Temporal patterns of land-use change and carbon storage in China and tropical Asia

R. A. Houghton

Woods Hole Research Center, P.O. Box 296, Woods Hole, MA 02543, USA (email: rhoughton@whrc.org)

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Abstract Evaluating the annual sources and sinks of carbon from land-use change helps constrain other terms in the global carbon cycle and may help countries choose how to comply with commitments for reduced emissions. This paper presents the results of recent analyses of land-use change in China and tropical Asia. The original forest areas are estimated to have covered 546×10^6 ha in tropical Asia and 425×10^6 ha in China. By 1850, 44% of China's forests had been cleared, and another 27% was lost between 1850 and 1980, leaving China with 13% forest cover (29% of the initial forest area). Tropical Asia is estimated to have lost 26% of its initial forest cover before 1850 and another 33% after 1850. The annual emissions of carbon from the two regions reflect the different histories over the last 150 years, with China's emissions peaking in the late 1950s (at 0.2—0.5 Pg $C \cdot a^{-1}$) and tropical Asia's emissions peaking in 1990s (at 1.0 Pg $C \cdot a^{-1}$). Despite the fact that most deforestation has been for new agricultural land, the majority of the lands cleared from forests in China are no longer croplands, but fallow or degraded shrublands. Unlike croplands, the origins of these other lands are poorly documented, and thus add considerable uncertainty to estimates of flux before the 1980s. Nevertheless, carbon emissions from China seem to have decreased since the 1960s to nearly zero at present. In contrast, emissions of carbon from tropical Asia were higher in the 1990s than that at any time in the past.

Keywords: carbon, China, deforestation, land-use change, tropical Asia.

Changes in land use are important in the global carbon cycle. They explain a large part of the carbon sink in northern mid-latitude lands and indicate a large source in the tropics. The better these fluxes from land-use change are defined, the better constrained are the magnitude, location, temporal pattern, and mechanisms for other carbon sinks, and thus the more predictable is the behavior of future sinks. A recent analysis of land-use change in China and recent revisions to the FAO's estimates of tropical deforestation offer opportunities for revising earlier estimates of carbon flux for large portions of Asia. This paper presents new estimates of the annual flux of carbon from land-use change in tropical Asia and China. The estimates cover the period 1850—2000 and show contrasting histories for the two regions.

1 Methods

1.1 Overall approach

The approach used to determine the annual net flux of carbon between terrestrial ecosystems and the atmosphere as a result of land-use change is based on observed patterns of change in vegetation and soil following a change in land use. When forests are cleared for croplands, for example, the carbon initially held in vegetation is released to the atmosphere rapidly when trees are burned and more slowly as dead plant material decays. Cultivation of soils also releases carbon to the atmosphere as soil organic matter decays. Conversely, when agricultural lands are abandoned and forests regrow, the net fluxes of carbon are reversed: carbon is removed from the atmosphere and accumulated again in vegetation and soils.

We have developed a bookkeeping model that tracks the carbon content of each hectare of land disturbed by human activity[1,2]. The model also tracks the fate of wood products removed from forests. Areas affected by land-use change and the carbon initially held in the disturbed ecosystem are tracked. Annual changes in the amount of carbon per hectare in living vegetation (during regrowth), dead vegetation (generated at the time of disturbance), soils, and wood products define the annual exchanges of carbon between the hectare affected (including products removed from that hectare) and the atmosphere.

The calculated flux is not the net flux of carbon between terrestrial ecosystems and the atmosphere because the analysis does not consider ecosystems undisturbed by direct human activity. Rates of decay and regrowth are defined in the model for different types of ecosystems and different types of land-use change, but they do not vary through time in response to changes in climate or concentrations of carbon dioxide. The processes explicitly included in the model are the ecological processes of disturbance and recovery, not the physiological processes of photosynthesis and respiration.

Two types of data are required for the model: rates of land-use change (number of hectares of each type of ecosystem cleared, abandoned, harvested, afforested) and rates of change in the carbon stocks of the vegetation and soil, including wood products, that follow a change in land use. Rates of land-use change are generally obtained from agricultural and forestry statistics, historical accounts, and national handbooks. Carbon stocks and changes in them following disturbance and growth are obtained both from field studies published in the ecological literature (to document biomass and soil carbon) and from forestry statistics and ecological and anthropological studies (to document the uses and half-lives of wood products). The data and assumptions used in the calculations reported here are more fully documented in ref. [3] (for tropical Asia) and for China[1)]. The fluxes presented here for tropical Asia extend the earlier estimate to the year 2000 and have been modified from an earlier study[3] to accommodate recent rates of deforestation given by the FAO's Forest Resource Assessment[4].

1.2 Tropical Asia

The countries included in "tropical" Asia are Pakistan, India, Bangladesh, Sri Lanka, Burma (Myanmar), Thailand, Malaysia, Laos, Cambodia (Kampuchea), Vietnam, Singapore, Brunei, Indonesia, the Philippines, and Papua New Guinea.

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1) Houghton, R. A., Hackler, J. L., Changes in land use and carbon storage in China between 1700 and 2000 (in preparation).

1.2.1 Land-use change. Three categories of land-use change are distinguished in tropical Asia. The first category includes those agents that replace forests permanently with open land. Primary among these agents is the clearing of forests for permanent croplands. The second category includes temporary reductions in forest cover. The agents include industrial logging, fuelwood harvest, and shifting cultivation. The third category includes the establishment or plantations.

(i) Clearing for permanent croplands. Rates of conversion of natural ecosystems to croplands were obtained from refs. [5—7]. After 1980, rates of increase in the area of croplands (and shifting cultivation) (see below) were assumed to equal rates of deforestation[4]. Recent estimates indicate that rates of deforestation increased between the 1980s and 1990s (Plate I), reversing the change reported earlier[3,8].

(ii) Rotational uses of forest (shifting cultivation and harvest of wood). The area in shifting cultivation was assumed to have been in steady state between 1850 and 1945 and then to have increased at rates given by ref. [9]. Generally, the forests cleared for shifting cultivation were fallow forests already in the shifting cultivation cycle. New forests were cleared only when the area in shifting cultivation increased (Plate I).

Rates of wood harvested (in m^3) for industrial wood (timber) were obtained from ref. [10] for the years 1960 to 2000 and from ref. [11] for earlier in the twentieth century. Rates of harvest were assumed to have increased slowly between 1850 and 1920. For this analysis, half of the initial biomass was assumed to be killed in the process of logging.

Most harvests in tropical Asia are for fuelwood. For the years 1980 to 2000, rates of fuelwood and charcoal production (m^3/a) were obtained from ref. [10]. Per capital use in 1980 (about 0.40 m^3/capita) was assumed to apply for the years before 1980 based on population data from ref. [12]. The assumption of a constant per capita rate probably underestimates fuelwood harvest in the early part of this analysis[13]. Annual harvests of industrial wood and fuelwood are shown in Plate I.

(iii) Plantations. The establishment of tropical plantations in tropical Asia was generally insignificant before 1960 but increased exponentially afterwards. By the year 2000 the total area in plantations was 54.6×10^6 ha, most of them established since 1980 (Plate I).

1.2.2 Carbon. The forests of tropical Asia were assigned to one of the three types: moist, seasonal, and dry (or open). The areas of these forests were initially estimated for 1750 on the basis of natural or potential vegetation maps. Biomass was 250, 150, and 60 Mg C/ha, respectively. Rates of growth (carbon accumulation) following logging in the three forest types were 5, 3.25, and 2.1 Mg C • ha^{-1} • a^{-1} for the first 20 a and 1.5, 0.9, and 0.45 Mg C • ha^{-1} • a^{-1} for the next 60—70 a. After 80—90 a, the forests had recovered to the initial carbon content of primary forests. Carbon in the vegetation of fallow forests reached 90 and 35 Mg C/ha in moist and dry forests, respectively, before these forests were cleared again for shifting cultivation.

Soil carbon to a depth of 1 m was 120, 80, and 50 Mg C/ha for moist, seasonal, and dry forests. Both permanent cultivation and shifting cultivation reduced soil carbon by 25% over 5 a[14]. In the fallowing part of the shifting cultivation cycle, soil carbon recovered to 80%—90% of the initial forest level. Soil carbon was unchanged as a result of logging.

1.3 China

The analysis divided China into six geographical regions. According to natural vegetation maps[15—17], about 45% of China (eastern and southern regions) was initially forested.

1.3.1 Land-use change.

Much of China was already deforested by 1700, but the extent of deforestation seems not to be known with any degree of certainty for past centuries[18]. The summary of data below is based on generally qualitative statements for different regions of China. A more complete documentation is found1). Open lands that were once forested are of two types in China: croplands (as in tropical Asia) and other lands. Other lands include lands that may have been used at least once for croplands but that have since become infertile, eroded, desertified, or otherwise unsuitable for crop production. They also include lands harvested, burned or browsed severely enough to prevent regrowth of forests.

(i) Croplands. Ref. [19] reports the area of Chinese croplands for nine years between 1400 and 1957. Since 1957, reported changes in the area of croplands are surprisingly variable, even as to the direction of change. Refs. [20, 21] report a decline, while ref. [10] reports an increase in cropland area. The decline is consistent with a recent analysis of urban areas using satellite data which show that 72% of the growth in urban areas during the 1990s came from arable lands[22]. This loss in croplands may have been offset by gains elsewhere, however. Evidence for an increase in cropland areas also comes from satellite data. A recent analysis comparing official statistics with estimates obtained from Landsat TM 2) suggests that the area of croplands in the 1990s was about 40% higher than that official estimates. Although the data from remote sensing are consistent with the higher estimates of cropland area, it is not clear whether cropland areas actually increased in recent decades or whether they have always been higher than that officially reported. Satellite data have not yet been used through time to demonstrate recent changes.

Despite the difference between the official Chinese estimates of cropland loss and the FAO estimate of increase, the uncertainty has little effect on carbon sources or sinks. Recent changes in the area of croplands are no longer related to changes in the area of forests (Plate II). Croplands have been reclaimed largely from wastelands and have been lost to expanding urban, suburban, and industrial areas[22]. The stocks of carbon in vegetation and soil in these different land uses are generally similar.

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1) See footnote 1) on page 11.
2) Frolking, S., Qiu, J., Boles, S. et al., Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China, Global Biogeochemical Cycles (in press).

(ii) Other lands. The current area in croplands in China explains, at most, only about half of the long-term loss of forests. In two regions (the northeast and northwest), the current area of croplands is equal to the area of forests lost. In the Eastern Plain, although the forest area lost is greater than the area in croplands, most of the forests were lost early (before 1700), and much of the cropland expansion after 1700 came from the previously cleared lands. For the three other regions (the north, the southeast, and the southwest), the long-term loss of forests exceeded the increase in croplands. Something besides expanding croplands must account for the deforestation, especially in southeastern and southwestern regions. The explanation seems to be that some of the forests logged or cleared for temporary croplands have not returned to forests. Several mechanisms are suggested in the literature: forests were regularly burned to eliminate habitats for bandits and tigers[23] grazing by sheep and cattle kept forests from returning[24]; and newly cleared lands were often abandoned after a few years, either to avoid taxation or because of low soil fertility[25]. Many of these lands were repeatedly recycled back into cultivation, preventing regrowth of forest. The process is similar to shifting cultivation, but the time for fallow was too short to allow forest recovery. According to ref. [26], the process continues today. In tropical and subtropical China, the reclamation of new croplands and abandonment of old ones occur annually at rates as much as 15 times higher than the net change in cropland. With the help of historical observations, we constructed early and late scenarios of forest clearing to bracket the uncertain history of this change.

(iii) Rotational uses of forest (harvest of wood). Wood has been harvested in China for millennia. By 1800 primary forests were largely gone in China properly, excluding the Northeast and Southwest (Tibet) of China, as a result of timber and fuel harvesting[25]. Rates of harvest are not well known, however, even for the present. In 2001 the FAO increased their estimates of industrial wood production by a factor of two. The increase applied to all the previous years (back to 1961) and all types of wood production (industrial wood as well as fuelwood). Official Chinese estimates often refer to harvests under the State Plan, while harvests outside of the State Plan may be as much as three times greater[27]. We used the FAO estimates after 1960 and assumed a low rate of increase prior to 1960 (Plate II).

(iv) Afforestation. The planting of trees became a national objective in 1949 with an announced goal of returning 30% of the country to forest. The program has been referred to as the greatest land-use change project of all time. Early attempts at afforestation were notoriously unsuccessful, however. Most of the successful plantations were initiated after 1970 and led to a plantation area of 34×10^6 ha in 1995 and 45×10^6 ha by 2000[10] (Plate II). Plantations include the planting of trees for timber as well as shelter belts (protection forests), fuelwood, and orchards (palm oil, rubber, and coconut).

1.3.2 Carbon. Values of forest biomass reported by ref. [27] were used initially to estimate the average biomass per ha in undisturbed forests. These estimates were subsequently adjusted to yield modeled biomass values in 1986 that were similar to those reported by ref. [28]. We used the results of the second national soil survey of China[28] to estimate average soil carbon values for the ecosystems included in this study. Total soil carbon for present-day China (94 Pg C using these data) agreed with the total reported by ref. [29].

2 Results and discussion

Before human disturbance, forests in tropical Asia are estimated to have covered 546×10^6 ha (62% of the region) and held 152 Pg C in vegetation and soil. In China, an initial forest area of 425×10^6 ha (44% of the area) held 106 Pg C. By 1850 China's forest area had been reduced by 44%, largely in the eastern plains and the north, around the Yellow River where domestication of crops began almost 10000 a ago[30]. In contrast, tropical Asia had lost only 26% of its initial forest area by 1850.

Over the 150 a (1850 and 2000), the emissions of carbon from land-use change were 43 and 23 Pg C from tropical Asia and China, respectively. The uncertain history of deforestation in China gave a range that varied from 15 to 30 Pg C. Annual emissions from China never exceeded 0.4 (range 0.2—0.5) Pg C • a^{-1}, while in the 1990s emissions from tropical Asia averaged 1.0 Pg C • a^{-1} (Plate III).

In the 1990s, rates of deforestation in the tropical forests of Asia averaged about 5.6×10^6 ha • a^{-1} [4] (Plate I). In contrast, forest area in China increased by about 20×10^6 ha after 1980. The increase of $>25\times10^6$ ha in plantations since 1980 suggests that all of the increase in forest area was the result of plantations, and that natural forests continued to decline[28].

In tropical Asia, the clearing of forests for permanent croplands between 1850 and 2000 accounted for about 77% of the carbon lost over this period (table 1). Reductions in forest biomass through logging, fuelwood harvest, and shifting cultivation accounted for the other 23%. Similarly, most of the carbon lost from China was from outright deforestation; only 15% resulted from reductions of carbon stocks within forests. Most of the emissions from deforestation in China, how-

Table 1 Changes in carbon storage (Pg C) as a result of changes in land use and wood harvest

	Before 1850	1850—1980	1980—2000
Tropical Asia			
Croplands	–3.03	–21.49	–6.63
Shifting cultivation	–10.79	–2.26	–2.12
Industrial harvest	–0.43	–1.95	–1.28
Fuelwood harvest	–0.53	–1.27	–0.50
Plantations	0.00	0.25	0.77
Total	–14.78	–26.73	–9.75
China			
Croplands	–6.01	–5.31	–0.55
Degradation	–6.15	–14.85	–0.31
Industrial harvest	–1.85	–1.24	–0.60
Fuelwood harvest	–2.56	–1.09	–1.04
Plantations	0.00	0.74	1.35
Total	–16.57	–21.75	–1.15

ever, resulted, not from a net increase in croplands, but from an increase in degraded lands, poorly documented.

Plate III shows that patterns of fossil fuel use were generally similar in the two regions, increasing from 1950 to the present, with the exception that the last few years have seen a decline in fossil fuel use in China. In contrast, net emissions from land-use change are different for the two regions. Half of China's forests had disappeared by 1910; tropical Asia did not reach the halfway mark until 1980. China's emissions have decreased since 1960, while emissions from tropical Asia have continued to increase. Total emissions of carbon from China, including both land-use change and fossil fuels, are currently about 1 Pg C • a^{-1}, all from fossil fuels. Current total emissions from tropical Asia are almost twice as large (1.8 Pg C • a^{-1}), dominated by emissions from land-use change. China's emissions of carbon from land-use change have fallen to zero in recent years. In tropical Asia, rates of deforestation and emissions of carbon are higher now than that at any time in the past.

3 Conclusions

History seems to show that deforestation continues until a nation's forests are nearly eliminated. Today, however, the Kyoto Protocol offers the opportunity to reverse past trends of deforestation before most forests are gone. Sustainable management of existing forests, and even an expansion of forest area, may now be economically viable through international trading of carbon. About 80% of the world's potential for increasing carbon storage in forests (estimated at 60—87 Pg C between now and 2050) lies in developing countries[31]. Managing degraded lands to increase carbon storage in these countries could enhance the prospects for sustainable development as well as reduce risks of climate change.

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