

## **A Preliminary Study on the Carbon Dynamics of China's Forest Ecosystems in the Past 20 Years**

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**Abstract.** Carbon balance is characterized by the net ecosystem productivity (NEP), the difference between net primary productivity (NPP) and the heterotrophic respiration (Rh), namely the decomposition of dead organic matter by soil microbes. At the global scale, NEP is of great interest because it indicates the capacity of terrestrial ecosystems absorbing/releasing CO<sub>2</sub> from/to the atmosphere. In this paper, we briefly review some of the research efforts that are related to the carbon balance of China. Direct field measurement of Rh is rare because separating root respiration (Rr) from the total soil surface CO<sub>2</sub> efflux is very difficult. Although the current global terrestrial ecosystems are most likely at non-equilibrium state due to various disturbances, such as fire, deforestation, and land-use change, as well as climate and atmospheric changes, we report in this paper our initial attempts towards the determination of carbon balance of China based on a new technique for estimating soil Rh. Based on the fact that at the equilibrium state NPP equals Rh, using NOAA AVHRR data and field NPP measurements we estimated the NPP of China's forest ecosystems between 1982–1998. Therefore, we were able to present preliminary results of NEP obtained for China's forest ecosystems.

**Keywords:** net ecosystem productivity (NEP), NPP, soil heterotrophic respiration

### 1. INTRODUCTION

In comparison to intensive studies of regional and global carbon balance in Europe and America, research activities on China's carbon cycling lag far behind. China occupies approximately one 15th of the world land area, covering from south to north a number of climate zones ranging from tropical, to subtropical, temperate and cold temperate zones, and from southeast to northwest humid, semi

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Project supported by Ministry of Science and Technology of China, Project Number #2001CB3094, 2001BA611B-01, and Outstanding Overseas Researcher Grant of Chinese Academy of Sciences.

humid, semi-arid to arid zones. Land use change in China is characterized by rapid alteration of landscapes shaped by centuries of human activities. The change has been particularly significant over the last two decades due to rapid economic growth. It occurred largely in the eastern part of China where the landscapes had been altered by intensive farming and industrialization. With its ambitious economic plan on the development of Western China launched in March 2000 by the Chinese Government, large-scale rapid changes in western China are expected in the next few decades. This has important implications to China's carbon budget for two reasons. First the west is China's main source of energy supply. It is expected that the energy consumption in quantity and spatial pattern will change. Second, the ecosystems in Western China represent some of the most fragile ecosystem types in the nation and in the world. The possible change in those ecosystems could strongly disturb the current carbon cycling, influence the functioning of the terrestrial ecosystems in China and, over time, reshape their structural and geographical patterns.

These structural changes could in turn affect the climate because of biospheric feedbacks in response to changes in carbon, water and heat regimes. The types and degree of likely ecosystem responses are not well understood but they will likely vary with the biome (forest, grasslands, agroecosystems, wetlands, etc.).

A critical issue in understanding the impact of climate change is to separate out direct human effects on the landscape from those attributable to indirect environmental changes such as climatic warming. A further critical problem in the study of ecosystem responses to climatic change is the non-linearity of relationships among various ecological processes when assessed operating at varying spatial scales, from leaf to landscape up to regional and continental scales. Satellite observations combined with flux data provide the key measurement techniques to allow bridging this range of scales for process studies and monitoring environmental and ecological changes. These short-term measurements can also be combined with historical climate and biotic disturbance records to investigate the long-term carbon dynamics of terrestrial ecosystems.

The long-term goal of this project is to estimate the carbon dynamics of the terrestrial ecosystems in China, so as to better understand the relationship between the global climate and terrestrial ecosystems. We will estimate the spatial and temporal pattern of NEP of China in the recent decades, so as to answer the question of when and where China's terrestrial ecosystems are carbon sink or source at 1 to 8 km resolution. The objectives are:

- 1) to develop and validate methods for the extraction of biophysical and biochemical parameters from optical and microwave satellite data for major Chinese biomes;
- 2) to develop methods for extending measurements or process understanding embedded in models across a range of spatial scales, from leaf to stand, landscape and region; and
- 3) to use satellite-derived parameters with data from other sources as inputs to models that allow spatially explicit assessment of various ecosystem performance in China at various time scales from day to season, year, decade and

century.

While the scope of this study is the entire China, we realize that estimating carbon balance in agroecosystems under various cultivation regimes cannot be accurate without using frequent high resolution satellite imagery of the entire country. We report here our initial results on the spatial distributions of NEP in forested areas.

## 2. EXISTING NET PRIMARY PRODUCTIVITY ESTIMATION OF CHINA

Estimation of net primary productivity (NPP) of China's terrestrial ecosystems has only been done recently based on primarily climate models or statistical models with satellite data as inputs. Xiao *et al.* (1996) made the first estimation of NPP over China using NDVI derived from NOAA AVHRR data. Sun and Zhu (2000) used fraction of absorbed photosynthetically active radiation (FPAR) derived from AVHRR data with soil and climate data to estimate NPP. They estimated an annual NPP of  $2.645 \times 10^9$  tC in China. With AVHRR data, some research has emphasized either on natural vegetation/forests (Jiang *et al.*, 1999) or on croplands (Zhang and Fu, 1999). However, none of these studies was verified nor did they use process-based models. Zheng and Zhou (2000) used AVHRR data to derive leaf area index (LAI) for estimating NPP in China's forests and compared their results with climate-based Miami (Lieth, 1975), Thornthwaite Memorial (Lieth and Box, 1972), and Chikugo (Uchijima, 1985) models using 13 field NPP measurements from selected forest ecosystems. They found the remote sensing based NPP estimation was most accurate among models tested. Fang *et al.* (2001) used an intensive number of field inventory data between 1950s and 1990s in an estimation of the NPP of China's forest. So far, there is no research reported on the estimation of net ecosystem productivity (NEP) of the entire China ( $NEP = NPP - Rh$ ). Rh in soils is difficult to estimate.

## 3. ESTIMATING CHINA'S SOIL CARBON POOL AND FLUXES

At the local and regional scales, Li *et al.* (1998) reported a carbon sink on protected grassland in Xilin River Basin, Inner Mongolia in north China. Li and Zhao (1998) estimated that the forest and agricultural areas of subtropical and tropical China was a net carbon sink. However, land use change in eastern China and overgrazing in northern China were reported to cause a carbon loss in soils (Cai, 1996; Li *et al.*, 1998). Bachelet *et al.* (1995) used FAO soil data with climate and published rice yield data to draw a conclusion that paddy fields of China have reached a carbon equilibrium condition ([http://daac.gsfc.nasa.gov/CAMPAIGN\\_DOCS/FTP\\_SITE/INT\\_DIS/readmes/soils.html](http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/FTP_SITE/INT_DIS/readmes/soils.html)). Studies related to China's soil carbon pools reported a large uncertainty of the total amount of soil organic carbon ranging from approximately  $9.24 \times 10^{11}$  tons (Wang *et al.*, 2001) to  $1.8568 \times 10^{11}$  tons constituting around 12.6% of the world total soil carbon (Fang *et al.*, 1996). Li and Zhao (1998) reported an estimation of  $1.06 \times 10^{10}$  tons of carbon in soils of southeast China. Few studies have been conducted to measure soil respiration in China. Chen *et al.* (1999) measured soil respiration at selected grassland sites in Xilin River Basin, Inner Mongolia, north China. Piao

*et al.* (2000) measured the seasonal pattern of soil carbon effluxes in yellow soils of karst areas in southwest China. However, so far, no research has been reported on the systematic measurement or estimation of soil respiration over the entire China.

Modeling of soil carbon flux at large spatial scale has suffered from neglecting the spatial heterogeneity in key model parameters. Our research at Berkeley has addressed such a concern. Our long-term field measurements was designed to characterize the magnitude of uncertainties associated with the spatial variability of soil carbon pools, fluxes, and the sensitivity of soil respiration to physical and biotic factors. For example, we have found that the temperature sensitivity of soil respiration, commonly called Q<sub>10</sub>, has a great degree of spatial and seasonal variability, while all major ecosystem models so far have failed to incorporate such a variability. Incorporating such factors in the ecosystem model is expected to considerably improve the accuracy of the soil carbon estimation.

The soil carbon pools and fluxes have been in a dynamic change due to the rapid change in land use and land cover. Therefore, the static approach based on soil texture cannot reflect the dynamics. It is necessary to use the data derived soil samples acquired over time. At present, China's soil databases based on soil inventory of the entire China in the 1980s are being developed by the Institute of Soil Sciences (ISS), Chinese Academy of Sciences. This will be a much more detailed data set than the FAO soil data in China based on soil data collected in the 1950s and 1960s.

#### 4. EXISTING MAPS OF CHINA'S LAND COVER AND LAND USE

Another critical component in the estimation of NEP of China is timely land-cover and land-use maps of the entire China. During 1980s, a 1:1 million land-cover land-use map of China was manually interpreted based on Landsat MSS imagery in early 1980s. In the 1990s, a digital copy of 1:100,000 scale land-cover land-use map was produced using Landsat TM imagery in 1990–1996 for eastern China and late 1980s for some of the western parts of China. In addition, a number of attempts have been made to map the LCLU of China by various organizations inside and outside China using AVHRR data in a selected year (Sheng *et al.*, 1995; DeFries *et al.*, 1998; Loveland *et al.*, 2000). Due to the lack of ground validation data, the quality of these maps is in question. Since maps obtained with Landsat data have spatial inconsistencies in time, we advocate use of AVHRR or MODIS data for LCLU mapping due to their high temporal frequency. Field observations, LCLU maps derived from aerial remote sensing and Landsat imagery can be used to calibrate or validate those derived from AVHRR and MODIS imagery. Through collaboration between Berkeley and Beijing Normal University, we developed a set of methods to map China's LCLU using monthly AVHRR data in a particular year in combination with climate and elevation data (Pan *et al.*, 2003). Based on some ground truth data collected in the northeast, northwest and south China, our map compares favorably to other maps derived from AVHRR data.

## 5. IMPROVING ESTIMATES OF CARBON BALANCE OF CHINA'S FORESTS USING TEMPERATURE AND PRECIPITATION DATA IN 1982–1998

Rh can be obtained based on the plot-level measurements of NPP in China's forests ([http://www-eosdis.ornl.gov/NPP/npp\\_home.html](http://www-eosdis.ornl.gov/NPP/npp_home.html)). If the soil carbon pool (Cs) and carbon turnover rate (k) are known, Rh can be simply calculated with  $Rh = k * Cs$ . Worldwide soil carbon density ( $gC/m^2$ ) data have been compiled from different sources ([http://www.daac.ornl.gov/daacpages/soils\\_collections.html](http://www.daac.ornl.gov/daacpages/soils_collections.html)) and new data are added to the databases to reflect the effect of disturbance/land-use change on Cs. China's soil carbon pool has been recently estimated based on the second national soil inventory data of more than 2000 soil profiles (Wang *et al.*, 2003). The real difficulty in estimating Rh is how to estimate the soil carbon turnover rate because the k value changes with environmental factors, such as temperature, moisture, and ecosystem type. A new approach is presented here. It can be reasonably assumed that the plot-level NPP approximates the heterotrophic respiration rate when the forest is under or close to the equilibrium state.

China has the best collection of NPP measurements in the world, especially for forest NPP. We examined 690 NPP plots measured in China's forests by checking stand age and disturbance history in the plots. We finally chose 23 out of the 690 NPP plots with stand age >180 years and minimal disturbance. Most of the selected plots are located in old-growth forests and we assume the forests are at or close to steady state ( $Rh \approx NPP$ ). Therefore, the soil carbon turnover rate was calculated using  $k = Rh/Cs$ . We found that the soil carbon turnover rate mainly depends on temperature and precipitation and the interactions between the temperature and precipitation. To co-register the plot with climate data, climate

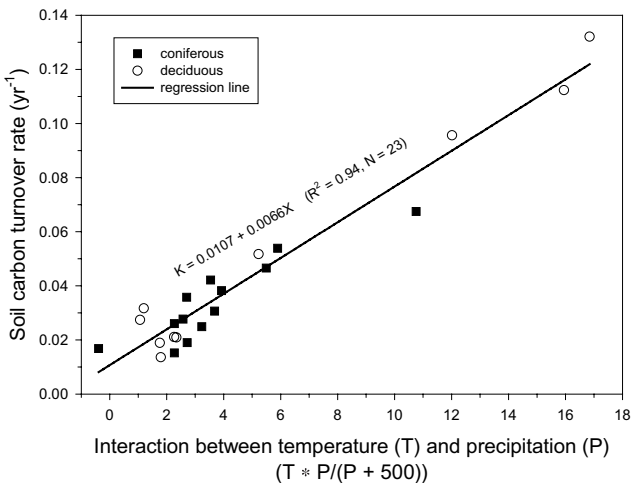


Fig. 1. The relationship between soil carbon turnover rate and the interaction of temperature and precipitation (average from 1980 to 1999).

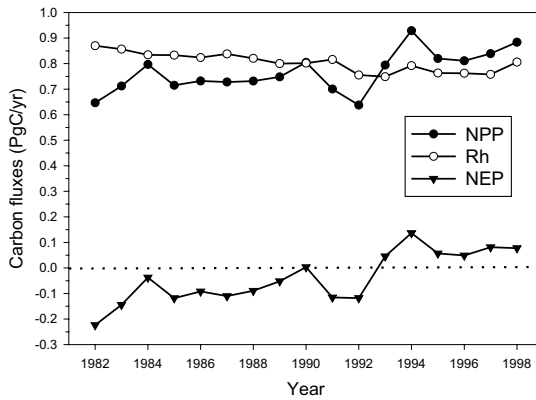


Fig. 2. Carbon balance in China's forest ecosystem from 1982 to 1998.

data were obtained from the nearest weather station. If there was no weather station within 0.5 degree latitude/longitude of the plot, the interpolated  $1 \times 1$  km grid data were used for the plot. The interpolation was based on the 20-year mean annual temperature (1980–99) and precipitation of 512 weather stations covering the territory of China. If soil organic carbon was not reported for a plot we used the second national soil inventory data (1980s) interpolated to  $1 \times 1$  km grid.

The interaction term alone explained about 94% of the variation in carbon turnover rate (Fig. 1). In addition, we did not find significant differences between coniferous and deciduous forests on carbon turnover rate (Fig. 1). Adding soil nitrogen content, soil carbon/nitrogen ratio (C:N), and soil carbon density did not significantly improve the model. This simple model suggests that: (1) soil decomposition was mainly determined by soil carbon pool and climate factors; (2) carbon turnover rates do not significantly differ between deciduous and coniferous forests under the same climate conditions; and (3) soil carbon turnover rate can be well modeled by annual mean temperature and precipitation in China's forests. Although the model was developed under the steady state assumption, it can be applied to non-steady-state forest ecosystems, at least in China, to estimate the  $k$  values because decomposition is determined by temperature and moisture in most ecosystems over the world (Raich and Nadehoffer, 1989). In a disturbed ecosystem, soil carbon pool is away from its steady state and the magnitude from the steady state accordingly indicates the disturbance intensity.

Using our method we estimated that the heterotrophic respiration rate of China's forest ecosystem was 0.8 PgC/yr averaged from 1982 to 1998 (Fig. 2). This Rh value is very close to the annual NPP of 0.77 PgC/yr for the same period independently estimated from remote sensing technique. This is accomplished by calculating forest NPP using AVHRR 10-day composite NDVI data based on the frame of CASA model (Potter *et al.*, 1993). The data were pre-processed for gap filling, cloud reduction, and noise removal. Ground measurements of NPP of 690

plots were used to calibrate the model. In general, NPP in China's forests increased from early 1980s to late 1990s except 1991 and 1992. The eruptions of Pinatubo might have contributed to the low NPP values in these two years by blocking solar radiation and hence reducing photosynthesis. Although Rh was more stable than NPP and NEP, a general decreasing trend was detected from early 1980s to early 1990s (Fig. 2).

China's forest was a net carbon source of 0.1 PgC/yr from 1982 to 1992 and a net carbon sink of 0.07 PgC/yr between 1993 and 1998. These findings are different from the results of a recent study of China's forest carbon dynamics based on forest inventory data (Fang *et al.*, 2001). The previous study found that the forests have accumulated carbon in biomass since early 1980s. This suggests that the young forests may sequester carbon rapidly in the form of biomass after disturbance, such as harvesting. However, the heterotrophic respiration rate may also be high at the early regrowth period due to the high soil carbon content from the harvesting residue. Therefore, the whole ecosystem is still a net carbon source in early stage of these young forests. Large scale harvesting in 1960s and 1970s and reforestation efforts since 1970s have created many young forests in China. These forests did not become net carbon sinks until 1990s though the rapid growth of the forest started much earlier. In addition, the study by Fang *et al.* (2001) found that the average carbon accumulation rate was 0.026 PgC/yr in China's forest from 1994 to 1998. We found a net carbon sequestration rate of 0.08 PgC/yr during the same period. This suggests that forest ecosystem can store a significant amount of carbon in non-biomass forms, such as litter and soil organic carbon, although Fang *et al.*'s work includes disturbance effects (direct carbon release) on C balance but these effects are not considered in our study.

Our method for estimating soil carbon turnover rate may have general implications to estimate soil heterotrophic respiration (Rh) at various scales. The International Geosphere-Biosphere Program (IGBP) has recently compiled more than 2000 records of NPP measurements over the world and many of them were measured in old-growth forests and grasslands with least disturbance. Therefore, these data can be used to estimate the global Rh. To our knowledge, Rh has not been estimated using field measurements at large scales. A limited number of studies on global soil respiration combined root respiration and Rh together by using the chamber measurements of soil surface CO<sub>2</sub> efflux. Our approach avoids the difficulties of separating root respiration from the soil surface measurements of CO<sub>2</sub> efflux. The contribution of root respiration varies greatly from 30% to 90% of the total soil surface CO<sub>2</sub> efflux in different ecosystems. In addition, NPP measured at plot level may better represent the ecosystem than the chamber measurements that normally cover a very small portion of the plot area. Before an ecosystem reaching its steady state its NPP is most likely larger than Rh. Therefore, our estimate of NEP is conservative if the steady state assumption is not met.

However, we realize that there are two most significant sources of errors in our study. One may result from the equilibrium assumption for the selected mature stands. If there has been enhanced forest growth resulting from the climate

and atmospheric changes (CO<sub>2</sub> and N composition), this assumption induces underestimation of C sinks. The other source of errors is the accuracy of NPP measurements. Using the equilibrium assumption, the percentage error in NPP becomes the percentage error in NEP.

## 6. FUTURE WORK

We will continue studying the carbon balance for the entire territory of China using NOAA AVHRR, EOS MODIS, and Landsat images, gridded climate data for the last 100 years, land cover/use maps developed in the 1980s and 1990s, and soil texture maps. We plan to evaluate a spatially explicit carbon dynamic model developed by Jing Chen's group (Chen, J. M. *et al.*, 2000; Chen, W. J. *et al.*, 2000; Liu *et al.*, 1997) using NOAA AVHRR data and further develop it to make use of MODIS imagery. We will attempt to quantify the regional carbon statistics over last 100 years (1901–2000) in China, but the emphasis will be placed on the spatial distribution of carbon sources and sinks in the last three decades when reliable land-cover and land-use information is available.

The process-based model originally developed for boreal ecosystems productivity simulation, named BEPS, is capable of assimilating various spatial data types in various formats to simulate carbon source and sink distributions. The model considers the long-term effects of climate, disturbance, atmospheric CO<sub>2</sub> concentration and nitrogen deposition. It has been used to estimate the magnitude of carbon sinks in Canada's forests since 1895. The model will be adjusted for use in China with available cover-type dependent data and will be calibrated and validated using an extensive amount of ground based biomass measurements collected during the past 50 years, historical aerial photographs and airborne remote sensing imagery.

We will provide useful quantitative information for improving the global carbon budget estimation and for predicting atmospheric CO<sub>2</sub> concentration in the near future. This will be accomplished based on previous achievements of this team gained from working both inside and outside China in the areas of biophysical and biochemical parameter mapping, plant canopy radiation modeling, soil inventory and land-cover and land-use mapping of China, net primary productivity (NPP) and net ecosystem productivity (NEP) modeling, topographic effect modeling on biophysical parameter estimation, and forest inventory based on digital photogrammetry and photo-ecometrics. We will scale up site specific information of various ecosystems located at over 30 field stations in China and inventory data over 260,000 permanent forest plots using aerial photography, airborne remote sensing, Landsat imagery, and moderate spatial resolution AVHRR and MODIS data.

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