CARBON STORAGE IN TERRESTRIAL ECOSYSTEMS OF CHINA: ESTIMATES AT DIFFERENT SPATIAL RESOLUTIONS AND THEIR RESPONSES TO CLIMATE CHANGE

JIAN NI*

Laboratory of Quantitative Vegetation Ecology, Institute of Botany, Chinese Academy of Sciences, Xiangshan Nanxincun 20, 100093 Beijing, China

E-mail: nijian@public.east.cn.net

Abstract. The carbon storage of terrestrial ecosystems in China was estimated using a common carbon density method for vegetation and soils relating to the vegetation types. Using median density estimates, carbon storage of 35.23 Gt (1 Gt = 10^{15} g) in biomass and 119.76 Gt in soils with total of 154.99 Gt were calculated based on the baseline distribution of 37 vegetation types. Total carbon storage of the median estimates at different spatial resolutions was 153.43, 158.08 and 158.54 Gt, respectively, for the fine (10′), median (20′) and coarse (30′) latitude × longitude grids. There were differences of –1.56, +3.09 and +3.55 Gt carbon storage between baseline vegetation and those at different spatial resolutions. Change in mapping resolution would change area estimates and hence carbon storage estimates. The finer the spatial resolution in mapping vegetation, the closer the carbon storage to the baseline estimation. Carbon storage in vegetation and soils for baseline vegetation is quite similar to that of biomes predicted by BIOME3 for the present climate and CO_2 concentration of 340 ppmv. Climate change alone as well as climate change with elevated CO_2 concentration will produce an increase in carbon stored by vegetation and soils, especially a larger increase in the soils. Total median carbon storage of terrestrial ecosystems in China will increase by 5.09 Gt and 15.91 Gt for the climate scenario at CO_2 concentration of 340 ppmv and 500 ppmv, respectively. This is mainly due to changes in vegetation areas and the effects of changes in climate and CO_2 concentration.

1. Introduction

Terrestrial vegetation and soils in the terrestrial biosphere play an active role in shaping the environmental systems of the Earth. They are essential in determining the state of the global climate system and carbon cycle (Schlesinger, 1991; Smith et al., 1993), which are both undergoing significant anthropogenic perturbations (Foley et al., 1996). In particular, the build-up of CO_2 in the atmosphere because of human activity (IPCC, 1996) has the potential to affect the carbon storage and carbon balance of terrestrial ecosystems (McGuire et al., 1997). An improved understanding of changes in carbon storage of terrestrial ecosystems is very important for assessing the impacts of increasing atmospheric CO_2 concentration and climate change on the terrestrial biosphere, as well as the interactions and feedbacks between the global climate system and the terrestrial biosphere.

* Present address: Global Ecology Group, Max Planck Institute for Biogeochemistry, Carl Zeiss Promenade 10, P.O. Box 10 01 64, D-07701 Jena, Germany. E-mail: jni@bgc-jena.mpg.de

Climatic Change **49:** 339–358, 2001.

Carbon storage in live vegetation (Olson et al., 1983) and in soils (Post et al., 1982; Zinke et al., 1984) has been estimated based on the natural distribution of major world ecosystem complexes. Global and continental carbon storage has been estimated using pollen data (e.g., Peng et al., 1994, 1995a–c), and simulated using different global models based on potential vegetation maps for the present climate (e.g., Woodward et al., 1995; Foley et al., 1996), future changing climate (e.g., Melillo et al., 1993, 1996; McGuire et al., 1997), and past climates (e.g., Adams et al., 1990; Prentice and Fung, 1990; Prentice et al., 1993). Proper classification and estimation of the area extent of vegetation are essential factors for simulated estimates of global and regional carbon storage. Specifically, estimates of the area extent of vegetation rely heavily upon the accuracy of mapped vegetation distributions. However, several definitions of vegetation types and different vegetation maps currently exist in the literature (Melillo et al., 1993; Haxeltine and Prentice, 1996). Furthermore, no single global or regional vegetation map contains all of the information required for estimation and simulation of carbon storage. Different world vegetation maps and different spatial resolution, therefore, may result in the variability of estimation on carbon storage.

China covers both a large area of land and represents several climate regimes. These climate regimes include perennial snow (high western mountains especially the Tibetan plateau), deserts (northwestern lowlands), cold temperate regions (northeast), and warm and humid tropics (southeastern coast) (Zhang, 1991). The contrast of East Asian summer and winter monsoons and high elevation of the Tibetan plateau result in a unique set of terrestrial ecosystems. These include the boreal coniferous forest (northeast), temperate deciduous forest (middle), warm temperate evergreen forest (southeast), tropical rain forest (south), temperate steppe (central north), desert (west), and special alpine vegetation (western mountains, specifically the Tibetan plateau) (Editorial Committee for Vegetation of China, 1980). The climatic variability, topographic complexity, natural ecosystem diversity, as well as human disturbance give China an important role in and large contribution to global carbon cycle (Fang et al., 1996a,b).

The terrestrial carbon storage of China for the last glacial maximum and the mid-Holocene has been estimated using palaeovegetation maps and an empirical Osnabrück biosphere model (Peng and Apps, 1997). This study also reconstructed terrestrial carbon storage of China for the present (Peng and Apps, 1997). However, Peng and Apps (1997) only used nine vegetation types including boreal coniferous forest, coniferous and deciduous broad-leaved mixed forest, deciduous and broad-leaved forest, deciduous and evergreen broad-leaved mixed forest, desert and semidesert, highland vegetation, subtropical evergreen broad-leaved forest, steppe and highland steppe, and tropical monsoon rain forest. The vegetation classification and the spatial resolution of $0.5° \times 0.5°$ grid level were very coarse. Modern climate data obtained from the IIASA global climate database had lower resolution ($0.5° \times 0.5°$ grid scale), sparse data coverage or a strong geographic variation and errors for China. The soil data used by Peng and Apps (1997), based on the soil map of the world (FAO-UNESCO, 1974), was given on a 1° × 1° grid, had the same problems.

Fang et al. (1996a,b) have presented the carbon cycle of terrestrial ecosystems in China in which terrestrial carbon storage of China was reconstructed from estimates of net primary production (NPP) derived from the field measurements of biomass for samples of most forest types and partial steppe and desert types. Although plantations were taken into account (Fang et al., 1996b), data derived from field samples could not summarise the regional carbon storage of China because of very sparse field samples, especially on the Tibetan plateau and in the temperate steppe and desert regions that cover nearly half of China.

More detailed and accurate regional climate, soil and vegetation data of China have recently become available. Using these data, an improved simulation of the geographical distribution and NPP of eighteen biomes in China was made with the process-based equilibrium terrestrial biosphere model BIOME3 under present climate and changed climate at CO_2 concentration of 340 and 500 ppmv (Ni et al., 2000). In this paper, I focus on the estimates of carbon storage in terrestrial ecosystems of China based on a baseline vegetation distribution (the Vegetation Map of China: Hou et al., 1982) and their accurate areas. Comparisons of carbon storage at fine, median and coarse spatial resolutions are performed in order to reveal the difference of carbon storage due to different spatial resolutions. Carbon storage of Chinese terrestrial ecosystems is then modelled using BIOME3 at present climate and CO_2 concentration according to a carbon density method and the simulated areas determined in Ni et al. (2000). Finally, responses of carbon storage to climate change alone and climate change with elevated CO_2 concentration are simulated using the same method.

2. Data and Methods

2.1. CLIMATE, VEGETATION AND SOIL DATA

Monthly mean temperature, precipitation, percent of sunshine hours, and absolute minimum temperature data for 841 standard weather stations between 1951 and 1980 in China (Chinese Central Meteorological Office, 1984) were interpolated to a 10′ × 10′ grid by the smoothing spline method developed by M. F. Hutchinson (Wolfgang Cramer, Potsdam, personal communication).

The climate scenario used in this study was the output for the end of the 21st century (2070–2099) from the Hadley Centre coupled ocean-atmosphere general circulation model (Mitchell et al., 1995; Johns et al., 1997), including the effects of both greenhouse gases and sulphate aerosols. The anomalies were interpolated to 10′ grid, and then added to the baseline climate to produce the climate fields used to drive BIOME3. The emission scenario of CO_2 was an increase of CO_2 concentration from 340 ppmv to 500 ppmv.

A digitised vegetation map, which consists of 113 vegetation types and 178 subtypes, was constructed from the vegetation map of China at 1:4,000,000 scale (Hou et al., 1982). The vegetation classifications on grid cells of 10′, 20′ and 30′ resolutions were extracted from the digitised map. Thirty-seven vegetation categories (Table I) used in this paper were assigned from 113 vegetation types. For the BIOME3 model, a digitised vegetation map on 10′ grid squares was constructed by assigning these units to the 18 BIOME3 categories (Ni et al., 2000).

A soil-texture data set of China was constructed on 10′ grid cell based on the textural information digitised from Xiong and Li (1987). The data set distinguished 12 classes of fine-, median-, and coarse-textured soils and combinations of these classes were assigned to the seven categories used in BIOME3 (Ni et al., 2000).

2.2. CARBON DENSITY

Biomass carbon densities of Olson et al. (1983) and Prentice et al. (1993) and soil carbon densities from Zinke et al. (1984) and Prentice et al. (1993) were used to give a range of carbon densities for each vegetation type (Table I) and biome (Table II). These values were multiplied by baseline, fine, median, coarse and future vegetation areas to product the carbon storage of vegetation.

2.3. RESPONSE OF CARBON STORAGE TO CLIMATE CHANGE

The vegetation distribution of China was successfully simulated (Ni et al., 2000) by the equilibrium terrestrial biosphere model BIOME3, which relies on ecophysiological constraints, resource availability and competition among plant functional types (Haxeltine and Prentice, 1996). Three climates and two CO_2 concentrations, i.e., present climate at CO_2 concentration of 340 ppmv, changed climate at CO_2 concentration of 340 ppmv and 500 ppmv were considered in Ni et al. (2000). The simulated vegetation distributions from these scenarios are compared with present values of carbon density in order to determine the future carbon storage of vegetation and soils.

3. Results

3.1. CARBON STORAGE FROM BASELINE VEGETATION AND AT DIFFERENT SPATIAL RESOLUTIONS

The total gigatons (1 Gt $= 10^{15}$ g) of carbon storage and their median values in 37 vegetation types for different spatial resolutions (Table III) were estimated by multiplying the area of vegetation (m^2) by the mass of carbon per unit area (kg m^{-2}) (Table I).

TABLE I

Carbon densities (kg m^{-2}) of vegetation and soils: low (L), median (M) and high (H) values for 37 vegetation categories from Olson et al. (1983), Zinke et al. (1984), and Prentice et al. (1993). Thirty-seven vegetation categories were assigned from 113 vegetation types from the vegetation map of China (Hou et al., 1982)

No	Vegetation type	Vegetation C			Soil C		
		L	M	H	L	M	H
1	Boreal southern continental taiga	6.0	11.0	14.0	12.7	16.6	20.5
2	Cool/cold temperate conifer forests	12.0	16.8	20.0	13.8	14.7	15.6
3	Temperate conifer forests	7.5	10.8	14.3	13.0	14.0	15.0
4	Warm temperate conifer and mixed forests	12.0	16.8	20.0	13.0	14.0	15.0
5	Temperate conifer and deciduous broad-leaved mixed forests	6.0	10.0	14.0	10.5	13.0	15.5
6	Temperate deciduous broad-leaved forests	8.0	10.0	14.0	12.7	15.2	17.7
7	Temperate deciduous broad-leaved mixed forest	5.8	8.0	12.0	12.0	15.0	17.0
8	Warm temperate evergreen broad-leaved and mixed forests	10.0	15.0	18.0	12.4	13.3	14.2
9	Tropical seasonal forest	10.0	14.0	17.0	9.5	10.4	11.3
10	Tropical rain forest	15.0	20.0	25.0	9.5	10.4	11.3
11	Conifer woodlands	6.0	10.0	14.0	12.0	13.0	14.0
12	Boreal forest and woodlands	4.0	8.0	11.0	12.7	16.6	20.5
13	Temperate semiarid woodlands	2.0	5.0	10.0	11.0	14.0	15.0
14	Tropical dry woodland	5.0	7.0	9.0	6.3	7.3	8.3
15	Temperate dry scrubs	2.0	4.0	8.0	10.0	13.0	14.0
16	Temperate semiarid scrubs	2.0	4.0	5.0	11.0	14.0	15.0
17	Warm-temperate scrubs	2.0	5.0	10.0	11.0	14.0	15.0
18	Tropical scrubs	3.0	6.0	10.0	11.0	14.0	15.0
19	Xeric succulent thorn woods and scrub or grass	2.0	4.0	6.0	6.7	7.3	7.9
20	Mangroves	3.0	7.0	10.0	6.7	7.3	7.9
21	Arid shrublands/steppe	1.0	1.6	3.0	7.0	8.0	9.0
22	Temperate savannas (grass-scrub)	2.0	3.0	4.0	9.5	11.2	13.3
23	Temperate typical steppe	0.8	1.3	2.5	11.6	12.3	13.0
24	Temperate deserted steppe	0.5	1.0	2.4	7.2	8.7	10.2
25	Temperate desert	0.3	0.6	1.0	4.1	6.2	8.3
26	Wooded tundra	1.0	2.0	5.0	10.0	16.6	23.2
27	Alpine meadows and swamps	0.5	1.0	4.0	15.7	18.2	20.7
28	Alpine steppe	0.5	1.0	2.0	14.0	17.0	19.0
29	Alpine desert	0.5	0.8	1.5	14.0	17.0	19.0
30	Bogs/mires of cool or cold climate	1.0	2.0	6.0	11.6	12.3	13.0
31	Wetlands, swamps and marshes	1.5	3.0	6.0	11.6	12.3	13.0
32	Cold-temperate cultivated vegetation	1.5	2.0	3.0	10.0	13.0	15.0

TABLE I

(Continued)

No	Vegetation type	Vegetation C			Soil C		
		L	M	H	L	M	H
33	Temperate cultivated vegetation	2.0	3.0	4.0	12.0	15.0	17.0
34	Warm-temperate cultivated vegetation	2.0	4.0	6.0	12.0	13.0	14.0
35	Tropical cultivated vegetation	2.0	4.0	6.0	9.0	10.0	11.3
36	Bare land	0.02	0.05	0.2	0	0	0
37	Ice/Polar desert	0.002	0.01	0.02	0.004	0.02	0.04

Each vegetation category was assigned from one or more vegetation types used in the vegetation map of China (Hou et al., 1982).

1. *Larix* forests: *Larix gmelinii*, *L. olgensis* and *L. sibirica.*

2. *Pinus* forests: *Pinus sylvestris* var. *mongolica* and *P. sibirica*; *Picea-Abies* forests: *Picea jeroensis, Abies obovata*, and *P. sibirica*; *Picea* forests: *Picea crassifolia, P. schrenkiana, P. wilsonii, P. meyeri*, and *P. jeroensis*; *Abies-Picea* forests with *Tsuga*: *Picea asperata, P. purpurea, Abies faxoniana, A. georgei, A. forrestii, P. likiangensis, A. fabri, A. spectabilis, P. spinulosa, A. kawakamii* and *P. morrisonicola.*

3. *Pinus* forests: *Pinus tabulaeformis, P. densiflora* and *Platycladus orientalis.*

4. *Pinus* forests: *Pinus massoniana* forest with *Rododendron, Vaccinium, Melastoma*; *Pinus armandii* forest with *Quercus, Cyclobalanopsis*; *Pinus yunnanensis* and *P. khasya* forests; *Cunninghamia lanceolata* forest; *Pinus densata* and *P. griffithii* forests.

5. Deciduous broadleaf trees-*Pinus koraiensis* forest; Mixed forest containing Ulmaceae, *Platycarya strobilacea* and *Cyclobalanopsis*; Mixed forest containing *Cyclobalanopsis, Castanopsis* and *Fagus*; Mixed forest containing deciduous broad-leaved trees (*Fagus longipetiolata, Acer, Betula*), evergreen oaks (*Cyclobalanopsis glauca, Quercus aquifolioides*) and *Tsuga*.

6. Deciduous oak forests: *Quercus mongolica, Q. liaotungensis, Q. dentata, Q. aliena, Q. variabilis, Q. acutedentata* and *Q. Glandulifera.*

7. Mixed forest containing *Acer, Tilia amurensis, Fraxinus mandshurica, Ulmus propinqua* and *Betula platyphylla*; Mixed forest containing Ulmaceae and *Pistacia.*

8. Mixed forest containing *Cyclobalanopsis, Castanopsis* and *Lithocarpus*; Mixed forest containing *Castanopsis*, Lauraceae, *Schima, Manglietia, Illicium* and *Wendlandia*; Mixed forest containing *Castanopsis*, Lauraceae, Theaceae with some trees belonging to tropical families; *Quercus aquifolioides* forest; *Phyllostachys pubescens* forest.

9. Seasonal forest on limestone soil: *Gironniera nitida, Pometia tomentosa, Colona sinica, Mallotus pseudoverticilata, Burretiodendron hsienmu, Drypetes confertiflora, Cleistanthus saichikii, Garcinia paucinervis* and *Muricococcum sinense*; Seasonal forest on acid lateritic soil: *Kleinhovia hospita, Spondias pinnata, Hainania trichisperma, Antiaris taxicaria, Lagerstroemia intermedia* and *Gironniera subaegualis.*

10. Tropical rain forest: *Vatica astrotricha, Amesiodendron chinense, Tarrietia parvifolia, Dipterocarpus yunnanensis, Tetrameles nudiflora, Crypteronia paniculata, Pometia tomentosa, Terminalia myriocarpa, Erythrina lithocarpa, Pterospermum niveum* and *Artocarpus lanceolata.*

11. *Pinus sylvestris* var. *mongolica woodland*; *Cupressus* woodland: *C. funebris* and *C. duclouxiana.*

12. *Betula* and *Populus* forests: *Betula platyphylla, Populus davidiana, B. ermanii, B. albo-sinensis* and *B. platyphlla* var. *szechuanica.*

13. *Ulmus pumila* woodland; *Populus diversifolia* with *Elaeagnus angustifolia* woodland.

14. *Scaevola frutescens, S. hainanensis*, and *Pisonia grandis* scrubs.

15. *Corylus heterophylla, Lespedeza bicolor*, and *Quercus mongolica* scrubs; *Ostryopsis davidiana* and *Spiraea pubescens* montane scrubs; *Vitex negundo* var. *heterophylla* scrub; *Exochorda racemosa, Forsythia suspensa, Quercus variabilis*, and *Platycarya strobilacea* scrubs.

16. *Caragana microphylla* var. *daurica, Salix, Artemisia halodendron* and *A. ordosica* scrubs; *Tamarix* scrub.
17. *Rhododendron* and *Vaccinium* scrubs; *Melastoma* and *Aporosa* scrubs; *Platycarya strobilacea, Zanthoxylum planispinum, Rosa microcarpa*, and *Viburnum* scrubs; *Rhododendron* and *Sinarundinaria* scrubs.
18. *Ficus, Alchornea trewioides, Boehmeria nivea*, and *Clausena excavata* scrubs.
19. *Heteropogon contortus* and *Cymbopogon distans* savannas with thorny scrubs: *Zizyphus mauritiana, Acacia farnesiana, Flacourtia indica* and *Pandanus tectorius*.
20. Mangrove containing *Kandelia candel, Rhizophora mucronata, R. apiculata* and *Bruguiera sexangula*.
21. *Haloxylon* sandy deserts: *Haloxylon persicum* and *H. ammodendron*; *Haloxylon ammodendron* and *Reaumuria soongarica* loamy deserts; *Haloxylon* gravely deserts: *Ephedra przewalskii, Haloxylon ammodendron* and *H. Persicum*.
22. *Filifolium sibiricum* steppe with *Stipa baicalensis, Festuca ovina, Prunus sibirica* and *Spodiopogon sibiricus*; *S. baicalensis* steppe with *F. sibiricum, Leymus chinense, P. sibirica* and *Sp. sibiricus*.
23. *Leymus chinense* steppe with rich forbs and *Stipa*; *Bothriochloa ischaemum* and *Themeda triandra* var. *japonica* steppes with rich forbs; *Stipa grandis* and *S. krylovii* steppes; *S. krylovii* and *Cleistogenes squarrosa* steppes; *S. bungeana* and *S. breviflora* steppes; *Festuca sulcata, S. capillata* and *S. krylovii* steppes.
24. *Stipa breviflora* steppe with *Artemisia frigida* and *Ajania fruticulosa*; *S. gobica* steppe with *A. frigida, Reaumuria soongarica, Salsola passerina, A. xerophylla, S. glareosa*, and *Caragana*.
25. *Sympegma regelii* rocky deserts: *Sympegma regelii* and *Iljinia regelii*; *Anabasis* gravely deserts: *A. salsa, Nanophyton erinaceum* and *A. brevifolia*; *Reaumuria soongarica* gravely deserts: *Reaumuria soongarica* and *Salsola passerina*; *Artemisia kaschgarica* and *A. borotalensis* loamy deserts with some ephemeral forbs; *Kalidium* saline deserts: *Kalidium, Nitraria sibirica, Halostachys belangeriana* and *H. strobilaceum*; *Ephedra przewalskii* gravely deserts: *Ephedra przewalskii, Zygophyllum xanthoxylum, Nitraria sphaerocarpa*, and *Calligonum*; *Potaninia mongolica, Ammopiptanthus mongolicus*, and *Tetraena mongolica* sandy gravely deserts; *Artemisia sphaerocephalla* and *A. ordosica* sandy deserts: *Oxytropis aciphylla* and *Calligonum mongolicum*; *Calligonum* sandy deserts: *Calligonum rigidum, C. leucocladum* and *Calligonum zaidamense*; Sparse *Tamarix* sandy desert.
26. *Salix, Dasiphora fruticosa* and *Caragana jubata* scrub; Montane tundra containing *Salix rotundifolia* and *Vaccinium vitisi-daea*.
27. Grass, *Kobresia*, and forb meadows; *Kobresia pygmaea* and *K. tibetica* meadows; Halophytic grass, forb and *Kobresia* meadows; *Phragmites communis* and *Carex rhynchophysa* swamps; *Calamagrostis epigeios, Betula fruticosa* and *Salix brachypoda* swamps; *Carex* and *Kobresia* swamps.
28. Montane dwarf shrub and *Stipa* steppe: *Festuca sulcata, Stipa capillata* and *S. glareosa*; Forb and *S. przewalskii* steppes, combined with *Pennisetum flaccidum* and *Orinus thoroldii* steppe; Forb, *Poa* and *Festuca* steppes; *S. purpurea* steppe; *S. subsessiliflora* var. *basiplumosa* and *Ceratoides compacta* steppes.
29. *Arenaria musciformis* and *Androsace tapete* cushion-like vegetation; *Ephedra przewalskii, Salsola abrotanoides* and *Ceratoides latens* deserts; *Caragana tibetica* and *Ceratoides latens* sandy gravely deserts; *Ceratoides compacta* and *Ajania tibetica* sandy gravely desert.
30. Gramenoid and forb meadows: *Sanguisorba officinalis, Artemisia laciniata, Carex, Deyeuxia angustifolia*, Graminoid and forb.
31. Halophytic grass and forb meadows: *Aeluropus littoralis* var. *sinensis, Suaeda salsa, Leymus chinense, Hordeum brevisubulatum, Achnatherum splendens, Leymus dasystachys, Phragmites communis, Poacynum hendersonii* and *Alhagi pseudalhagi*; Grass, Forb and *Carex* meadow.
32. Spring wheat, soybean, corn, millet, sugar beet and flax; plum, apricot and Chinese apple; Spring wheat, millet, potatoes, sugar beet and flax.
33. Spring barley, spring and winter wheat, pea, potatoes and rapeseed; Winter wheat, soybean (corn) and two crops annually; Peanut, sweet potatoes, tobacco; apple, pear, and grape; Winter wheat,

coarse grains (kaoliang, corn, millet) and three crops in two years; Soybean and cotton; Chinese date, apple, pear, grape, persimmon, chestnut and walnut; Winter wheat, coarse grains (corn, millet, sweet potatoes) and two crops annually; Cotton, peanut and soybean; Chinese date, apple and pear; Winter (spring) wheat, corn, millet and three crops in two years or two crops annually; cotton; Grape, Hami melon, pear and apricot.

34. Summer rice, winter wheat (rapeseed) and two crops annually (double-cropping rice locally); Cotton and peanut; Tea, pomegranate, peach, pear and loquat; Summer rice (corn), winter wheat (rapeseed) and two crops annually; Potatoes and tobacco; tea, lacquer, red bayberry, walnut, apple and pear; Double-cropping rice followed by winter wheat (rapeseed) or green manure; Cotton, ramie, mulberry and orange; Single or double-cropping rice followed by winter wheat (rapeseed) annually; Sweet potatoes, peanut, grains and five crops in two years; Sugarcane and ramie; Orange, tungoil, mulberry and palm; Single or double-cropping rice followed by winter wheat (rapeseed) or green manure annually, or sweet potatoes, grains, soybean, three upland crops annually, ramie and jute; Tea, teaoil, red bayberry, orange and loquat.

35. Double-cropping rice followed by sweet potatoes and double-cropping corn; Sugarcane and manioc; Litchi, longyan, banana and pineapple; Thrice-cropping rice, winter peanut, sugarcane, vanolla and sisal; Rubber, coconut, coffee and oil palm.

36. Salt crust, wandering sanddune, bare gobi and bare rocky hill.

37. Sparse vegetation of high-mountains with rocky fragments and glaciers.

Based on the area of baseline vegetation distribution, the low, median and high values of carbon storage in vegetation and soils of China were 120.47, 154.99 and 189.23 Gt, respectively. The carbon storage varied among different vegetation types. Using the median carbon storage estimates, total carbon storage of 35.23 Gt in biomass and 119.76 Gt in soils was calculated (Table III). The highest carbon storage values of 17.92 Gt occurred in warm-temperate scrubs because of the largest area and higher carbon density. Carbon storage of 31.75 Gt for forests (vegetation types 1–10 in Table I), 37.5 Gt for woodlands, shrublands and scrubs (types 11–22), and 37.02 Gt for alpine vegetation (types 26–29) were higher than steppes, deserts and swamps. Alpine vegetation had low carbon storage of 1.95 Gt in live vegetation, but they had high carbon storage of 35.07 Gt in soils. Cultivated vegetation (types 32–35) covered about 19.12% of total area of China and had 30.55 Gt of stored carbon, representing 19.71% of total carbon storage in China (Table III). Forests had the largest carbon storage per unit area (10^4 km^2) of 0.28 Gt, based on the area of each vegetation type. Woodlands, shrublands and scrubs (0.17 Gt/10^4 km^2), steppes (0.13 Gt/10^4 km^2), alpine vegetation (0.18 Gt/10^4 km^2), swamps (0.15 Gt/10^4 km^2) and cultivated vegetation (0.17 Gt/10^4 km^2) had median carbon storage per unit area. Deserts (0.07 Gt/10^4 km^2), bare land and ice/polar desert ($\cong 0$) had the lowest carbon storage per unit area.

Total carbon storage of the median estimates was 153.43, 158.08 and 158.54 Gt, respectively, for the fine (10′), median (20′) and coarse (30′) spatial resolutions (Table III). Comparison to carbon storage of baseline vegetation, the differences of total carbon storage were –1.56, +3.09 and +3.55 Gt for 10′, 20′ and 30′ resol-

TABLE II

Carbon densities (kg m^{-2}) in vegetation and soils: low (L), median (M), and high (H) values for 18 biomes from Prentice et al. (1993), Olson et al. (1983) and Zinke et al. (1984). Eighteen biomes originally used in BIOME3 (Haxeltine and Prentice, 1996) and then in China (Ni et al., 2000), were assigned from 113 vegetation types for the vegetation map of China (Hou et al., 1982)

Biomes		Vegetation C			Soil C		
		L	M	H	L	M	H
1	Boreal deciduous forest/ woodland	4.4	8.7	11.7	12.7	16.6	20.5
2	Boreal evergreen forest/ woodland	6.0	11.0	14.0	10.0	13.0	15.0
3	Temperate/boreal mixed forest	6.0	10.0	14.0	10.5	13.0	15.5
4	Temperate conifer forest	12.0	16.8	20.0	13.8	14.7	15.6
5	Temperate deciduous forest	8.0	10.0	14.0	12.7	15.2	17.7
6	Temperate broad-leaved evergreen forest	6.0	10.0	14.0	12.4	13.3	14.2
7	Tropical seasonal forest	10.0	14.0	17.0	9.5	10.4	11.3
8	Tropical rain forest	10.0	20.0	25.0	9.5	10.4	11.3
9	Tropical deciduous forest	3.2	4.6	6.6	6.3	7.3	8.3
10	Moist savannas	2.0	4.0	6.0	9.5	11.2	13.3
11	Dry savannas	2.0	3.0	5.0	8.0	10.0	12.0
12	Tall grassland	0.8	1.3	2.5	7.2	8.7	10.2
13	Short grassland	0.5	1.0	2.4	11.6	12.3	13.0
14	Xeric woodland/scrub	2.0	4.1	7.3	6.7	7.3	7.9
15	Arid shrubland/steppe	1.0	1.6	3.0	7.0	8.0	9.0
16	Desert	0.3	0.6	1.0	4.1	6.2	8.3
17	Arctic/alpine tundra	0.5	0.8	1.3	15.7	18.2	20.7
18	Ice/polar desert	0.002	0.01	0.02	0.004	0.02	0.04

utions, respectively. The biggest difference occurred between baseline vegetation and coarse spatial resolution.

Carbon storage in each vegetation type varied for the fine, median and coarse resolutions because of the differences in the estimated area for each vegetation type at different resolutions (Table III). When vegetation data were extracted from the baseline to fine, median and coarse resolutions, vegetation types covering large areas would replace those vegetation types in small areas because of the sparser and more mosaic distributions of the latter. For example, the conifer forests of taiga, cold temperate conifer forest, temperate conifer forest and warm-temperate conifer forest are usually distributed in small fragments within the zones of broad-leaved forests (deciduous or evergreen). At coarser resolution, the broad-leaved

TABLE III

Median (M) carbon storage (Gt) and areas (10^4 km^2) in vegetation and soils based on baseline vegetation distribution and different spatial resolutions of fine (10′), median (20′) and coarse (30′). The vegetation types are the same as in Table I

Vegetation	Baseline		10 × 10		20 × 20		30 × 30	
	Area	M	Area	M	Area	M	Area	M
1	10.72	2.96	13.03	3.60	12.56	3.47	13.25	3.66
2	14.59	4.59	13.83	4.36	15.89	5.01	13.25	4.17
3	0.53	0.13	0.67	0.17	0.56	0.14	0.25	0.06
4	35.99	11.09	33.08	10.19	32.11	9.89	34.75	10.70
5	13.40	3.08	13.72	3.16	13.33	3.07	15.25	3.51
6	9.81	2.47	11.08	2.79	11.44	2.88	9.00	2.27
7	3.52	0.81	3.72	0.86	4.11	0.95	3.75	0.86
8	19.20	5.43	17.47	4.94	20.22	5.72	20.00	5.66
9	1.78	0.43	1.47	0.36	1.44	0.35	1.25	0.31
10	2.49	0.76	2.11	0.64	2.11	0.64	2.25	0.68
11	1.31	0.30	1.44	0.33	1.67	0.38	1.25	0.29
12	4.86	1.20	5.97	1.47	2.67	0.66	3.00	0.74
13	6.18	1.18	6.42	1.22	6.56	1.57	6.50	1.56
14	0.01	0.001	0.00	0.00	0.00	0.00	0.00	0.00
15	56.64	9.63	58.78	9.99	56.56	9.61	61.75	10.50
16	16.19	2.91	17.36	3.13	17.33	3.12	17.25	3.11
17	94.31	17.92	83.69	15.90	86.89	20.85	86.50	20.76
18	2.00	0.40	1.61	0.32	2.11	0.42	1.75	0.35
19	6.56	0.74	5.83	0.66	5.33	0.60	5.50	0.62
20	0.08	0.01	0.08	0.01	0.11	0.02	0.00	0.00
21	17.21	1.65	18.67	1.79	19.44	1.87	18.00	1.73
22	11.02	1.56	12.81	1.82	13.44	1.91	12.75	1.81
23	46.39	6.31	50.17	6.82	49.56	6.74	53.25	7.24
24	12.15	1.18	13.19	1.28	14.56	1.41	13.25	1.29
25	83.82	5.70	89.00	6.05	88.44	6.01	89.25	6.07
26	5.86	1.09	6.11	1.14	6.00	1.12	5.25	0.98
27	61.64	11.83	59.81	11.48	45.56	8.75	46.00	8.83
28	71.70	12.91	70.89	12.76	69.78	12.56	70.25	12.65
29	62.89	11.19	60.50	10.77	61.89	11.02	60.75	10.81
30	12.71	1.82	15.56	2.22	12.11	1.73	12.00	1.72
31	20.48	3.13	21.89	3.35	18.00	2.75	17.50	2.68
32	46.73	7.01	49.44	7.42	45.67	6.85	50.00	7.50
33	66.03	11.89	66.03	11.89	67.78	12.20	65.50	11.79
34	58.44	9.93	53.31	9.06	72.22	12.28	70.75	12.03
35	12.26	1.72	10.50	1.47	10.78	1.51	11.50	1.61
36	29.42	0.01	30.42	0.02	30.67	0.02	30.25	0.02
37	40.73	0.00	40.31	0.00	40.78	0.00	39.75	0.00
Total	959.63	154.99	959.97	153.43	959.67	158.08	962.50	158.54

forests would often replace the conifer forests found in grid cells at finer resolution. Boreal forest and woodlands (deciduous) are mostly distributed at higher elevations with conifers and arboreal deciduous trees, where nearly half of the total area was changed at different resolutions. Tropical dry woodlands are found in the islands of the South China Sea, in a very small area. This vegetation type was lost at fine, median and coarse resolutions. Mangroves from the coast of southern China were also lost at coarse resolution. Warm-temperate scrubs and alpine vegetation have larger areas and higher carbon densities than the other vegetation types, and so changes in their area distribution significantly influenced the values of carbon storage (Table III). Thus, differences of area of each vegetation type at varying spatial resolutions resulted in different estimates of carbon storage (Table III).

3.2. RESPONSES OF CARBON STORAGE TO CLIMATE CHANGE AND CO_2 ENRICHMENT

The simulation of vegetation and NPP in China showed that the global process-based equilibrium terrestrial biosphere model BIOME3 could be used successfully at a regional scale (Ni et al., 2000). Using BIOME3, the present-day distribution of eighteen vegetation types and their changes of area in response to climate change and CO_2 concentration enrichment were modelled across China (Ni et al., 2000; Figure 1a). Carbon storage based on carbon densities of 18 biomes (Table II) at present climate and at climatic scenario with CO_2 concentration at 340 ppmv and 500 ppmv were then estimated respectively (Figures 1b–d, Table IV).

Total carbon storage in vegetation and soils for baseline vegetation for the present climate is quite similar to that of biomes predicted by BIOME3 for the present climate and CO_2 concentration at 340 ppmv (Table IV) because numerical comparison showed a good agreement between baseline vegetation and biome maps predicted by BIOME3 (Ni et al., 2000). However, the carbon storage (in vegetation, soils and total) of some biomes, such as temperate/boreal mixed forest, temperate conifer forest, temperate deciduous forest, tall grassland and short grassland, shows large differences between baseline vegetation and predicted biome (Figures 1b–d) due to large differences in area extent (Figure 1a). Both climate change alone and climate change with CO_2 enrichment will produce an increase in carbon stored by vegetation and soils, especially a large increase in the soil carbon (Table IV). Total carbon storage of terrestrial ecosystems in China will increase by 5.09 Gt and 15.91 Gt, respectively, for the climate scenario at CO_2 340 ppmv and 500 ppmv, based on the median carbon estimates. Carbon storage in vegetation and soils as well as total carbon of some biomes will increase, whereas some of them will decrease under changing climate and CO_2 concentration (Figures 1b–d). The change in carbon storage of each biome is related to the change in area of each biome (Figure 1a). The main contributions to the change in carbon storage between vegetation in future climate with CO_2 at 340 ppmv and baseline vegetation are the increase of 6.97 Gt in temperate/boreal mixed forest, 4.23 Gt in tropical rain

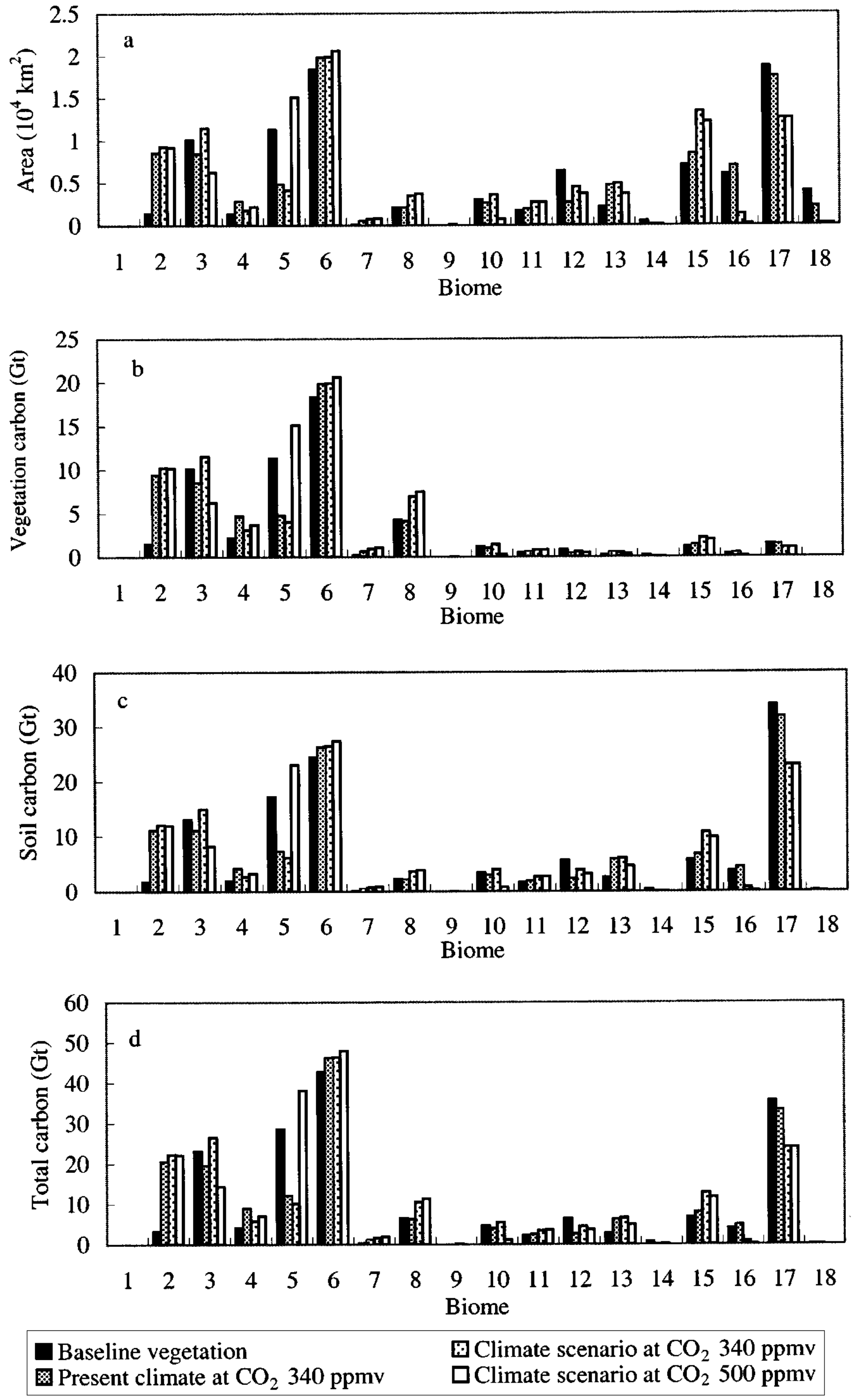

Figure 1. Changes in (a) area, (b) vegetation carbon, (c) soils carbon, and (d) total carbon of baseline vegetation and 18 biomes predicted by BIOME3 model (Haxeltine and Prentice, 1996) based on the median estimates. Eighteen biomes are the same as in Table II.

TABLE IV

Changes of carbon storage (Gt) in vegetation and soils: low (L), median (M) and high (H) values for baseline vegetation and biomes of China predicted by BIOME3 for different climates and CO_2 concentrations. The spatial resolution is 10′ latitude × 10′ longitude

Climate and CO_2	Vegetation C			Soil C			Total carbon		
conditions	L	M	H	L	M	H	L	m	H
Baseline vegetation	34.31	53.96	76.17	101.40	117.84	134.26	135.71	171.80	210.42
Present climate at CO_2 340 ppmv	35.20	57.74	79.88	102.09	118.54	134.24	137.29	176.28	214.12
Climate scenario at CO_2 340 ppmv	37.97	63.36	87.98	102.05	118.01	133.18	140.02	181.37	221.16
Climate scenario at CO_2 500 ppmv	43.99	69.43	95.84	106.27	122.76	138.36	150.26	192.19	234.20

forest, 4.85 Gt in arid shrubland/steppe, and the decrease of 3.92 Gt in desert, and 9.19 in arctic/alpine tundra (Figure 1d). The main contributions to the change in carbon storage between vegetation in future climate with CO_2 at 500 ppmv and baseline vegetation are the increase of 26.04 Gt in temperate deciduous forest, 5.03 Gt in tropical forest, 3.73 Gt in arid shrubland/steppe, and the decrease of 5.12 Gt in temperate/boreal mixed forest, 4.66 Gt in desert, and 9.19 in arctic/alpine tundra (Figure 1d). The significant increase of carbon storage in temperate deciduous forest and the decrease in temperate/boreal mixed forest and moist savannas between climate scenario with CO_2 at 340 ppmv and 500 ppmv are mainly due to CO_2 fertilization resulting in the increase in area for the former and the decrease in area for the latter (Figure 1a).

4. Discussion

A number of studies have estimated the terrestrial carbon storage of the world and have examined its sensitivity to changes in global climate, both past and future (e.g., Prentice and Fung, 1990; Smith et al., 1992; King and Neilson, 1992; Prentice et al., 1993; Cramer and Solomon, 1993; Smith and Shugart, 1993; Neilson, 1993). All of these studies shared a common methodology, combining a mapping system for global patterns of vegetation with carbon density estimates for vegetation and soils relating to the classification units, i.e., vegetation or ecosystem types (Smith et al., 1993). The global distribution of vegetation was mapped by applying the different biogeographical modelling approaches to global databases of climate, soils and topography. Carbon density for each vegetation type and associated soil (i.e., classification units) were estimated from published sources (e.g., Olson et al., 1983; Post et al., 1982; Zinke et al., 1984) and these densities were multiplied by the area estimates for each of the vegetation types (classification units) as predicted by the biogeographical models. This paper follows the same methodology for terrestrial ecosystems of China.

In general, the value of carbon storage relies on the vegetation area and carbon densities in vegetation and soils. The area determines the carbon storage in vegetation and soils for a fixed carbon density. Therefore, carbon storage of terrestrial ecosystems should be changed for the fine, median and coarse spatial resolutions because of changes in vegetation areas (Table III). Additionally, differences in vegetation classification schemes result in the different estimates of carbon storage in vegetation and soils because of changes in carbon densities and vegetation areas (Tables I and II). In theory, the finer the vegetation classification, the more accurate the estimate of carbon storage. Of course, this depends on how well we know the carbon densities in vegetation and soils.

My current estimates of carbon storage in terrestrial vegetation and soils for China, using median estimates, are summarised in Table V. These values are also compared with other carbon storage values for China and the world that were de-

TABLE V

Comparisons of median carbon storage (Gt) in terrestrial ecosystems of China to other estimates in China and in the world

Model or vegetation classification	Biome	Vegetation C	Soil C	Spatial resolution	Reference
Baseline vegetation	37	35.23	119.76		This paper
Baseline biome	18	53.96	117.84	$10' \times 10'$	This paper
BIOME3 model	18	57.74	118.54	$10' \times 10'$	This paper
Osnabrück model	9	57.9	100.0	$0.5^\circ \times 0.5^\circ$	Peng and Apps, 1997
Data-based estimates	9	47.1	101.1	$0.5^\circ \times 0.5^\circ$	Peng and Apps, 1997
Terrestrial ecosystems	32	6.1 [a,b]	185.7		Fang et al., 1996a,b
China mean		43.01	123.82		
Ecosystem complexes	34	558 [a] (461–665) [a,b]		$0.5^\circ \times 0.5^\circ$	Olson et al., 1983
Holdridge life zone	22		1395 [b]	$0.5^\circ \times 0.5^\circ$	Post et al., 1982
Holdridge life zone	39	737.2	1158.5	$0.5^\circ \times 0.5^\circ$	Smith et al., 1992
Modified Holdridge model	14	748	1143	$0.5^\circ \times 0.5^\circ$	Prentice and Fung, 1990
BIOME1 model	14	754(457–574) [a]	1367	$0.5^\circ \times 0.5^\circ$	Cramer and Solomon, 1993
BIOME1 model	17	785	1337	$0.5^\circ \times 0.5^\circ$	Prentice et al., 1993
World mean		756(537) [a]	1280		

[a] With extensive and sparse agricultural vegetation; others only with natural vegetation.
[b] Based on field estimates from various ecosystem studies; others based on estimates from Olson et al. (1983), Post et al. (1982) and Zinke et al. (1984) combined with potential vegetation maps from biogeographical model.

termined using a variety of data-based and modelling approaches (carbon density method: Post et al., 1982; Olson et al., 1983; Prentice and Fung, 1990; Smith et al., 1992; Prentice et al., 1993; Cramer and Solomon, 1993; Peng and Apps, 1997; Data-based method: Peng and Apps, 1997; and biomass and soil organic matter method: Fang et al., 1996a,b).

In China, carbon storage in soils for 37 baseline vegetation types, 18 baseline biomes and 18 predicted biomes of this study is quite similar, and slightly higher than that for 9 vegetation types estimated and modelled by Peng and Apps (1997). However, carbon storage in vegetation for 37 baseline vegetation types of this study is lower than that for 18 baseline and predicted biomes of this study, and for 9 vegetation types of Peng and Apps (1997). This may be due to finer vegetation classification and different values of carbon density for different vegetation types. Data-based estimates of carbon storage in vegetation and soils between this study and Peng and Apps (1997) are similar because of the same methods of estimation, although both the vegetation classifications and spatial resolutions are quite different (Table V). Fang et al. (1996a,b) estimated carbon storage of terrestrial ecosystems in China based on field biomass measurements and soil organic matter contents. The carbon storage of 6.1 Gt in vegetation (Fang et al., 1996a,b) is much lower than any estimates from this study and Peng and Apps (1997). However, their estimate of 185.7 Gt carbon in soils is much larger than that of this study and Peng and Apps (1997). The differences between the Fang et al. (1996a,b) study and this one result from several causes: (1) samples of biomass measurements were very sparse for some vegetation types; (2) methods for estimating of NPP had shortcomings; and (3) the depth and carbon density in soils were both higher than this study and Peng and Apps (1997). Therefore, low and high values of carbon storage in vegetation and soils result from many factors, such as vegetation classification schemes, spatial resolutions, modelling approaches, and environmental databases.

The average world carbon storage under conditions of natural vegetation is only 756 Gt for biomass and 1280 Gt for soils. When both sparse and extensive agronomic cultivation are included with natural vegetation, this number is reduced to 537 Gt for biomass (Table V) for a world area of 150×10^6 km^2. In China, the median estimate of carbon storage is 35.23 Gt for biomass and 119.76 Gt for soils with the total area of 9.6×10^6 km^2 included agronomic cultivation (Table V). Based on the above estimates, in the area of 6.4% of the world, carbon storage of China is 4.7% for biomass and 9.4% for soils of the world potential carbon storage, and 6.6% of the world carbon storage for biomass when considered the cultivation. Using the carbon storage predicted by BIOME3, China’s proportion of the global carbon storage would be even larger.

Peng and Apps (1997) indicated that the present total carbon storage in China was lower than that of the mid-Holocene (MH), which experienced warmer and moist conditions. Furthermore, MH terrestrial carbon storage was larger than that of the last glacial maximum (LGM), which was colder and had lower atmospheric CO_2. Although the MH is not an analogue to possible future warm climates because of the Earth's orbital configuration was different than at present, the increasing tendency of terrestrial carbon storage from the LGM to the MH is similar to the change of that from the present to the future warm climates induced by human activities. This is mainly due to changes in vegetated areas and the effects of change in climate and CO_2 concentration.

It is very important that the accuracy of carbon density estimate should be discussed. Although the future vegetation types have been predicted by BIOME3 under a changed climate and CO_2 regime (Ni et al., 2000), present values for carbon density (Table II) were still used to calculate the future carbon storage in Chinese terrestrial ecosystems in this study (Table IV). However, this is not entirely accurate because carbon density in the future will be changed under future climate conditions (Peng et al., 1998; Cramer et al., 1999). Carbon sequestration depends on vegetation composition and climate (Peng et al., 1998). Although many vegetation types in the past and future may have compositions close to that of the present ones, they may have different carbon densities under these different climate conditions (Friedlingstein et al., 1995; Peng et al., 1998; Cramer et al., 1999). Hence, the application of the modern carbon density database (e.g., Olson et al., 1983; Zinke et al., 1984) would underestimate or overestimate the past and future terrestrial carbon storage values (Peng et al., 1998; Cramer et al., 1999). Thus, changes in carbon density under future climate conditions could have a significant impact on the estimates of carbon storage in China. In this sense, the new approaches such as the Dynamic Global Vegetation Models (DGVMs) coupling biogeography and biogeochemistry models are encouraging (VEMAP Members, 1995; Foley et al., 1996, 1998; Beerling et al., 1997; Betts et al., 1997; Cramer et al., 1999) because they take into account the effects of changes in climate and atmospheric CO_2 concentration on both vegetation redistribution and carbon density (Peng et al., 1998). The Lund-Potsdam-Jena DGVM (LPJ: Sitch et al., 2000) are being applied in China (Liu et al., in preparation) and will incorporate the dynamics of vegetation to estimate more accurate carbon storages in the future.

Acknowledgements

The author gratefully thanks Alex Haxeltine, I. Colin Prentice and Martin T. Sykes for providing the BIOME3 model and helpful assistance. Thanks also to five anonymous reviewers for commenting on the manuscript and for very valuable information. I also wish to thank Karen E. Kohfeld and Ming Dong for improving the English. The research was funded by the National Natural Science Foundation of China (NSFC#39970154, 39700018 and 49731020).

References

Adams, J. M., Faure, H., Faure-Denard, L., McGlad, J. M., and Woodward, F. I.: 1990, 'Increases in Terrestrial Carbon Storage from the Last Glacial Maximum to the Present', *Nature* **348**, 711–714.

Betts, R. A., Cox, P. M., Lee, S. E., and Woodward, F. I.: 1997, 'Contrasting Physiological and Structure Vegetation Feedbacks in Climate Change Simulations', *Nature* **387**, 796–799.

Chinese Central Meteorological Office: 1984, *Climatological Data of China*, China Meteorology Press, Beijing.

Cramer, W. and Solomon, A. M.: 1993, 'Climatic Classification and Future Redistribution of Global Agricultural Land', *Clim. Res.* **3**, 97–110.

Cramer, W., Shugart, H. H., Noble, I. R., Woodward, F. I., Bugmann, H., Bondeau, A., Foley, J. A., Gardner, R. H., Lauenroth, W. K., Pitelka, L. F., Sala, O., and Sutherst, R. W.: 1999, 'Ecosystem Composition and Structure', in Walker, B. H., Steffen, W. L., Canadell, J., and Ingram, J. S. I. (eds.), *The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems*, Cambridge University Press, Cambridge, pp. 190–228.

Editorial Committee for Vegetation of China: 1980, *Vegetation of China*, Science Press, Beijing.

Fang, J. Y., Liu, G. H., and Xu, S. L.: 1996a, 'Carbon Cycle of Terrestrial Ecosystems in China and Its Global Significance', in Wang, R. S., Fang, J. Y., Gao, L., and Feng, Z. W. (eds.), *Hot Spots in Modern Ecology*, China Science and Technology Press, Beijing, pp. 240–250.

Fang, J. Y., Liu, G. H., and Xu, S. L.: 1996b, 'Carbon Pools in Terrestrial Ecosystems in China', in Wang, R. S., Fang, J. Y., Gao, L., and Feng, Z. W. (eds.), *Hot Spots in Modern Ecology*, China Science and Technology Press, Beijing, pp. 251–277.

FAO-UNESCO: 1974, *Soil Map of the World*, 1:5 000 000, Vols. I–X, UNESCO, Paris.

Foley, J. A., Levis, S., Prentice, I. C., Pollard, D., and Thompson, S. L.: 1998, 'Coupling Dynamics Models of Climate and Vegetation', *Global Change Biol.* **4**, 561–579.

Foley, J. A., Prentice, I. C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S., and Haxeltine, A.: 1996, 'An Integrated Biosphere Model of Land Surface Processes, Terrestrial Carbon Balance, and Vegetation Dynamics', *Global Biogeochem. Cycles* **10**, 603–628.

Friedlingstein, C., Prentice, K. C., Fung, I. Y., Jone, J. G., and Brasseur, G. P.: 1995, 'Carbon-Biosphere-Climate Interaction in the Last Glacial Maximum Climate', *J. Geophys. Res.* **100**, 7203–7221.

Haxeltine, A. and Prentice, I. C.: 1996, 'BIOME3: An Equilibrium Terrestrial Biosphere Model Based on Ecophysiological Constraints, Resource Availability and Competition among Plant Functional Types', *Global Biogeochem. Cycles* **10**, 693–709.

Hou, X. Y., Sun, S. Z., Zhang, J. W., He, M. G., Wang, Y. F., Kong, D. Z., and Wang, S. Q.: 1982, *Vegetation Map of the People's Republic of China*, China Map Publisher, Beijing.

Intergovernmental Panel on Climate Change (IPCC): 1996, *Climate Change 1995: The Science of Climate Change*, Cambridge University Press, Cambridge.

Johns, T. C., Carnell, R. E., Crossley, J. F., Gregory, J. M., Mitchell, J. F. B., Senior, C. A., Tett, S. F. B., and Wood, R. A.: 1997, 'The Second Hadley Centre Coupled Ocean-Atmosphere GCM: Model Description, Spinup and Validation', *Clim. Dyn.* **13**, 103–134.

Matthews, E.: 1984, 'Global Inventory of the Pre-Agricultural and Present Biomass', *Prog. Biometeorol.* **3**, 237–247.

McGuire, A. D., Melillo, J. M., Joyce, L. A., Kicklighter, D. W., Grace, A. L., Moor III, B., and Vorosmarty, C. J.: 1992, 'Interactions between Carbon and Nitrogen Dynamics in Estimating Net Primary Productivity for Potential Vegetation in North America', *Global Biogeochem. Cycles* **6**, 101–124.

McGuire, A. D., Melillo, J. M., Kicklighter, D. W., Pan, Y., Xiao, X., Helfrich, J., Moore III, B., Vorosmarty, C. J., and Schloss, A. L.: 1997, 'Equilibrium Responses of Global Net Primary Production and Carbon Storage to Doubled Atmospheric Carbon Dioxide: Sensitivity to Changes in Vegetation Nitrogen Concentration', *Global Biogeochem. Cycles* **11**, 173–189.

Melillo, J. M., McGuire, A. D., Kicklighter, D. W., Moore III, B., Vorosmarty, C. J., and Schloss, A. L.: 1993, 'Global Climate Change and Terrestrial Net Primary Production', *Nature* **363**, 234–240.

Melillo, J. M., Prentice, I. C., Schulze, E.-D., Farquhar, G. D., and Sala, O. E.: 1996, 'Terrestrial Ecosystems: Biotic Feedbacks to Climate', in Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K. (eds.), *Climate Change: The IPCC 1995 Assessment*, Cambridge University Press, Cambridge, pp. 449–481.

Mitchell, J. F. B., Johns, T. C., Gregory, J. M., and Tett, S. F. B.: 1995, 'Climate Response to Increasing Levels of Greenhouse Gases and Sulphate Aerosols', *Nature* **376**, 501–504.

Ni, J., Sykes, M. T., Prentice, I. C., and Cramer, W.: 2000, 'Modelling the Vegetation of China Using the Process-Based Equilibrium Terrestrial Biosphere Model BIOME3', *Global Ecol. Biogeog.* **9**, in press.

Olson, J. S., Watts, J. A., and Allison, L. J.: 1983, *Carbon in Live Vegetation of Major World Ecosystems*, ORNL-5862, Oak Ridge National Laboratory, Oak Ridge.

Olson, J. S., Watts, J. A., and Allison, L. J.: 1985, *Major World Ecosystem Complexes Ranked by Carbon in Live Vegetation: A Database*, Oak Ridge National Laboratory, Oak Ridge.

Peng, C. H. and Apps, M. J.: 1997, 'Contribution of China to the Global Carbon Cycle since the Last Glacial Maximum: Reconstruction from Palaeovegetation Maps and an Empirical Biosphere Model', *Tellus* **49B**, 393–408.

Peng, C. H., Guiot, J., Van Canpo, E., and Cheddadi, R.: 1994, 'The Vegetation Carbon Storage Variation in Europe since 6000 BP: Reconstruction from Pollen', *J. Biogeogr.* **21**, 19–31.

Peng, C. H., Guiot, J., and Van Canpo, E.: 1995a, 'Reconstruction of the Past Terrestrial Carbon Storage of the Northern Hemisphere from the Osnabrück Biosphere Model and Palaeodata', *Clim. Res.* **5**, 107–118.

Peng, C. H., Guiot, J., Van Canpo, E., and Cheddadi, R.: 1995b, 'The Variation of Terrestrial Carbon Storage at 6000 Years BP in Europe: Reconstruction from Pollen Data Using Two Empirical Biosphere Models', *J. Biogeogr.* **22**, 581–591.

Peng, C. H., Guiot, J., Van Canpo, E., and Cheddadi, R.: 1995c, 'Temporal and Spatial Variations of Terrestrial Biomes and Carbon Storage Since 13 000 Years in Europe: Reconstruction from Pollen Data and Statistical Models', *Water Air Soil Pollut.* **82**, 375–391.

Peng, C. H., Guiot, J., and Van Campo, E.: 1998, 'Estimating Changes in Terrestrial Vegetation and Carbon Storage: Using Palaeoecological Data and Models', *Quatern. Sci. Rev.* **17**, 719–735.

Post, W. M., Emanuel, W. R., Zinke, P. J., and Stangenberger, A. G.: 1982, 'Soil Carbon Pools and World Life Zones', *Nature* **298**, 156–159.

Prentice, I. C.: 1993, 'Biome Modelling and the Carbon Cycle', in Heimann, M. (ed.), *The Global Carbon Cycle*, Springer, Berlin, pp. 219–238.

Prentice, K. C. and Fung, I. Y.: 1990, 'The Sensitivity of Terrestrial Carbon Storage to Climate Change', *Nature* **346**, 48–50.

Prentice, I. C. and Sykes, M. T.: 1995, 'Vegetation Geography and Global Carbon Storage Changes', in Woodwell, G. M. and Mackenzie, F. T. (eds.), *Biotic Feedbacks in the Global Climatic System: Will the Warming Speed the Warming?*, Oxford University Press, New York, pp. 304–312.

Prentice, I. C., Cramer, W., Harrison, S. P., Leemans, R., Monserud, R. A., and Solomon, A. M.: 1992, 'Global Biome Model: Predicting Global Vegetation Patterns from Plant Physiology and Dominance, Soil Properties and Climate', *J. Biogeogr.* **19**, 117–134.

Prentice, I. C., Sykes, M. T., Lautenschlager, M., Harrison, S. P., Dennissenko, O., and Bartlein, P. J.: 1993, 'Modelling Global Vegetation Patterns and Terrestrial Carbon Storage at the Last Glacial Maximum', *Global Ecol. Biogeog. Lett.* **3**, 67–76.

Schlesinger, W. H.: 1991, *Biogeochemistry: An Analysis of Global Change*, Academic Press, New York.

Sitch, S., Prentice, I. C., Smith, B., and LPJ Consortium Members: 2000. 'LPJ: A Coupled Model of Vegetation Dynamics and the Terrestrial Carbon Cycle', in Sitch, S., *The Role of Vegetation*

Dynamics in the Control of Atmospheric CO_2 Content, Doctoral Dissertation, Lund University, Lund, pp. 1–53.

Smith, T. M., Cramer, W. P., Dixon, R. K., Leemans, R., Neilson, R. P., and Solomon, A. M.: 1993, 'The Global Terrestrial Carbon Cycle', *Water Air Soil Pollut.* **70**, 19–37.

Smith, T. M., Leemans, R., and Shugart, H. H.: 1992, 'Sensitivity of Terrestrial Carbon Storage to CO_2 Induced Climate Change: Comparison of Four Scenarios Based on General Circulation Models', *Clim. Change* **21**, 367–384.

VEMAP Members: 1995, 'Vegetation/Ecosystem Mapping and Analysis Project (VEMAP): A Comparison of Biogeography and Biogeochemistry Models in the Context of Global Change', *Global Biogeochem. Cycles* **9**, 407–437.

Woodward, F. I., Smith, T. M., and Emanuel, W. R.: 1995, 'A Global Land Primary Productivity and Phytogeography Model', *Global Biogeochem. Cycle* **9**, 471–490.

Xiong, Y. and Li, Q. K.: 1987, *Soil of China*, 2nd edn., Science Press, Beijing.

Zhang, J. C.: 1991, *Climate of China*, China Meteorology Press, Beijing.

Zinke, P. J., Stangenberger, A. G., Post, W. M., Emanuel, W. R., and Olson, J. S.: 1984, *Worldwide Organic Soil Carbon and Nitrogen Data*, ORNL/TM-8857, Oak Ridge National Laboratory, Oak Ridge.

(Received 6 April 1999; in revised form 8 August 2000)