil palm resulted in a more than 9% reduction in potential emissions compared with cultivation of an annual crop, even one with a relatively high mean standing biomass.

Conclusions

The above estimates, although only rough, point to an overall loss in Malaysia of carbon stored in the major terrestrial vegetation form (forests and tree crops) of the country. It follows that continued agricultural expansion, even in the form of plantation crops, will inevitably involve further loss of biomass and reduction in carbon stocks. There is a limit, governed by the economic life of the crops, to the carbon accumulation that is possible in plantations. However, plantation tree crops are substantially larger sinks for carbon than are annual crops with their limited capacity to accumulate biomass. Thus, with respect to carbon emissions, forest loss is at least partially compensated for by tree crop plantations.

The role of plantations may be further enhanced by management practices such as zero-burning (Teoh *et al.* 1999) and the recycling of waste materials, which should additionally contribute towards carbon sequestration. The impact of soil organic matter (SOM) changes on carbon sequestration and the effect of cropping on SOM accumulation remain important areas for future investigation.

Acknowledgements

I am most grateful to K. C. Chang and K. W. Chan of the Malaysian Palm Oil Board for their critical comments and suggestions.

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