

Sources and sinks of carbon from land-use change in China

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[1] Changes in land use contribute to the current terrestrial carbon sink in most regions of the northern midlatitudes but are poorly documented for China, the world's third largest country. We attempted to reconstruct the last 300 years of land-use change in China, emphasizing changes in the area of forests. Changes in the area of croplands were inadequate for reconstruction of forest loss because the long-term loss of forest area was more than twice the current area of croplands. We used historical information to reconstruct changes in forest area over time and the ecological literature to estimate the carbon stocks of the major natural ecosystems (vegetation and soil). We used a bookkeeping model to calculate the flux of carbon to or from living vegetation, dead vegetation, soils, and wood products under different types of land use. According to the data and assumptions, 180 (range: 80 – 200) $\times 10^6$ ha of forest were lost, and 17 – 33 PgC were released to the atmosphere between 1700 and 2000. About 25% of the loss was from soils. The accelerated clearing and logging of forests in northeastern and southwestern China led to emissions of carbon that reached peaks of 0.2 – 0.5 PgC yr⁻¹ from the late 1950s through the 1970s. Lower rates of deforestation since then, as well as expanding areas of tree plantations, reversed the net flux of carbon from a source to a sink during the 1990s.

INDEX TERMS: 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0330 Atmospheric Composition and Structure: Geochemical cycles; 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* carbon balance, China, forests, land-use change, sources and sinks of carbon, terrestrial ecosystems

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1. Introduction

[2] The magnitude, geographical distribution, and causes of a northern midlatitude terrestrial carbon sink are uncertain. Inverse calculations based on atmospheric data and transport models suggest a net sink of 1 – 2.5 PgC yr⁻¹ for the region [Prentice *et al.*, 2001; Schimel *et al.*, 2001; Gurney *et al.*, 2002], distributed relatively evenly between North America and Eurasia. These continental-scale estimates of net carbon flux do not identify the mechanisms responsible for the sink, yet attribution is important because understanding the mechanisms responsible for past and current fluxes provides a basis for predicting future concentrations of atmospheric CO₂. Understanding the mechanisms is also important for political reasons. Nations participating in the UN Framework Convention on Climate Change (FCCC) are engaged in deciding which sources and sinks of carbon will be counted in meeting their obligations for emissions reductions under the Kyoto Protocol. Distinguishing between the sources and sinks that result, on the one hand, directly from human activity from those that result, on the other hand, either indirectly from human activity or from natural processes is scientifically and

technically difficult. The purpose of this study is to calculate the annual sources and sinks of carbon that can be attributed to direct human activity in China; that is, to changes in land use, including the harvesting of wood.

[3] China is the world's third largest country, most of it within northern midlatitudes. Estimates of the magnitude of China's terrestrial carbon balance vary considerably, from net sinks of 0.1 PgC yr⁻¹ [Streets *et al.*, 2001b] and 0.02 PgC yr⁻¹ [Xu, 1992; Fang *et al.*, 2001], to a net source of 0.06 PgC yr⁻¹ [Houghton, 1999]. The analysis presented here provides a new estimate based on new and more spatially detailed data. We attempt to reconstruct changes in land cover since 1700 because past changes in land use and management play a major role in the current carbon balance [Houghton *et al.*, 1999].

[4] Our approach is to calculate annual sources and sinks of carbon in six regions of China (Figure 1) (not including Taiwan) based on rates of land-use change and per hectare changes in carbon that accompany changes in land use. The data and assumptions used in the calculations are described in section 2. They include, first, the history of land-use change and, second, carbon stocks. Fluxes of carbon are calculated with a bookkeeping model described in section 3. The emphasis of this study is on changes in the area of forests because they contain 2 to 4 times more carbon per

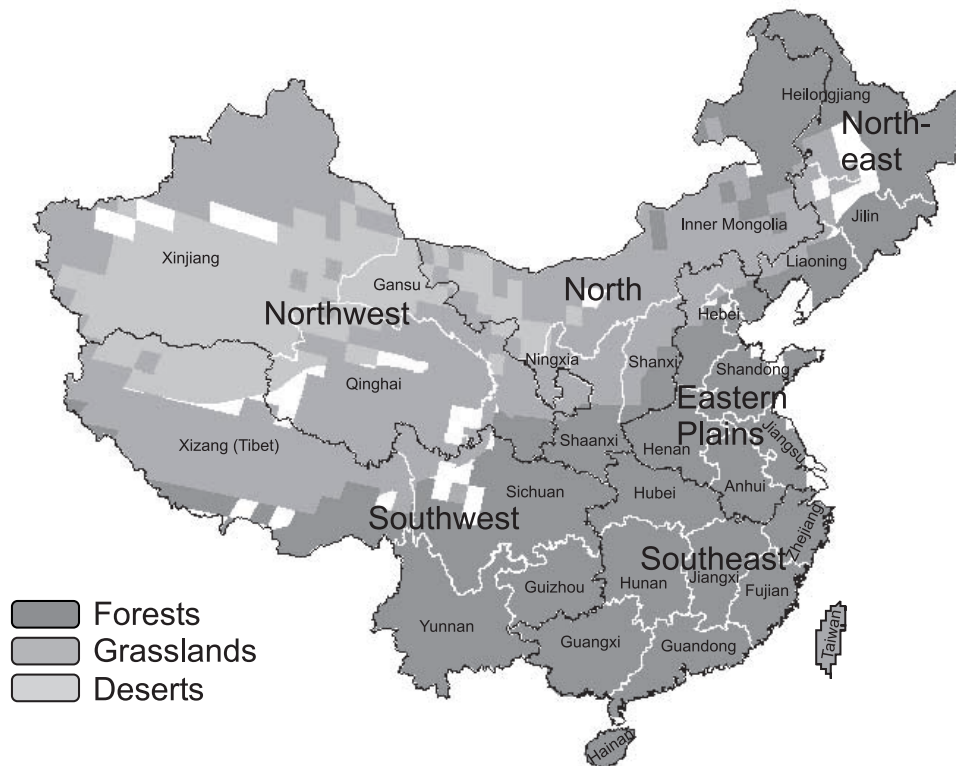


Figure 1. Six regions of China defined in this analysis and the distribution of forests, grasslands, and deserts within them. Taiwan is not included in this analysis.

unit area (~20 times more carbon in vegetation) than open ecosystems, such as grasslands and croplands (section 2.2).

2. Data and Assumptions

2.1. Areas of Ecosystems and Changes in Area

2.1.1. Natural Ecosystems of China

[5] China has a total area of 959.7×10^6 ha and a rich variety of ecosystems. The country has a north-south gradient in temperature and an east-west gradient in precipitation driven by the summer monsoon [Hou, 1983; Fullen and Mitchell, 1994; Menzies, 1996]. The natural ecosystems in the east grade from boreal forests in the northeastern provinces, through cold-, then warm-temperate deciduous forests, to mixed evergreen and deciduous subtropical forests, to evergreen tropical forests in the south [Hou, 1983]. With less precipitation to the west and higher elevations, forests are replaced by steppe and desert ecosystems. China is also a country with numerous mountain ranges and high plateaus, that interrupt and exaggerate the broad geographic patterns in temperature and precipitation.

[6] Controversy exists as to whether most of eastern China was initially forested or not [Menzies, 1996; Fang and Xie, 1994]. We constructed a map of natural ecosystems from the

predisturbance maps of Leemans [1990] and Matthews [1983] and the natural regions described by Hou [1983]. At least two of these three sources agreed on broad types of vegetation in 97% of China, and we used this agreement to define the natural, or predisturbance, land cover (Figure 1). Although the figure shows only three classes (forests, grasslands, deserts), we defined six classes from Hou [1983]: mixed temperate zone forests (including the boreal forests of the far north), mixed sub-tropical forests, tropical forests, temperate grasslands, high-altitude grasslands, and deserts. The distribution of these classes helped define six geographical regions (combinations of provinces) (Figure 1).

2.1.2. Today's Ecosystems

[7] The current area of forest in China depends on definition. Fang *et al.* [2001] use data from the latest forest inventory (1994–1998) conducted by the Chinese Ministry of Forestry (CMOF) to report a total forest area (including both planted and natural forests) of 105.82×10^6 ha. Elsewhere in their paper they report a forest area of 133.7×10^6 ha, citing the same official inventory. The reasons for the difference of 28×10^6 ha are not given, but the higher value seems to include additional non-timber plantations and disputed border areas of Tibet (Table 1). Estimates of current forest area in China vary between

Table 1. Areas of Forests, Plantations, and Woodlands (10⁶)^a

Inventory	Third 1984–1988	Fourth 1989–1993	Fifth 1994–1998
Forest cover ^b	102.19 (107.26)	108.64 (113.7)	105.82
Natural	83.45	87.27	
Planted	18.74	21.37	
Timber forests	80.07	84.93	
Shelter forests ^c	14.56	16.07	
Fuelwood	4.44	4.29	
Special use ^d	3.12	3.35	
Additional forest			
Economic plantations ^e	13.74	16.10	
Bamboo forests	3.55	3.79	
Forest cover and additional	119.48 (124.64)	128.53 (133.70)	
Presently unforested land and nursery			
Former forest	7.29	7.14	
Unregenerated clearcut	3.1	2.76	
Burned	1.33	0.91	
Nursery	0.18	0.11	
Total forest area	131.38	139.45	
Woodland ^f	19.64	18.03	
Other land for forest			
Shrubland	28.12	29.71	
Wasteland	76.61	63.03	
Sandy waste	5.57	6.57	
Total land for forest	261.32 (267.43)	256.79 (262.89)	

^aValues in parentheses include areas in Tibet with border disputes. Sources are Fang *et al.* [2001] and Shirong Liu (personal communication, November 2000).

^bCanopy coverage: >0.3 before 1994; >0.2 starting in 1994.

^cWater and soil conservation, road protection.

^dDefense, experimental, scenic and nature reserves.

^eFruit, nut, oil, etc.

^fCanopy coverage: 0.1–0.3.

105.82 and about 260×10^6 ha. All estimates are based on the National Forest Resource Inventories collected between 1949 and 1998 [Chinese Ministry of Forestry, 1999], and the variation results from the types of lands included in the total. The estimate of about 140×10^6 ha best defines the area covered by forests, including both plantations and natural forests as well as recently logged or burned areas expected to return to forest. It excludes woodlands, shrublands, and areas that are designated to be afforested in the future. The 140×10^6 ha of forest is similar to the estimate obtained independently by DeFries and Townshend [1994], and we used their classification to distribute the current area of forests and other ecosystems among the six regions. Their classification was based on a monthly time series of NDVI from AVHRR data for the year 1987 [Los *et al.*, 1994]. Spatial resolution was $1^\circ \times 1^\circ$.

2.1.3. Changes in Area

[8] The difference between the predisturbance area of forest [Leemans, 1990; Matthews, 1983; Hou, 1983] (Figure 1)

and the current area [DeFries and Townshend, 1994] provides an estimate of the total, long-term loss of forests. Many of these losses occurred before 1700, but neither the area of forest in 1700 nor the rate of loss over time is well documented. Direct estimates of forest area do not appear until the middle of the twentieth century, and the first systematic forest inventory including the entire country did not appear until 1983. With the exception of cultivated areas [Perkins, 1969], most of the information available to us prior to 1950 was drawn from historical descriptions, many of which relied on primary Chinese records. We divide our historical reconstructions into two periods: ~1981–2000 and 1700–1980. We consider the more recent changes first.

2.1.3.1. Rates of Land-Use Change From 1981 to 2000

2.1.3.1.1. Forests

[9] It is often reported that the forest area of China reached its minimum in 1949, and that, since the start of the Communist Republic of China, forest area has increased as a result of massive afforestation campaigns. Early attempts at afforestation were notoriously unsuccessful, however, and data from the national surveys conducted since 1950, indicate that the minimum forest area was not in 1949 but during the 1977–1981 inventory [Fang *et al.*, 2001].

[10] The earliest forest inventories were incomplete and inappropriate for determining changes in forest area. Although 11 nationwide forest surveys were carried out between the 1940s and the early 1980s, not until the 1977–1981 inventory (published in 1983) were the inventories comprehensive enough to reflect adequately changes in forest cover [Zhang, 1988]. The forest area reported for Tibet, for example, “increased” from 0.71×10^6 ha in the 1963 inventory to 11.97×10^6 ha in the 1978 inventory. We used the inventories to determine changes in the area of forests only after 1981. Before 1981 we used historic descriptions to constrain the changes in forest area (see below).

2.1.3.1.2. Plantations

[11] The planting of trees became a national objective in 1949 with an announced goal of returning 30% of the country to forests. The program has been referred to as the greatest land-use change project of all time. According to Ross [1980], plantings between 1949 and 1978 totaled about 130×10^6 ha, some accounts reporting as much as 18.7×10^6 ha planted in a single year. However, the area of plantations in existence in 1985 was only 6×10^6 ha [Richardson, 1990], indicating a very low survival rate for these early plantations. We assumed that most of the successful plantations were initiated after 1970 and used the rates given by S. Rozelle *et al.* (Forest exploitation and protection in reform China: Assessing the impact of policy, tenure, and economic growth, 1999 (available at <http://www.cifor.cgiar.org/news/china6.htm>) (hereinafter referred to as Rozelle *et al.*, paper, 1999)) and Food and Agriculture Organization (FAO) [2001] for our reconstruction (Figure 2). This assumption yielded a plantation area of 34×10^6 ha in 1995 and 54.6×10^6 ha by 2000.

[12] Several types of plantations are documented: shelter belts or protection forests [Li *et al.*, 1999], fuelwood

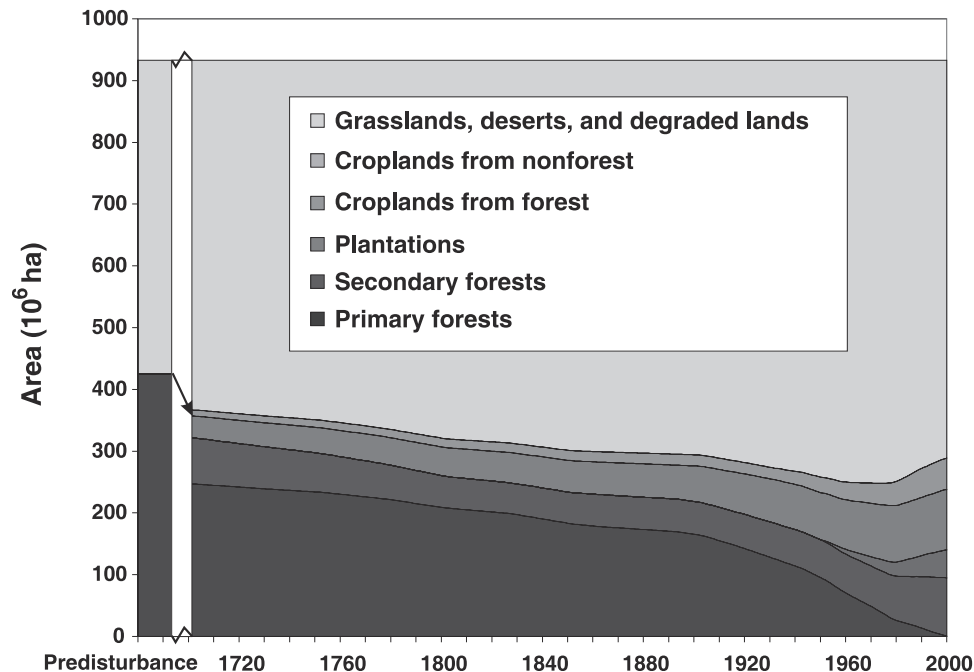


Figure 2. Long-term changes in the areas in different types of land cover and land use according to the reference analysis described in the text. Secondary forests result from either industrial harvest (timber) or other anthropogenic disturbances, including fuelwood harvest.

plantations, economic plantations, and orchards (including palm oil, rubber, and coconut). We distributed the different kinds of plantations among regions as indicated by Rozelle et al. (paper, 1999). We did not specifically simulate the establishment of timber plantations, but, instead, included them implicitly in the area of forest as *Fang et al.* [2001] did.

2.1.3.1.3. Croplands

[13] Neither the current area of cropland nor changes over the last decades are well known. Even the direction of change is in dispute. The China Agriculture Yearbooks [*Agricultural Publishing House*, 1991] and the *U.S. Department of Agriculture* [1992] report a decline in cropland area, while the *FAO* [2001] reports an increase. The decline is consistent with a recent analysis of urban areas using satellite data, which showed that 72% of the growth in urban areas during the 1990s came from arable lands [*Ji et al.*, 2001]. This loss in croplands may have been offset by gains elsewhere, however. The overall loss of croplands in eastern and central regions, for example, was partially compensated by increases in the north and west [*Yang and Li*, 2000]. A net increase in croplands is consistent with recent satellite-based assessments that exceed official estimates by 30–40% [*Frolking et al.*, 1999, 2002; *Keto et al.*, 2000], but it is not clear whether cropland areas actually increased in recent decades or whether they have always been higher than officially reported [*Yang and Li*, 2000]. Satellite data have not yet been used through time to demonstrate recent changes.

[14] We used the *FAO* [2001] estimates, which were consistent with satellite data from *Frolking et al.* [2002] and showed an increase in croplands through the 1990s

(Figure 3). 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 because changes in cropland area during the last few decades have been largely independent of changes in forest area. Croplands have been reclaimed largely from wastelands and have been lost to expanding urban, suburban, and industrial areas [*Li and Zhao*, 1998; *Ji et al.*, 2001]. The stocks of carbon in the vegetation and soil of these different land uses are generally similar. Exceptions to this generalization exist, especially in the tropical and subtropical forests of southeastern China, largely in Hainan and Yunnan provinces, where shifting cultivation was

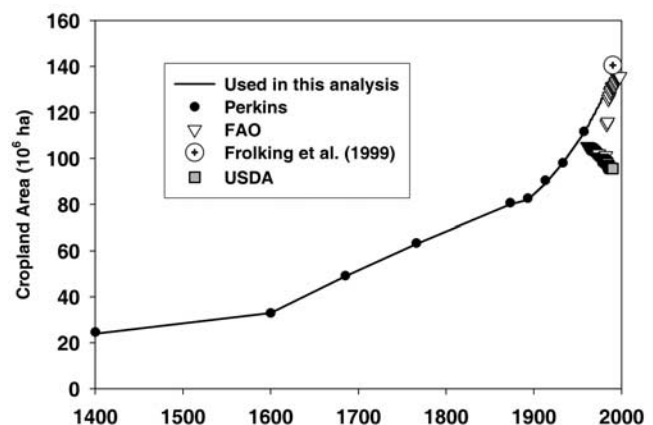


Figure 3. Estimates of the area of cropland in China.

responsible for about 30% of the deforestation between the early 1950s and 1990 [Wu and Zhou, 1996]. We did not simulate shifting cultivation explicitly, but we did convert forests to croplands when a loss in croplands [FAO, 2001] coincided with an increase in forest areas [Fang et al., 2001].

2.1.3.1.4. Pastures and Desertification

[15] The largest change in land use since 1960 was an increase in permanent pastures (at an average rate of 5.6×10^6 ha yr⁻¹ between 1960 and 1989) [FAO, 2001]. The increase came almost entirely from “other lands” (defined by FAO [2001] as being neither croplands, forests, nor pastures). The “conversion” of other lands to pastures is believed to have resulted from the expansion of domestic herds of sheep and cattle onto western grasslands. Grazing animals increased by more than 300% in parts of Inner Mongolia in the second half of the twentieth century [Sheehy, 1992]. The changes in carbon are likely to have been small, although overgrazing may have led to desertification in some regions.

[16] Deserts and desertified land cover 149×10^6 ha of land in China according to one estimate [Fullen and Mitchell, 1994] and 262×10^6 ha according to a more recent estimate [Fan and Zhou, 2001]. Desertified lands have been expanding for centuries, largely as a result of human activities, including conversion of grazing land to cropland, improper farming practices, fuelwood gathering, overgrazing, and warfare [Sheehy, 1992]. Despite a long history of desertification, including a period in the mid-eighteenth century when the Qing government attempted to populate northern border regions, Vermeer [1998] claims that serious desertification may not have begun until the end of the nineteenth century, when foreign missionaries promoted cultivation projects at the edges of deserts.

[17] Recent analyses report that the rate of desertification is increasing. Rates averaged 0.156×10^6 ha yr⁻¹ from the early 1950s to the mid-1970s [Fullen and Mitchell, 1994; Fan and Zhou, 2001], 0.210×10^6 ha yr⁻¹ between the mid-1970s and 1980s, and 0.246×10^6 ha yr⁻¹ most recently [Fan and Zhou, 2001; Feng et al., 2001]. The estimates are net rates of desertification; they include the rehabilitation of deserts. Thus, although efforts to combat desertification have been successful in individual areas [Runnström, 2000; Gao et al., 2001], the overall trend in desertification is accelerating. We assumed that the rate of desertification increased linearly from zero in 1900 to 0.156×10^6 ha yr⁻¹ by the 1950s and then used the estimates above to the year 2000.

2.1.3.1.5. Other Land Uses

[18] We did not explicitly consider the expansion of urban lands, in part because the rate (0.17×10^6 ha yr⁻¹ in the 1990s) [Ji et al., 2001] was small relative to other changes in land use, and in part because most of the lands converted to urban areas were agricultural lands already low in carbon.

2.1.3.2. Forest Cover in 1700 and Changes in Land Use Between 1700 and 1980

[19] Much of China was already deforested by 1700, but the extent of deforestation is not known with any degree of certainty for past centuries [Murphey, 1983]. A decline in

arboreal pollen in the middle and lower reaches of the Yellow River (the northern region, including the Loess Plateau, and the Eastern Plain) suggests that changes in land use began at least 5000 years ago [Ren, 2000] and radiated out from the sites of origin over the following millennia. The spatial pattern is similar to the expansion of cultivated lands presented by Wang and Zhao [1995], although no quantitative estimates of forest cover seem to exist for all of China until ~1950. Qualitative descriptions exist for some regions, however. Vermeer [1998], for example, describes deforestation in the eighteenth century as being driven by the demand for timber and fuelwood (for tea and tobacco production as well as for household use), whereas in the nineteenth and twentieth centuries, it was driven by the increased need for farmland. Before the Ming dynasty (1368–1644), most agriculture was found along rivers and near cities. Hilly and mountainous areas had few settlements. Cultivation of mountainous regions did not begin until the late Ming or Qing dynasty (1644–1911), and most of the settlement occurred in the eighteenth century [Vermeer, 1998]. Despite the modest clearing of forests for early agriculture, large areas were, nevertheless, logged. The demand for timber and fuel was such that primary forests in the mountainous regions were largely gone by 1800. By the mid-nineteenth century “China had become treeless...in the east and south” [Vermeer, 1998]. “The most extensive remaining tracts of forest were located in the northeast (Manchuria), the subtropical and tropical southwest (Yunnan, Guangxi, Hainan), and some isolated ‘internal frontier’ areas such as the Qinling Mountains in Shaanxi, Hubei, and Sichuan provinces” [Menzies, 1998]. Extensive logging did not begin in the northeast until the second half of the nineteenth century; and in the southwest, including Tibet, the greatest logging occurred between 1950 and the present (J.F. Studley, Progress, biodiversity and environmental degradation in SW China, 2001 (available at http://www.geocities.com/john_f_studley/China_re.htm) (hereinafter referred to as Studley, paper, 2001); W. Hongchang, Deforestation and desiccation in China: A preliminary study, 2001 (available at <http://www.library.utoronto.ca/pes/state/chinaeco/forest.htm>, 2001) (hereinafter referred to as Hongchang, study, 2001)). Most scholars believe that rates of deforestation accelerated during the nineteenth and twentieth centuries [Murphey, 1983], although Vermeer [1998] argues that the rates were probably as high in the eighteenth century as in the nineteenth century, but less well documented. Additional descriptions of land-use change for individual regions are summarized in Appendix A.

[20] We used this information to estimate areas of forest in existence in 1700 and rates of deforestation between 1700 and 1980. For two regions (the northeast and the Eastern Plain) changes in forest area seemed related to the rate of change in cropland areas until recent decades. For the northeast, we assumed that the increase in cropland area defined the rate of deforestation (Figure 4). In the Eastern Plain, most of the forest loss was early (before 1700), and much of the cropland expansion after 1700 came from previously cleared lands. In the northwest, forest area has always been small, and only a fraction of the croplands came from forests. For these three regions (the northeast,

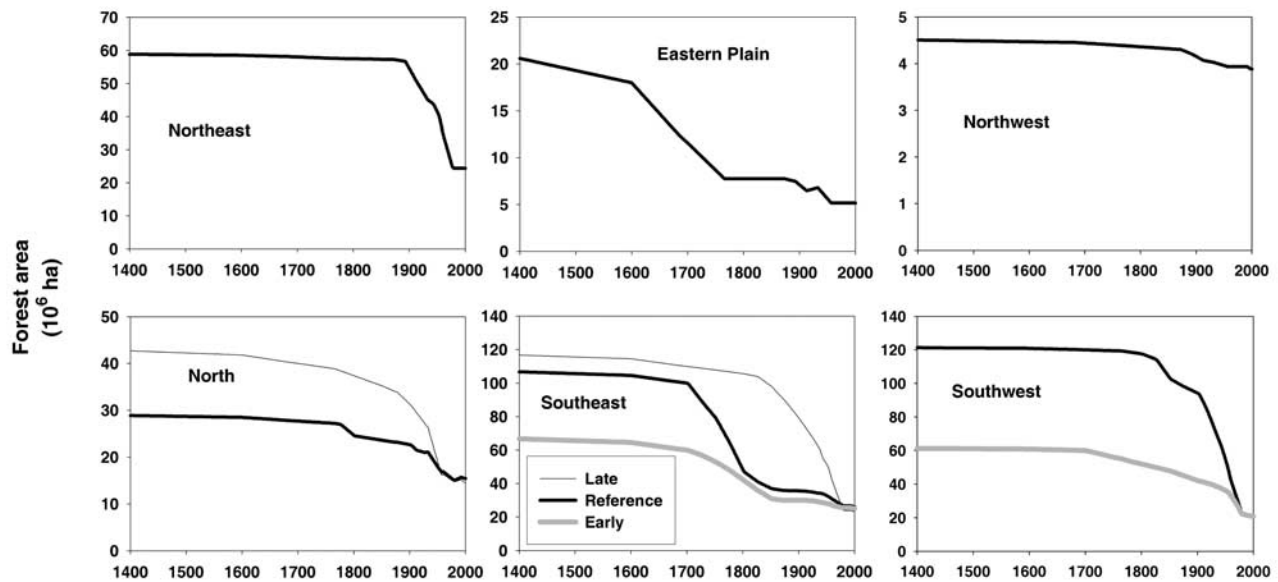


Figure 4. Changes in the area of forests in six regions of China. Early and late scenarios are shown for the north, southeast, and southwest regions. Note that the vertical axes vary among regions.

Eastern Plain, and northwest), changes in forest area are reasonably well constrained.

[21] For the three other regions (the north, southeast, and southwest) historic changes in forest area were poorly constrained and not well linked to changes in croplands. The current area of croplands is considerably less than the long-term change (predisturbance to present) in forest area (Table 2). The disparity suggests that something besides expanding croplands must have accounted for deforestation. There are two likely explanations. One explanation is suggested by the dynamics of croplands. Net changes in cultivated areas (as determined from estimates of *Perkins* [1969]) underestimate the actual rates of simultaneous clearing and abandonment. In southeastern China, particularly, newly cleared lands were abandoned after a few years, either to avoid taxation or because of low soil fertility [*Vermeer*, 1998]. Before these abandoned lands could return to forests, they were either burned to eliminate habitat for bandits and tigers [*Marks*, 1998] or recultivated. According to *Zhong and Zhao* [1998], the process continues today in tropical and subtropical China. Clearing and abandonment of croplands are largely simultaneous, and the net effect is a reduction in forest area, an increase in cropland area, and an increase in fallow lands that are neither forests nor croplands.

[22] A second explanation for the loss of forests is unsustainable logging practices. In many parts of southwestern China, especially on steep slopes, logging has scarred the land surface, leading to erosion. The combination of erosion, large areas logged (eliminating nearby sources of seed), and seasonally cold and dry environment has prevented or retarded the recovery of logged forests.

[23] For the north, southeast, and southwest, we reconstructed early and late scenarios of change in forest area for the period 1700 to 1980. The early scenario assumed a greater loss of forests prior to 1700. Because the scenarios converge to the same forest area in 1981, rates of deforestation after 1700 were higher in the late scenarios (Figure 4). In the north, because of the long history of deforestation, we assumed in the late scenario that the only forests remaining in 1700 were those present today plus those that were converted to cropland over the period 1700 to 2000. For the early (preferred, or reference) scenario, we assumed a smaller forest area in 1700 and reduced rates of deforestation thereafter. In both scenarios the most intense period of deforestation was after the middle of the eighteenth century [*Fang and Xie*, 1994]. In the southeast, deforestation increased geometrically up to 1850 [*Marks*, 1998]. In the southwest, much of the deforestation was

Table 2. Initial (Predisturbance) and Recent Areas of Forest and Croplands (10^6 ha)

Region	Predisturbance Forest Area	1988 Forest Area [Fang et al., 1998]	Change in Forest Area	Present Cropland Area [Frolking et al., 1999]	Additional Forest Area Lost
Northwest	6	4	-2	7	-5
Northeast	58	25	-33	31	2
Eastern Plain	65	5	-60	52	8
North	53	18	-35	19	16
Southeast	116	27	-89	15	74
Southwest	121	24	-97	15	82
All China	419	103	-316	139	177

delayed until the second half of the twentieth century. Beginning in the 1950s and accelerating in the 1960s, deforestation in Tibet, Sichuan, and Yunnan reduced forest area by more than half [Li and Lai, 1991; Studley, paper, 2001; P. Shi and J. Xu, Deforestation in China, 2001 (available at <http://www.ccap.org.cn/english/talk/WP-00-E16.pdf>) (hereinafter referred to as Shi and Xu, paper, 2001)]. We constructed a late (preferred) scenario of forest loss assuming that the rates of change in Sichuan (Hongchang, study, 2001) were representative of the region (Figure 4). We also constructed an early scenario with lower rates of deforestation in recent decades.

[24] For the north, southeast, and southwest regions, we simulated deforestation through two processes. First, as in the other regions, we cleared forests for the expansion of cropland area given by Perkins [1969]. Second, we cleared additional forests to match the decline in forest area estimated in our scenarios. This second kind of deforestation was simulated in the bookkeeping model (described below) by clearing forests, as above, abandoning the cleared land after a few years, and then clearing the lands again after only a few years. The repeated clearing and abandonment of lands kept a large area in fallow.

[25] We set the rates of these two types of deforestation so as to satisfy two requirements simultaneously: changes in the area of croplands [Perkins, 1969] and changes in the area of forests (for early or late scenarios). The decrease in forest area that exceeded cropland expansion appeared as degraded land. These degraded lands were repeatedly harvested of wood, thus providing fuelwood yet keeping the lands in a state of low carbon, consistent with repeated burning [Marks, 1998] and grazing by sheep and cattle [Zhang, 1988].

2.1.4. Harvest of Wood

[26] Although wood has been used for thousands of years in China, quantitative estimates of harvest are generally incomplete or altogether lacking. Wood has been used not only domestically for heating and cooking, but in the production of iron, ceramics, salt, paper, and bricks and the drying of tobacco and tea. During the Ming (1328–1644) and Qing (1644–1911) dynasties, the three major regions of timber were Fujian and Hunan provinces (southeast) and Sichuan province (southwest) [Marks, 1998]. In the early nineteenth century, “entrepreneurs employed tens of thousands of loggers, felling trees for timber and ... fuel” [Vermeer, 1998]. Industries had to move to new areas periodically as wood sources were exhausted. Erosion as well as deliberate burning of cleared lands often kept the forests from growing back [Marks, 1998]. In China proper, excluding the northeast (Manchuria) and Tibet (in the southwest), primary forests were largely gone by 1800 as a result of demand for timber and fuel [Vermeer, 1998].

2.1.4.1. Industrial Wood

[27] Rates of harvest are not well known, even today. In 2001, for example, FAO [2001] temporarily increased estimates of wood production in China by a factor of 2. The increase applied to all previous years (back to 1961) and all types of wood production (industrial wood as well as fuelwood). Estimates before 1960 are rare, although during World War II the Japanese are estimated to have harvested

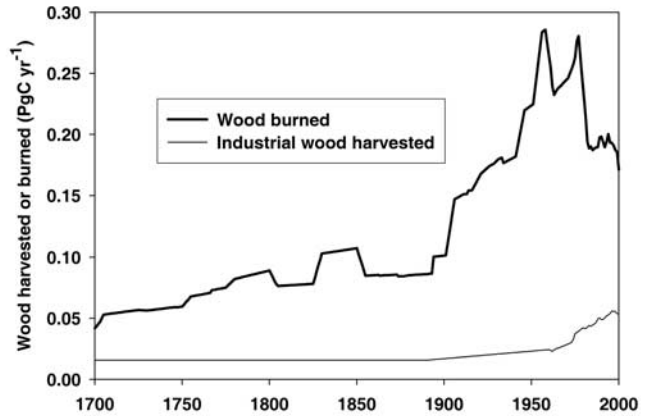


Figure 5. Rates of industrial wood harvest and rates of wood burning as a result of anthropogenic disturbances, including harvest of fuelwood and fires. Industrial wood production from 1961–2000 was obtained from the temporarily doubled rates reported by FAO [2001]. Rates were constant before 1960 except in the north and northeast, where harvests began late in the eighteenth century.

70 million m³ from northeastern China (Manchuria) [Vermeer, 1998] (an average of 10×10^6 m³ yr⁻¹). Other estimates suggest that annual rates of harvest increased from about 20×10^6 m³ in the 1950s to 64×10^6 m³ in 1964 [Zhang et al., 2000]. After 1964, rates declined to 23×10^6 m³ in 1999 and 14×10^6 m³ in 2000 [Zhang et al., 2000]. The reported declines after 1964, however, refer to harvests of natural forests only, and total harvests may not have declined. More importantly, these estimates of timber harvest refer to harvests under the State Plan, while harvests outside of the State Plan have often been greater. In 1985, for example, harvests outside the State Plan were more than three times larger than harvests under the Plan [Richardson, 1990]. The additional harvests included legal harvests within provincial plans, illegal harvests, and fuelwood harvests. Although the State Plan seems well documented and accurate, harvests outside that Plan are problematic [Richardson, 1990; Shi and Xu, paper, 2001].

[28] To account for unreported harvests, we used the higher estimates of industrial wood production temporarily reported by FAO [2001] from 1961 to 2000. According to the FAO, rates of industrial wood harvest tripled over this period, from 60 to 200×10^6 m³ yr⁻¹. Before 1960 we assumed that rates of industrial wood harvest were constant at 1961 rates, except in the north and northeast, where industrial logging began in 1890 (Figure 5).

[29] The areas harvested annually were calculated for each region with the following equation:

$$\text{Area harvested (ha)} = \frac{\text{Total harvest (m}^3\text{)} \times \text{wood density (Mg/m}^3\text{)} \times 0.5}{\text{Biomass (Mg/ha)} \times \text{harvest efficiency}},$$

where wood density was 0.45, 0.5 converts biomass to carbon, and harvest efficiency was 0.6–0.75 (the fraction of total biomass/ha that was converted to wood products).

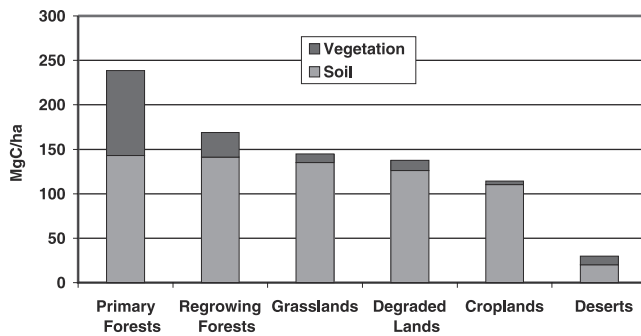


Figure 6. Average carbon stocks (MgC/ha) in vegetation and soil of different types of ecosystems. Differences indicate the relative losses and gains of carbon associated with transitions from one type of ecosystem to another.

2.1.4.2. Fuelwood

[30] Rates of fuelwood use are even less well known than rates of industrial wood harvest. *Richardson* [1990], for example, cites studies of fuelwood harvest in China that range between 80 and $800 \times 10^6 \text{ m}^3$ annually for rural domestic use. The doubled estimate of *FAO* [2001] for the 1990s was $\sim 400 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$, near the middle of *Richardson's* range. According to this estimate, fuelwood production is currently twice the magnitude of industrial wood production.

[31] Generally, we assumed that the harvest and consumption of fuelwood was included in the wood burned during the clearing of forests for croplands and during the repeated burning of fallow lands. However, we increased “fuelwood harvests” in the eighteenth century to convert primary forests to secondary forests in central China. The fuelwood harvested to eliminate primary forest may have overestimated actual fuelwood use, but it presumably represents the accidental and deliberate burning of forests in wars and for protection [*Marks*, 1998]. We explicitly included the harvest of fuelwood also to reduce forest biomass to the values observed in 1986 [*Fang et al.*, 1998]. The amount of carbon annually burned from these activities is shown in Figure 5. Emissions have varied between 0.15 and 0.30 PgC yr^{-1} since 1940. For comparison, *Streets et al.* [2001a] report 1995 rates of biofuel consumption in China of $\sim 0.25 \text{ PgC}$, somewhat more than twice the rate reported by *FAO's* temporarily high estimate [*FAO*, 2001]. Wildfires were not included in our analysis. We assumed that emissions of carbon from wildfires were generally offset in the long term by forest regrowth. For reference, the unusually large fire in northeastern China in 1987 is estimated to have released $0.025\text{--}0.050 \text{ PgC}$ [*Wang et al.*, 2001a].

2.2. Stocks of Carbon

[32] The conversion of one type of ecosystem to another generally changes the amount of carbon held in the vegetation and soil of a unit of land. The paragraphs below document the stocks of carbon in different ecosystems and the changes that occur as a result of land-use change. Figure 6 shows the relative differences in carbon stocks among ecosystems.

2.2.1. Carbon in Living Vegetation

[33] We used data from *Fang et al.* [1998] to estimate the average amount of biomass per hectare in undisturbed forests and then adjusted these estimates to obtain average regional biomass values in 1986 similar to those reported by *Fang et al.* [1998]. Values for starting biomass (1400 AD) and average values for secondary forests are shown in Table 3. Average biomass values for grasslands and deserts were obtained from *Olson et al.* [1983]. We varied the biomass of forests in alternative analyses to determine the effect on the calculated flux of carbon.

2.2.2. Carbon in Soil

[34] We used the results of the second national soil survey of China [*Wang et al.*, 2001b] to estimate average soil carbon values for the ecosystems included in this study (Table 3). The soil survey included 2473 soil profiles for a total area of $877.63 \times 10^6 \text{ ha}$. Surface water, glaciers, bare rock and gravel hills, as well as Taiwan, were excluded. Unlike most soil inventories that determine the amount of carbon to a depth of 1 m, the Chinese soil survey included the carbon measured to the depth of the soil. The average depth was 0.83 m, with some soils considerably deeper. We estimated average soil carbon values from the map given by *Wang et al.* [2001b]. The value is an estimate of current soil carbon stocks and was presumably higher before natural ecosystems were converted to croplands and cultivated.

2.2.3. Changes in Carbon in Response to Land-Use Change

2.2.3.1. Tree Plantations

[35] As discussed above, we did not explicitly distinguish timber plantations from natural forests. We did consider shelter-belt, or protective, forests, areas of commercial trees, and orchards. We assumed that plantations are generally established on degraded, formerly cultivated lands, and that biomass and soil carbon recover to natural forest levels as the plantations grow [*Mao et al.*, 1992; *Guo and Gifford*, 2002].

2.2.3.2. Croplands

[36] The conversion of forests to croplands transferred the carbon initially in trees to slash (dead material left on site) and to wood products that released carbon to the atmosphere at rate constants of 1 yr^{-1} , 0.1 yr^{-1} , and 0.01 yr^{-1} . The three wood product pools represent burned, short-lived, and long-lived wood products. We assumed that logging and mining generally preceded settlement, and that the forests converted to croplands were generally secondary (lower biomass) forests. Cultivation of forest soils resulted in a rapid 25% loss of the carbon in the upper 1 m. Cultivation of desert soils was assumed to have no effect on carbon storage unless desertification resulted (see below). Abandoned croplands returned to the ecosystems from which they were initially cleared, accumulating carbon in living biomass and soil at rates shown in Table 3.

2.2.3.3. Pastures

[37] Most of the pastures in China are in the natural steppe regions, and we assumed that grazing had no effect on either above- or below-ground carbon stocks. Overgrazing that resulted in desertification is addressed below.

Table 3. Carbon Stocks (MgC ha⁻¹) for The Major Ecosystems of China, Growth Rates Following Agricultural Abandonment and Afforestation (MgC ha⁻¹ yr⁻¹), and Exponential Decay Constants for Woody Debris Left in the Ecosystems at Harvest^a

	Carbon in Vegetation		Carbon in Soil	Rate of Growth		Decay Constant
	Primary	Secondary		Vegetation	Soil	
<i>Northeast</i>						
Temperate forest	120	45	150	0.8	0.5	0.03
Temperate grassland	10	10	150			
<i>North</i>						
Temperate forest	70	50	125	1.0	0.625	0.03
Temperate grassland	10	10	150			
Desert	3	3	20			
<i>Northwest</i>						
Temperate forest	80	60	100	1.1	0.75	0.03
Temperate grassland	10	10	100			
Desert	3	3	20			
<i>Eastern Plain</i>						
Temperate forest	50	35	100	0.6	0.5	0.1
Temperate grassland	10	10	135			
<i>Southeast</i>						
Subtropical forest	80	35	130	0.9	0.93	0.3
<i>Southwest</i>						
Subtropical forest	160	80	200	1.5	1.0	0.3
High-altitude grassland	10	10	175			
Desert	3	3	20			

^aBiomass of primary forests was obtained from *Fang et al.* [1998]. Biomass of secondary forests (the biomass at which the forests could be harvested again) was adjusted to yield average regional values in 1986 similar to those reported by *Fang et al.* [1998]. Average biomass values for grasslands and deserts were obtained from *Olson et al.* [1983]. Average soil carbon values were obtained from *Wang et al.* [2001c]. Average rates of growth were chosen so that forests recovered in approximately 100 years. Decay constants for wood were obtained from *Houghton* [1999].

2.2.3.4. Desertification

[38] The organic carbon content of soils in different stages of desertification was obtained from *Feng et al.* [2001], who measured soil carbon in 17 sites across northern China. Weighted averages varied from 31 MgC/ha (to a depth of 1 m) for lands prone to desertification to 3.2 MgC/ha for lands severely degraded.

2.2.3.5. Degraded Lands

[39] As discussed above, a large area previously forested is now neither forested nor in croplands or pastures. The biomass on such lands is low, generally similar to that of grasslands, but the carbon in soils is less certain. We simulated two possibilities. In the reference analysis, we assumed that degraded lands had been cultivated and abandoned, and thus soils lost 25% of the organic carbon initially held in forest soils. In the second alternative we assumed no change in soil carbon, as might occur if degraded lands originated through logging.

2.2.3.6. Harvest of Industrial Wood

[40] The harvest of industrial wood transferred 40% of the carbon initially in trees to slash, which decayed exponentially (Table 3), and 60% of the biomass to wood products, as follows: 30% of the initial biomass was oxidized in 1 year, 20% decayed exponentially over 10 years, and 10% decayed exponentially over 100 years. Before about 1900, harvests were preferentially of primary forests. After 1900, secondary forests that had recovered from earlier harvests were harvested again if they had recovered sufficiently;

otherwise primary forests were harvested. Soil carbon was assumed not to change with harvest. Rates of forest regrowth following harvest are shown in Table 3. We varied these rates of growth in alternative analyses to determine their effect on the calculated flux of carbon.

2.2.3.7. Harvest of Fuelwood

[41] As described above, fuelwood was not explicitly modeled except to reduce the area of primary forest before 1800 or to reduce the average biomass of forests prior to 1986. Instead, the wood transferred to the 1-year decay pool in the clearing of forests and in the harvesting of industrial wood was assumed to include fuelwood.

2.3. An Overview of Approach, Data, Assumptions, and Alternative Scenarios

[42] Because quantitative data on forest area and forest biomass in 1700 and changes in the area of forests over the years 1700 to ~1980 were incomplete, we supplemented the existing data with the assumptions described above to reconstruct changes over time. Here we summarize the general steps in that reconstruction and describe additional constraints that helped yield internally consistent changes through time.

[43] The primary data we relied on were data on cropland areas, by province, over the period 1400 to 1957 [*Perkins, 1969*]. We assumed that new croplands were cleared from forests. Where forest area was not sufficient, croplands expanded into grassland ecosystems. In three regions (the

northeast, northwest, and eastern plain), historical information about croplands and forests provided reliable estimates of changes in area. In three other regions (the north, southeast, and southwest), where the increase in croplands was not large enough to account for the loss of forests, we used historical descriptions to construct early and late scenarios of forest clearing (in excess of cropland expansion) to bracket the uncertain history of change. After we estimated the changes in forest area, we added logging (including both industrial wood harvest and fuelwood extraction) to the analysis.

[44] Thus, for each region we constructed (1) rates of cropland net expansion or contraction, (2) rates of industrial wood harvest, and (3) rates of other disturbances. This third category included harvest of fuelwood, fires, and additional industrial wood removals not reported in the item (2). Rates of fuelwood harvest were defined to insure that primary forests were largely gone by 1800 in all but the northeast and southwest [Vermeer, 1998]. For three regions we also constructed alternative scenarios for (4) rates of deforestation in excess of cropland expansion.

[45] For the years 1700 to 1986 we also developed alternative scenarios of biomass and growth rates. To assess the uncertainty of the flux of carbon from degraded lands, we assumed, in the reference analysis, that degradation included a 25% reduction in soil organic carbon (SOC) and, in an alternative scenario, that no changes in SOC occurred with degradation. For the years after 1986 we continued the alternative biomass scenarios and constructed three additional scenarios to account for uncertainties in recent land-use data. In one scenario we continued the rates of deforestation and harvest presumed to exist in the 1980s. In a second scenario we assumed that only degraded lands (not forests) were cleared for new croplands. And in the third scenario we halved the 1980s rates of industrial and nonindustrial wood harvest after 1986. The halved rates were similar to official estimates.

3. A Bookkeeping Model

[46] To calculate annual emissions of carbon from changes in land use, we used a bookkeeping model similar to models used previously [Houghton *et al.*, 1983, 1999; Houghton and Hackler, 1995]. Annual per hectare changes in vegetation and soil following a land-use change were defined in the model for different ecosystems and land uses. For example, when a forest is cleared for crops, some of the initial biomass is left on the site (slash) and some is removed (wood products). Plant material left on the site either is burned or decays exponentially, releasing carbon to the atmosphere in the year of burn, or releasing a diminishing amount of carbon in subsequent years, respectively. Material removed from the site is distributed among pools that decay with time constants of 1 yr^{-1} for fuelwood, 0.1 yr^{-1} for short-lived wood products, and 0.01 yr^{-1} for long-lived wood products. When soils are cultivated, 25% of the carbon initially held in the top meter of soil is also released to the atmosphere over a few years [Davidson and Ackerman, 1993].

[47] Following the abandonment of croplands and following harvest, forests are generally permitted to grow back. In the model, annual rates of carbon accumulation in regrowing vegetation (Table 3) defined the amount of carbon in each age class, thus allowing annual uptake as well as average biomass of forests to be calculated.

[48] The model tracks the areas of different land uses and the amounts of carbon held in live vegetation, slash, wood products, and soil. Changes in the pools from one year to the next define the annual net flux of carbon between land and the atmosphere. The time step is annual. The model was run for 300 years before 1700 with the initial rates of agricultural clearing and harvest so that the amount of carbon in different pools and the areas of forest in different ages of regrowth approximated conditions at the start of the period.

[49] The model calculates the flux of carbon that is attributable to direct human activity. It does not include the effects on carbon storage of increased atmospheric CO_2 , increased deposition of nitrogen, or changes in climate. Rates of decay and growth vary across ecosystem types in the model, and growth varies as a function of age, but the rates are not affected by temporal changes in environmental variables. Ecosystems that were not cleared, abandoned, grazed, or harvested were not included in the analysis.

4. Results

4.1. Changes in Area

[50] Estimates of potential forest cover (that is, forest cover in the absence of human disturbance) [Matthews, 1983; Leemans, 1990; Hou, 1983] suggest that about 45% of China was initially forested ($\sim 425 \times 10^6$ ha). According to the changes reconstructed in this analysis, approximately 100 (range $80\text{--}200$) $\times 10^6$ ha of forest were lost before 1700, and another 200 (range $100\text{--}227$) $\times 10^6$ ha were eliminated between 1700 and 1980, when China's forest area reached its minimum [Fang *et al.*, 2001]. Half of China's original forest area was lost by 1729 in the early scenario but not until 1907 and 1935 in the reference and late scenarios, respectively. Rates of deforestation varied by region but generally increased for all of China between 1700 and 1980 (Figure 4). After 1980, forest cover increased by about 20×10^6 ha. The $20\text{--}25 \times 10^6$ ha increase 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 in area [Fang *et al.*, 2001; Rozelle *et al.*, paper, 1999] (Figure 2). Rozelle *et al.* (paper, 1999) estimate that the net increase of 5×10^6 ha in forest area between 1980 and 1993 resulted from a loss of natural forests (16×10^6 ha clear-cut and not reforested) and a gain of engineered timber plantations (21×10^6 ha). As discussed above, the long-term loss of forest area was greater than the increase in cropland area. According to this analysis, the total loss of 180×10^6 ha of forest since 1700 was distributed between croplands (40×10^6 ha) and degraded lands (140×10^6 ha) (Figure 2 and Table 4). Croplands also replaced grasslands. Some of the degraded lands are thought to have been farmed, at least once; others are thought to have resulted from

Table 4. Areas (10⁶ ha) of Major Ecosystem Types in China According to the Reference Analysis^a

	Predisturbance	1700	1850	1950	1980	1990	2000
Forest	425	322	234	157	121	131	142
Grassland and Pasture	345	401	394	380	357	345	335
Desert, rock and ice	163	163	163	167	172	174	177
Croplands	0	47	72	106	128	135	140
Degraded lands	0	0	70	123	155	148	139
Water	27	27	27	27	27	27	27
Total area	960	960	960	960	960	960	960

^aPredisturbance areas were determined from *Leemans* [1990], *Matthews* [1983], and *Hou* [1983]. Current areas were obtained from *DeFries* and *Townshend* [1994]. Changes between these two dates were estimated as described in the text.

unsustainable logging. Forests may someday return to these areas but, to date, they have not.

4.2. Changes in Carbon

[51] The initial carbon content of China's lands is estimated to have been 160 PgC, with 48 PgC in vegetation and 112 PgC in soils (Table 5). By the year 2000 the total amount of carbon had been reduced to 117 PgC in the reference analysis, with only 11.6 PgC in vegetation, 101.9 PgC in soils, and 3.9 PgC in wood products and slash. The long-term loss of 42 PgC is attributable to human activity. About 75% of this long-term loss (or 32 PgC) occurred in the last 300 years, according to the data and assumptions used in the reference, or preferred, analysis. Early and late scenarios yielded losses of 17 and 33 PgC, respectively, over the last 300 years (43 and 78% of the long-term loss,

respectively). In all three scenarios, 75–80% of the carbon lost was from vegetation and 20–25% from soils. If degraded lands are assumed to originate from unsustainable logging practices rather than from abandonment of croplands, soils contribute only 12% to the 300-year flux of 23 PgC. Of the 15–29 PgC lost from vegetation in the last 300 years, only 14–25 PgC were released to the atmosphere; 2–4 PgC accumulated in wood products and woody debris in forests (slash).

[52] The annual emissions of carbon from changes in land use increased over time, reaching a peak of 0.4 PgC yr⁻¹ (range 0.2–0.5) in the late 1950s and declining rapidly after the late 1970s (Figure 7). The historical pattern of emissions varied by region (Figure 8). Early in history the greatest losses of carbon were from eastern regions, where both large forest areas and dense human populations existed. In the north and eastern plains, forests were largely gone before 1700. In the northwest, there were not many forests to begin with. The exception to the early loss in eastern forests was in the northeast where logging did not begin until late in the nineteenth century. In the last 300 years, the greatest losses of carbon were from the southwest, some of which was outside of China proper and not heavily exploited until after 1950.

[53] The contributions of different land uses to the total flux of carbon are shown in Figure 9. Two of the curves result from losses of forest area (to croplands and degraded lands), and two result from changes in carbon stocks within forests (from industrial logging and other processes). The flux of carbon attributed to "croplands" (a net release of 11 PgC over the 300-year period 1700–2000) is calculated

Table 5. Carbon Stocks and Changes in Carbon Stocks (PgC) for the Reference Analysis^a

	Carbon Stocks			Changes	
	Predisturbance	1700	2000	Predisturbance to 1700	1700–2000
<i>Reference Scenario</i>					
Vegetation	47.5	38.9	11.6	-8.6	-27.3
Soil	112.0	109.9	101.9	-2.1	-8.0
Wood products and slash	0.0	0.5	3.9	0.5	3.4
Total	159.5	149.3	117.4	-10.2	-31.9 ^b
<i>Early Scenario</i>					
Vegetation	47.5	27.6	12.2	-19.9	-15.4
Soil	112.0	108.3	104.7	-3.7	-3.6
Wood products and slash	0.0	0.8	2.7	0.8	1.9
Total	159.5	136.7	119.6	-22.8	-17.1 ^b
<i>Late Scenario</i>					
Vegetation	47.5	39.8	11.3	-7.7	-28.6
Soil	112.0	109.3	100.7	-2.7	-8.6
Wood products and slash	0.0	0.9	4.7	0.9	3.8
Total	159.5	150.0	116.6	-9.5	-33.4 ^b
<i>"Soil" Scenario^c</i>					
Vegetation	47.5	38.8	11.3	-8.7	-27.5
Soil	112.0	111.5	108.7	-0.5	-2.8
Wood products and slash	0.0	0.5	4.0	0.5	3.5
Total	159.5	150.8	124.0	-8.7	-26.8*

^aPredisturbance areas were determined from *Leemans* [1990], *Matthews* [1983], and *Hou* [1983]. Predisturbance biomass for forests was obtained from *Fang et al.* [1998], and for other ecosystems, from *Olson et al.* [1983]. Average soil carbon values were obtained from *Wang et al.* [2001c]. Sources used to calculate carbon stocks as a result of human activity are described in the text.

^bThese values represent the 300-year net fluxes of carbon.

^cIn this scenario, degraded lands were assumed to originate through unsustainable logging practices. Soil carbon was not reduced in degraded lands as it was in the reference scenario.

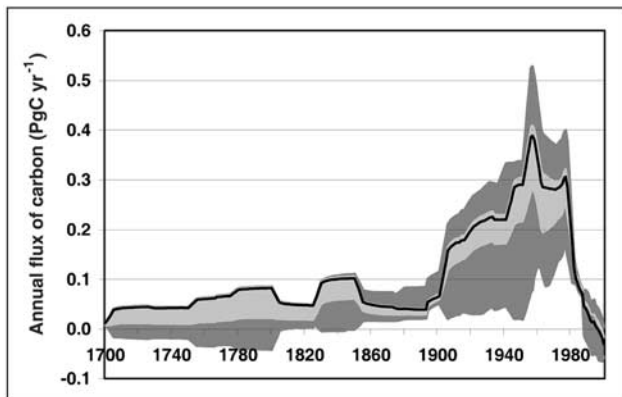


Figure 7. Annual net flux of carbon to the atmosphere from changes in land use in China. The thick line represents the reference analysis. The shading around the line represents the variability in annual flux from uncertainty in rates of deforestation (dark) and carbon stocks (light). Positive values indicate a release of carbon to the atmosphere.

from net changes in cropland areas. The largest flux (19 PgC) is attributed to the conversion of forests to degraded lands, which may have been caused by either logging or cultivation. Accounting for pastures does not help explain forest loss because the expansion of pastures was largely into natural grasslands. To the extent that pastures were cleared from forests, the associated fluxes of carbon are included in the “degraded lands” curve.

[54] The two curves in Figure 9 attributable to changes in biomass within forests result from harvest of industrial wood (3 PgC) and other disturbances (2 PgC). Industrial logging is to some extent documented, while the other disturbances include a number of poorly documented processes, such as harvest of fuelwood, fire (either accidental or deliberate), and browsing and grazing by domestic animals within forests. All of these disturbances are followed by recovery (if they were not, they would be included in the conversion of forests to degraded lands, above). Although the disturbances are not generally documented, they are ubiquitous. The fact that the average biomass of forest has declined is apparent from recent analyses of forest biomass in China [Fang *et al.*, 1998; Wang *et al.*, 2001c].

[55] Outright deforestation accounted for about 90% (29 PgC) of total emissions in the intermediate scenario. Reductions in biomass within forests as a result of wood harvest and other anthropogenic disturbances accounted about 14% (5 PgC). Afforestation offset these losses to a small extent (2 PgC). The uptake of carbon through afforestation was distributed almost equally between vegetation (1.1 PgC) and soils (0.9 PgC) because we assumed the growth of forests on degraded lands would gradually restore the initial carbon content of the soils [Guo and Gifford, 2002]. If we had distinguished timber plantations from natural forests, the estimated uptake in plantations would be somewhat larger, but the loss of carbon from deforestation of natural forests would also be larger.

[56] The relative contributions of these different land uses shifted in the last 2 decades as deforestation declined

relative to harvests and afforestation. After 1986 the major source of carbon was from harvest of fuelwood and industrial wood (Figure 9). The major sink was in plantations. The pools of carbon contributing to the net source averaging $0.008 \text{ PgC yr}^{-1}$ in the 1990s are shown in Figure 10. Emissions of $0.344 \text{ PgC yr}^{-1}$ resulted from the burning of living vegetation (fires) and the decay of wood products, slash, and soil organic matter. Gross sinks of $0.336 \text{ PgC yr}^{-1}$ resulted from the growth of biomass and the build-up of soil carbon in plantations. Soils were a net sink of $0.029 \text{ PgC yr}^{-1}$, and vegetation was a net source of $0.028 \text{ PgC yr}^{-1}$. Changes in the amount of carbon held in products and slash were small (a net loss of $0.009 \text{ PgC yr}^{-1}$ and no

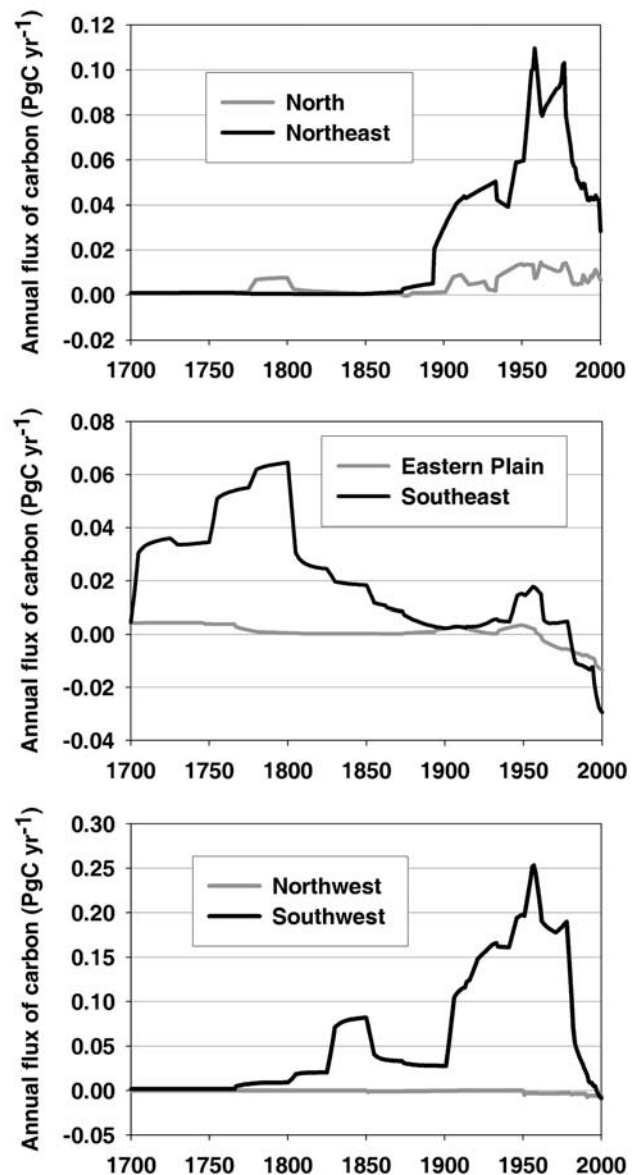


Figure 8. Annual net flux of carbon from changes in land use in individual regions of China according to the reference analysis.

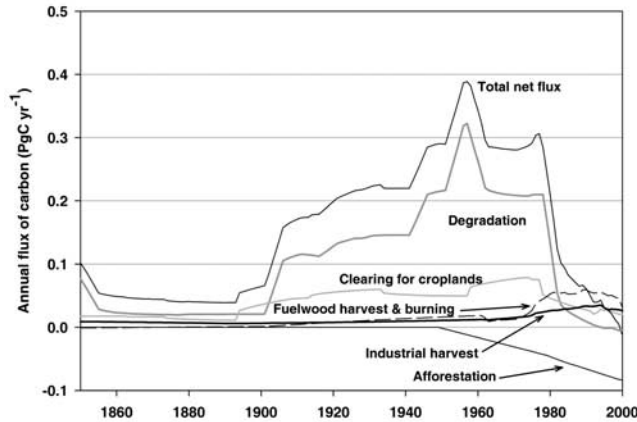


Figure 9. Annual flux of carbon from deforestation, either for croplands or as a result of degradation, from harvesting of industrial wood and other anthropogenic disturbances, and from afforestation. Values refer to the reference analysis. Positive values indicate a release of carbon to the atmosphere.

change, respectively). The fluxes into and out of these two pools were large, however.

[57] The rapidly declining emissions during the last several decades suggest that China’s terrestrial ecosystems might become a significant carbon sink in the twenty-first century. We investigated this possibility by constructing a simple scenario for the future. Deforestation and afforestation were stopped after the year 2000, but logging and other disturbances continued at average 1990s rates. Under these conditions, the annual sink grew to $\sim 0.05 \text{ PgC yr}^{-1}$ in 2000

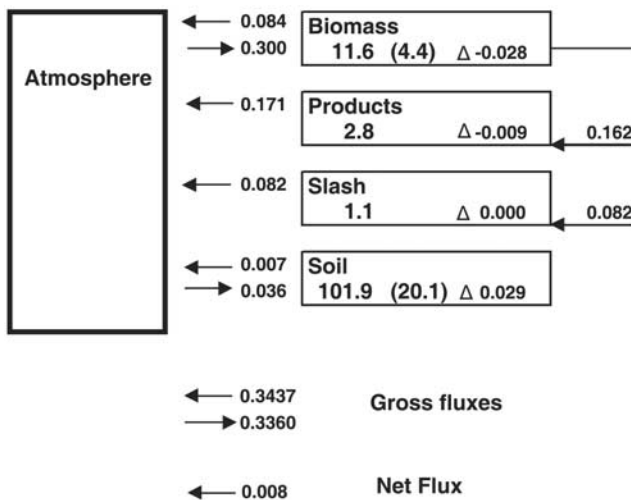


Figure 10. Average annual fluxes of carbon (PgC yr^{-1}) between the major pools of terrestrial carbon in China during the 1990s according to the reference analysis. Pool sizes (larger fonts) in the year 2000 are for all ecosystems and, within parentheses, for forests and plantations alone. Negative values for Δ indicate an average annual loss of carbon.

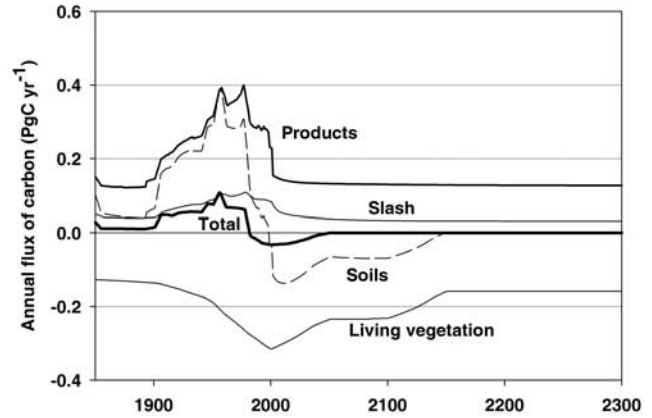


Figure 11. Annual fluxes of carbon between terrestrial pools and the atmosphere. After the year 2000, harvests continued at a constant rate but deforestation and afforestation were stopped. Positive values indicate a release of carbon to the atmosphere.

and then declined over the next 50 years to an average flux of nearly zero (Figure 11). The net flux of zero results from a balance between harvests and growth. The scenario suggests that there is little inertia to the growing carbon sink. There is a large area of forests recovering from logging activities, but this sink is largely offset by pools of slash and wood products that will release carbon over the next years. The future source/sink of carbon from land-use change in China depends on how lands are managed. The extremes include, on the one hand, complete deforestation of the remaining $140 \times 10^6 \text{ ha}$ of forests and plantations, releasing as much as 13 PgC (10 PgC from vegetation and 3 PgC from soils); and, on the other hand, complete afforestation of the $139 \times 10^6 \text{ ha}$ of degraded lands, which might accumulate as much as 22 PgC (16 PgC in vegetation and 6 PgC in soils).

4.3. Desertification

[58] The emissions of carbon from desertification were small, less than 0.01 PgC yr^{-1} in the 1990s. Even assuming a 90% loss of soil carbon with desertification [Feng et al., 2001], the initial carbon content of desert soils is so low ($22.3\text{--}37.3 \text{ MgC ha}^{-1}$ in northern China) [Wang et al., 2001b], that total emissions were calculated to be only $0.005\text{--}0.008 \text{ PgC yr}^{-1}$. Feng et al. [2001] did not address the rate at which carbon was lost from the soil profile. Instead, they used changes in the area of different stages of desertification over 40 years to calculate losses, in effect assuming that the losses of soil carbon were instantaneous. We made a similar assumption and thus may have overestimated the emissions of carbon associated with desertification. On the other hand, we probably underestimated emissions because we assumed that the soils affected were desert soils, which have very low carbon stocks to begin with [Feng et al., 2001; Wang et al., 2001b]. In contrast to this assumption, desertification, because it is caused by human activity, is not confined to arid zones (existing deserts) [Feng et al., 2001].

[59] Our estimate of the net emissions of carbon from desertification is an order of magnitude less than the

estimate by *Feng et al.* [2001], but their calculations are in error (the last column in their Table 2 is 10 times too high). Our estimate of $0.006 \text{ PgC yr}^{-1}$ for the 1990s is similar to a recent study by *Duan et al.* [2001], who reported a net loss of 0.091 PgC over the last 40 years. Their average rate ($0.0023 \text{ PgC yr}^{-1}$) would have been lower in the 1950s and higher in the 1990s because of the accelerating rate of desert expansion.

[60] Thus essentially all of carbon lost from China was from forests in our analysis. The conversion of grasslands to croplands did not result in a loss of carbon because croplands and grasslands are similar in both above- and below-ground carbon stocks. Although cultivation of native grasslands generally results in a loss of soil carbon, we believe that most of the non-forested lands converted to croplands after 1700 had already been cultivated and abandoned, and thus had already lost carbon. Desertification is estimated to have released only 0.420 PgC over the last century, 1.3% of the total flux.

5. Discussion

5.1. Uncertainties

[61] The major uncertainties are the rates of land-use change (rates of deforestation and harvests) and the carbon stocks of forests. The sensitivity of the calculated flux to uncertainties in these two types of data was estimated as follows. Over the last 300 years, the difference between the fluxes calculated by the early and late scenarios (16 PgC) gives a crude estimate of error. Because no scenario consistently produced the highest or lowest annual fluxes over the last 300 years, however, a more conservative estimate of error is calculated by the difference between the highest and lowest estimates of annual flux (the regional histories of deforestation are largely independent). The annual difference summed over the period 1700 to 2000 yielded a total difference of 24 PgC attributable to uncertain histories of land-use change. Alternative estimates of biomass gave estimates of flux that differed by 3.5 PgC over the period 1700–2000, and uncertainty in the loss of organic soil carbon with the formation of degraded lands (from cultivation or logging) gave a difference of 7 PgC . Historical data for land-use change and data for carbon stocks are largely independent, and thus about 70% ($24/(24 + 3.5 + 7)$) of the variability in the long-term flux of carbon resulted from uncertainties in land-use change and 30% resulted from uncertainties in carbon stocks (Figure 7). The relative proportions were similar for the 1990s. Three scenarios of forest biomass generated an uncertainty (range) of $\pm 0.015 \text{ PgC yr}^{-1}$; and three scenarios of rates of land use after 1986 generated a range of $\pm 0.035 \text{ PgC yr}^{-1}$. Thus, the total error is estimated to be $\pm 0.05 \text{ PgC yr}^{-1}$ for the 1990s. The average net flux of $0.008 (\pm 0.05) \text{ PgC yr}^{-1}$ is indistinguishable from zero.

[62] Clearly, better data on rates of land-use change would have the greatest effect in reducing the error associated with estimates of carbon flux. The greatest uncertainty overall is in the timing and rate of deforestation in the southwest, the region with the largest release of carbon (Figure 8).

[63] In other regions of the world, changes in the area of forests may be inferred from changes in the area of croplands and, sometimes, pastures, which are reasonably well documented (for example, *Houghton et al.* [1999]). In China, that approach is inadequate. One of the characteristics of China is the large land area that is defined by the *FAO* [2001] as “other land” (deserts, ungrazed grasslands, shrublands, and industrial, urban, and residential areas as well as roads). The combined area of these categories is large, individual categories may hold different amounts of carbon, and changes in them are not well documented, especially before 1960. In contrast, changes in the area of croplands are relatively well documented historically but, as discussed above, do not define or explain changes in forest area.

[64] Even in regions where the areas of different land uses or land covers are well documented, the calculated changes in them over time yield only net changes in area. These net changes hide a dynamic system of land-use conversion that has consequences for carbon storage. In tropical and subtropical China, for example, about $0.15 \times 10^6 \text{ ha}$ of land were added to (and simultaneously abandoned from) the cultivated area each year between 1989 and 1992 [*Li and Zhao*, 1998]. New cropland areas came from wastelands; abandoned croplands returned to forests, grazing lands, and other uses (industrialization and urbanization). Over the last 20 years the annual rates of cropland clearing and abandonment in all of China were 2–3 times higher than net changes in cropland areas [*Yang and Li*, 2000]. The significance of such dynamics is that carbon may not accumulate again or may be delayed in abandoned croplands. Although satellite data with high spatial resolution are not available historically, they could be used over the last 3 decades to reduce the uncertainties introduced by the dynamics of land-use change. The spatial information such data provide has the potential to constrain the age and carbon stocks of fallow lands and secondary forests.

[65] One other aspect of historical changes in croplands is noteworthy. The geographic distribution of cropland areas in China has shifted over the last 600 years. In 1400 about 40% of the cultivated lands were in northern regions and 60% were in east-central and southern regions. By 1957 these proportions had reversed. The area of croplands in the east-central region declined from 45% of the total in 1400 to 23% in 1957. The northeastern provinces had essentially no cropland in 1400, yet accounted for 15% of the cultivated area in 1957. In the last 2 decades the loss of croplands in southeastern China has been somewhat compensated by increases in the northwest [*Yang and Li*, 2000]. Thus, the current distribution of agricultural lands does not necessarily define the historic distribution as is sometimes assumed [*Ramankutty and Foley*, 1999].

5.2. Comparison With Other Estimates

5.2.1. Carbon Stocks

[66] The amount of carbon stored in the ecosystems of China prior to human disturbance (160 PgC according to this analysis) is close to other estimates (158 PgC [*Peng and Apps*, 1997]; 155 PgC [*Ni*, 2001]). The distribution between

living vegetation and soils (48 and 112 Pg, respectively) is intermediate between other estimates (57.9 and 100 PgC [Peng and Apps, 1997]; 35.23 and 119.76 PgC [Ni, 2001].

[67] The amount of carbon stored in forest vegetation in 2000 (4.4 Pg according to this analysis) (Figure 10) is between estimates based on recent forest inventories (3.26 Pg for 1988 [Wang et al., 2001c] and 4.75 Pg for 1998 [Fang et al., 2001]). Wang et al. [2001c] attribute their lower value to the use of different conversion factors (stem volume to total biomass) for different age classes within each species. Fang et al. [2001] used a single conversion factor for all age classes within a species.

[68] Our estimate of the amount of carbon currently in soils (101.9 Pg) is larger than the estimates by Wang et al. [2001c] (92.4 PgC) and Wu et al. [2003] (77.4 PgC). Both of their studies were based on the second national soil survey of China. The reason for their difference is unclear.

5.2.2. Carbon Flux

[69] The net release calculated in this analysis (22.6 PgC between 1850 and 1990) is higher than an earlier estimate of 9.4 PgC for China [Houghton, 1999] (Figure 12). The changes resulted from the more spatially disaggregated analysis and more detailed and recent information.

[70] Other estimates of the current flux of carbon from land-use change in China vary between net sinks of 0.020 PgC yr⁻¹ [Xu, 1992; Fang et al., 2001; Wang et al., 2001c], 0.04 PgC yr⁻¹ [Goodale et al., 2002], and 0.1 PgC yr⁻¹ [Streets et al., 2001b]. Estimates vary, in part, because they pertain to different years and often include only partial accounting of carbon. Fang et al. [2001] report an average release of carbon (0.022 PgC yr⁻¹) for the years 1949 to 1980 and an average uptake (0.021 PgC yr⁻¹) for the years 1980 to 1998. Their estimates are based on changes in forest biomass only; they did not include soils or changes in wood products. The same is true for the estimate for Chinese forests from Goodale et al. [2002]. Including soils as well as living vegetation, Zhou [2000] calculated a net forest uptake of 0.048 PgC yr⁻¹ for the period 1989–1993. Streets et al. [2001b] report an annual sink of 0.098 PgC in 1990 and of 0.112 PgC in 2000. Although our mean estimate for the 1990s was a small source, annual emissions were declining sharply during the last decades, and the last several years of the 1990s showed a net annual sink ranging between 0.02 and 0.05 PgC yr⁻¹ (Figure 7). These recent sinks are similar to the estimates, above. The variability of approximately ±0.05 PgC yr⁻¹ for the 1990s suggests that only the estimate by Streets et al. [2001b] is higher than ours.

[71] The similarity among estimates of flux is somewhat misleading, however, because the net sink in this study is largely in the soils of afforested lands (Figure 10), while the sinks reported in other analyses are largely in biomass. The finding here that forest biomass was a source of carbon is the result of forcing the biomass to match current estimates in 1986 [Fang et al., 1998]. The primary means for reducing biomass in our analysis was through rates of wood harvest (forest area was constrained by inventory data). If we lowered the rates of harvest, the net source of carbon would have become a net sink earlier, but the 1986 biomass of the model would have been larger than

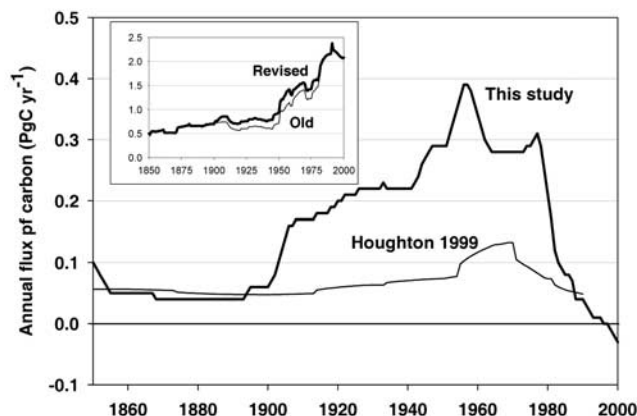


Figure 12. Estimates of the annual flux of carbon from China as a result of changes in land use 1850–2000 (reference analysis). Insert: The global flux from land-use change showing the effect of revisions reported in this study. The new global estimate [Houghton, 1999] includes this update for China. The “old” curve suggests what the global estimate would have been prior to this study. Positive values indicate a release of carbon to the atmosphere.

observed in the inventories. Although the rates of harvest we used were higher than official estimates, most “unofficial” estimates agree that the official ones are low [Richardson, 1990]. If we assumed a greater harvesting efficiency (less slash generated), the effect is similar: a reduction in areas harvested (because the demand is met by taking more m³/ha from a smaller area) and an average 1986 biomass higher than reported in the forest inventories. Although the estimated net sink is smaller and occurs later in this analysis than in other studies, our results are consistent with the observation by Shi and Xu (paper, 2001) that, despite recently reduced rates of harvest, much of the remaining logging is of older stands, and thus the average age (and biomass) of natural forests is still declining.

[72] In one of the recent scenarios, we halved the rates of both fuelwood and industrial harvest after 1986. The halved values are consistent with official estimates of harvest, and the average net flux for the 1990s was a net sink of 0.035 PgC yr⁻¹. Living biomass was a sink of 0.030 PgC yr⁻¹, slightly higher than the average (1980–1998) sink calculated by Fang et al. [2001], based on inventory data. The sink in vegetation and soils was offset to some extent by sources from slash and wood products. It is satisfying that official estimates of harvest in our simulation yield the increase in carbon stocks recorded by forest inventories. Whether the official estimates reflect the actual rates of harvest, however, is unclear. Many researchers believe the rates are higher than officially reported.

[73] The sink in afforested soils is consistent with the findings of Guo and Gifford [2002] if afforestation has been on degraded, formerly cultivated, lands, as we assumed. If the plantations were, instead, established on lands recently

cleared from forests, afforested soils are more likely to have been a carbon source.

[74] Our estimate of a 10 Pg (range 7.3–11.3) loss of carbon from soils since predisturbance conditions is larger than the estimate by *Wu et al.* [2003]. That analysis compared cultivated and never-cultivated soils from the second national soil survey and estimated a long-term loss of ~ 7.1 PgC. They found that 31% of the land surface of China had lost soil carbon, while 5% had accumulated it (in southern paddy soils and in some irrigated soils of the northwest). The area showing a loss is twice the area of existing croplands, suggesting that at least twice the present area under cultivation was cultivated at some time in the past. The finding is consistent with our inference, above, that the current area of cropland underestimates the area that was cleared for cropland and subsequently degraded.

[75] In the shorter term, our estimate of the loss of carbon from soils as a result of cultivation is similar to estimates reported by *Li et al.* [2001], who found that cultivated soils in tropical and subtropical China held 20–63% less carbon than their natural counterparts, but less than other estimates. *Cai* [1996] estimated a total loss of 1.646 PgC from an area of 32.76×10^6 ha in eastern China. For a corresponding area averaged for the Eastern Plain and the southeast, we estimated a loss of only 0.6 PgC. Relative to the initial carbon stocks, the losses estimated by *Cai* [1996] were 68% for upland croplands, 52% for fuel forests, orchards, and (eroded) wastelands, and 45% for paddy rice fields. In contrast, we assumed a loss of 25% for cultivated land. *Cai* [1996] found that paddy rice fields held 68.1% more carbon than upland cultivated soils but considerably less than the amount held in natural wetlands. We did not consider the area in paddy rice that may have been established on upland soils through irrigation. Such “new” paddies may have been and may still be carbon sinks, although a full accounting of their radiative forcing must account also for their emissions of methane.

[76] We also missed changes in soil organic carbon that resulted from changes in agricultural management. Trends in cropland soils between the 1950s and the 1980s suggest a decline in organic matter [*Lindert et al.*, 1996a, 1996b]. This loss is in addition to the initial $\sim 25\%$ loss that follows the cultivation of native soils (which we included). The losses between the 1950 and 1980s were observed in both northern and southern China and appear to have been caused by changes in the intensity of agricultural use (multicropping), rather than erosion [*Lindert et al.*, 1996a, 1996b].

6. Conclusions

[77] Four aspects of Chinese history are important in determining current emissions of carbon from land-use change. First, 19–48% of the forests lost in China were lost before 1700, and the emissions resulting from these changes occurred well before the industrial revolution. Second, despite these early reductions in forest area, rates of deforestation seem to have accelerated in the remaining

forested regions during the eighteenth and nineteenth centuries, and have continued until the present in the northeast and southwest. Third, rates of wood harvest have until recently exceeded rates of forest growth. Fourth, massive reforestation programs during the second half of the twentieth century helped offset the losses of carbon from logging and deforestation. The balance of these historic and current forces yields a flux of carbon that has recently become a net annual sink.

[78] China is attempting a major transition. Twenty years ago, only 12.5% of the country was forested, harvests exceeded growth, and stocks of carbon were declining. In contrast, the results of this analysis and the most recent forest inventories show that forests are currently accumulating carbon, due in large part to the large-scale efforts to increase the area in plantations [*Fang et al.*, 2001]. The moratorium on logging in 1998 shows that China has the political will to reverse the long-term trend of forest loss. On the other hand, the moratorium was introduced at a time when the resources were, in fact, largely gone. Whether the recent trend continues and China increases the accumulation of carbon on its lands will depend on the management of these renewable resources.

Appendix A: Historical Sketches

A1. Northeast Region (Heilongjiang, Jilin, and Liaoning)

[79] The Northeast region (Manchuria) was officially closed to Chinese settlement between 1700 and 1878 [*Murphey*, 1983; *Vermeer*, 1998], and, as a result, the region was largely forested until late in the nineteenth century. Some settlement occurred, but population numbers were low and confined to river valleys. Forest exploitation did not begin until Russia, and later Japan, built railroads in the region in the late 1800s and early 1900s. One estimate is that forest cover in the region was reduced by almost one half between 1840 and 1947 [*Vermeer*, 1998]. Another estimate suggests that the forest resources as of 1890 “had hardly been scratched,” but that today only about 10% of the late nineteenth-century forest area remains [*Murphey*, 1983]. Other activities besides logging that contributed to the loss of forests included clearing for agriculture, cutting of fuelwood for residential as well as industrial uses (porcelain, salt, metals), and both accidental and intentional fires associated with internal struggles and war.

A2. Northern Region (Inner Mongolia, Ningxia, Shaanxi, and Shanxi)

[80] *Fang and Xie* [1994] describe the Loess Plateau as having gone from the cradle of ancient Chinese civilization to one of the poorest, most backward regions of the country. This is the region where agriculture developed, yet “...by the time of the Western Han [dynasty] (206BC–AD 8), vegetation in the region had been largely removed” [*Fang and Xie*, 1994]. Much of the vegetation recovered between the third and sixth centuries when nomads from Mongolia occupied the area and replaced farmlands with grazing lands, but the recovered systems were deforested again when farmers moved back after the sixth century AD. Since

that time, the most serious deforestation of the region took place during the construction of the Great Wall in the sixteenth century, and since the middle eighteenth century as a result of more intensive clearing for agriculture and population increase. *Fang and Xie* [1994] attribute deforestation to four major factors: fuelwood collection, charcoal making for heating in winter, clearing for croplands, and brick making and construction of houses and palaces.

A3. Eastern Plain (Hebei, Beijing, Tianjing, Shandong, Henan, Anhui, Jiangsu, and Shanghai)

[81] “The Huang-Huai-Hai [three rivers] Plain, the largest plain in eastern China (approximately 35×10^6 ha) is now one of the key agricultural regions of China. Cities existed along the northern edges of the plain from the sixteenth century BC, but the central part was largely unsettled until dikes were built, starting in the middle of the second century BC” [*Zuo and Zhang*, 1990]. Drainage systems constructed during the Wei Dynasty in 361 BC and 422 BC allowed permanent settlement, but also destroyed much forest and pasture. Grazing replaced farming (and preserved forests) following the migration of nomadic tribes into the region.

[82] In the fifth century BC, the mountains north of Beijing were heavily forested, and until the Yuan Dynasty (AD 1271-1368), the mountains of the Plain were also forested. By 1426-1435 the royal fuel source had been moved east of the capital to protect the remaining Beijing forest for defense. Forest cover was lost to agriculture as well as to fuelwood and timber harvests. Between 1375 and 1403, for example, the cultivated area in Beijing grew from 160×10^6 ha to 420×10^6 ha. The remaining forest was cut during the Qing Period (1644–1911) [*Zuo and Zhang*, 1990].

[83] The Ming dynasty had declared many mountain and forest areas to be protected, but starting in the eighteenth century forests in the highlands of the lower Yangtze region (Anhui, Zhejiang, Jiangsu) began to be cleared as a result of expanding populations and the need for food [*Osborne*, 1998]. *Vermeer* [1998] gives an example of a hunting preserve in Hebei province. Imperial hunting grounds were established in 1681. Encroachment by poachers, cattle thieves, and loggers started before 1800, and imperial hunting stopped around 1820. Within a few decades, over 250 ha had been converted to farmland, and by 1905, when its special status was lifted, the preserve’s forest cover was only 5%.

[84] The erosion and flooding associated with deforestation in the mountains is believed to have been a major reason why the population in this region actually declined between 1850 and 1953 [*Osborne*, 1998]. Large tracts of cultivated land were laid waste during World War II. For example, in Henan province, the area of cultivated land was 30% lower in 1946 than it had been in 1936. Cultivated land also decreased after the 1950s, from 23×10^6 ha in 1957 to 18.2×10^6 ha in 1983.

A4. Southeastern China (Hubei, Zhejiang, Fujian, Jiangxi, Hunan, Guangxi, Guangdong, and Hainan)

[85] During the Ming and Qing dynasties two of the three major sources of timber were in this region (Fujian and Hunan). Historical changes in the region of Lingnan

(now approximately Guangdong and Guangxi provinces) are described by *Marks* [1998]. Paddy rice cultivation appeared in the region in the eleventh century, replacing slash-and-burn, or swidden cultivation. Population size and cultivated lands went through a series of ups and downs, with peaks in 1200 and 1600 and large decreases in the fourteenth and seventeenth centuries as a result of wars and foreign conquests (Mongol and Manchu, respectively). The decline in the mid-seventeenth century, associated with the first 40 years of the Qing dynasty (1644–1911), reduced the areas of cultivated lands by 35% in Guangdong (from 2×10^6 ha in 1600 to 1.3×10^6 ha around 1650) and by 50% in Guangxi. Recovery was rapid, however, and by 1800 both population and cultivated areas were at levels twice as high as at any previous time. By 1853, all of Guangdong province that could be cultivated was. The cultivated area was similar to that of the twentieth century when only 10% of the land was in forest. Forest cover in Guangxi diminished as well. Between 1693 and 1853 2.5×10^6 ha were added to the cultivated area of Lingnan, most of it from marginal hilly land. The rates of deforestation that accompanied this increase in cultivated lands increased geometrically. Forests disappeared faster than population increased, first, because much of the added croplands were for the production of commercial products (export), and, second, because people burned the hills repeatedly, and forests could not recover. Burning removed the hiding places of bandits and tigers. As early as 1800 whole prefectures in Lingnan were without fuelwood.

A5. Southwestern China (Yunnan, Sichuan, Guizhou, Xizang (Tibet))

[86] Although the area of cropland in Tibet increased an average of 59% between 1930 and 1990 [*Ryavec*, 2001], the major factor responsible for forest loss in southwestern China has been logging. Sichuan province was one of three major sources of timber during Ming and Qing dynasties. According to *Vermeer* [1998], the exploitation of forests along the southwestern frontier did not change during the Qing dynasty; it just moved higher and further away from the centers of population, driven by population growth and increased economic demands. In the early nineteenth century, the Bashan mountains on the border of Shaanxi and Sichuan were one of the last remaining original forest areas in China proper [*Vermeer*, 1998]. “Entrepreneurs employed tens of thousands of loggers, felling trees for timber and to provide fuel for mines, salt wells, iron and paper factories” [*Vermeer*, 1998].

[87] Despite these early harvests, large areas of forest escaped harvest because they were remote from population centers. Since 1950, however, annual harvests of wood have been four times greater than sustainable yields, reducing forest cover in Tibet from 9% in 1950 to 5% in 1985, in Yunnan from 55% to 30%, and in Sichuan from 30% to 6.5% (Studley, paper, 2001). Hongchang (study, 2001) reports a decline of forest cover in Sichuan that began at least as early as 1937. *Li and Lai* [1991] report a 60% decrease in forest area over the period 1950 to 1982 in a 1.9 million ha region of southwestern China.

A6. Northwestern China (Xinjiang, Qinghai, and Gansu)

[88] The high elevation, cold, largely desert conditions of this province seem to have discouraged human activity. Little of the initial forest area has been lost.

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