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# The Climatic–induced Net Carbon Sink by Terrestrial Biosphere over 1901–1995①

Yang Xin (杨 昕), Wang Mingxing (王明星) and Huang Yao (黄 耀)

*LAPC, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

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## ABSTRACT

The spatial and temporal variability of land carbon flux over the past one hundred years was investigated based on an empirical model directly calculating soil respiration rate. Our model shows that during 1901–1995, about 44–89 PgC (equals to 0.5, 0.9 PgC / yr respectively) were absorbed by terrestrial biosphere. The simulated net ecosystem productivity (NEP) after the 1930s was close to the estimated value of " missing C sink" from deconvolution analysis. Most of the total carbon sink happened during 1951–1985 with the estimated value of 33–50 PgC. Three major sinks were located in the tropics (10°S–10°N), Northern mid–latitudes (30°–60°N) and Southern subtropics (10°–40°S). During 1940s–mid–1970s, carbon sinks by terrestrial ecosystem increased with time, and decreased after the mid–1970s. These may be due to the changing of climate condition, as during the 1940s–1970s, temperature decreased and precipitation increased, while after the mid–1970s, an opposite climate situation occurred with evident increasing in temperature and decreasing in precipitation. Usually, warmer and dryer climate condition is not favor for carbon absorption by biosphere and even induces net carbon release from soil, while cooler and wetter condition may induce more carbon sink. Our model results show that the net carbon flux is particularly dependent on moisture / precipitation effect despite of temperature effect. The changing of climate in the past century may be a possible factor inducing increases in carbon sink in addition to $CO_2$ and *N* fertilizer.

**Key words:** Climate, Terrestrial biosphere, Missing carbon sink, Model

## 1. Introduction

Currently the global carbon budget cannot be balanced. The $CO_2$ released by fossil fuel and land–use changes is apparently greater than the amount remaining in the atmosphere and removed by the known sinks (Keeling et al., 1989; IPCC, 1992; Sundquist, 1993). The " missing carbon sink" is estimated to be 1.3–4.7 PgC / yr (Tans et al., 1990; Sarmiento and Sundquist, 1992; Fan et al., 1998; Woodwell, et al., 1998). Although there is a wide ranges of the " missing sink" which stems from uncertainties in estimates of other carbon sinks and sources, terrestrial ecosystem is thought absorbing most of the missing carbon (Ciais et al., 1995; Fan et al., 1998). It is important to balance the carbon budget or it will impose considerable uncertainty on predictions of future atmospheric $CO_2$ concentrations and future climate (Dixon et al., 1994; Houghton, 1995; Woodwell et al., 1998).

There are many possible mechanisms that could result in the increases in terrestrial carbon sinks, such as $CO_2$–*fertilisation, nitrogen (N) fertilization (from pollution deposition)* and changing climate induced growth in ecosystem (D'Arrigo and Jacoby, 1993; Solomon

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et al., 1993; DeLucia et al., 1999).

The effect of climate variability on terrestrial ecosystem C–cycling has been widely studied. The current / decadal–term (and time–lag) correlation between climatic variables, such as temperature and precipitation, and atmospheric $CO_2$ growth rate indicates that terrestrial ecosystem has complex feedback to climate changing (Siegenthaler, 1990; Keeling et al., 1995; Braswell et al. 1997; Woodwell et al., 1998; Cao and Woodward, 1998; Yang and Wang, 2000).

In an important exploratory study, using very simple "empirical" relationships between climate and net primary productivity / soil respiration, Dai and Fung (1993) suggested that the terrestrial biosphere sequestered up to an additional 20 PgC between 1940 and 1988 due to climate variability that would represent half of the budget deficit. They identified middle latitudes in the Northern Hemisphere as an important region for C flux. They highlighted the possible critical role of climate in influencing the spatial and temporal variability of the terrestrial ecosystem C flux focusing on the possible large variability in both time and space domains. In Dai and Fung's (1993) models, the heterotrophic respiration ($R_h$) is derived from Raich and Schlesinger's (1992) soil respiration data, which is the sum of $R_h$ and root respiration. Here we use a new method directly calculating soil heterotrophic respiration rate.

## 2. Climatic data

Space–time climatic data is demanded in understanding the role of climate in biogeochemical cycles. A newly 0.5° × 0.5° latitude / longitude monthly climate data over relatively longer period of 1901–1995 was provided (New et al., 1999; New et al., 2000) that could be used in searching for biosphere response to climate changes. Annual precipitation ($P$), mean temperature (MAT) and mean biotemperature ($T_b$) were three basic factors used in our models. $T_b$ is the mean annual temperature considering only positive monthly temperatures ($< 30$°C). The annual precipitation is the sum of monthly rainfall value.

## 3. Description of carbon flux model

The net ecosystem productivity (NEP) or net carbon flux between the atmosphere and terrestrial biosphere can be expressed as

$$\mathrm{NEP} = \mathrm{NPP} - R_h \ . \qquad (1)$$

where NPP is the net primary productivity. A modified Miami model (Friedlinstein et al., 1992) was used to calculate NPP. Soil heterotrophic respiration $R_h$ can be estimated by

$$R_h = C_0 R_r \ , \qquad (2)$$

where $C_0$ is the mean soil carbon density (kgC / $m^2$) at steady state, and $R_r$ is the soil respiration rate. If we assumed that $C_0$ kept fixed on short–time scales, the changes of $R_h$ could be thought mainly due to the variation of $R_r$. Compared with the large soil carbon density, the relatively small variation of soil carbon on decadal time scales can be neglected.

We used a new way in calculating soil respiration rate $R_r$. At equilibrium situation, NPP= $R_h$, so $R_r$ can be expressed as

$$R_r = \mathrm{NPP} / C_0 \ . \qquad (3)$$

Zinke et al. (1986) compiled more than 3500 soil carbon density data (1 meter in depth)

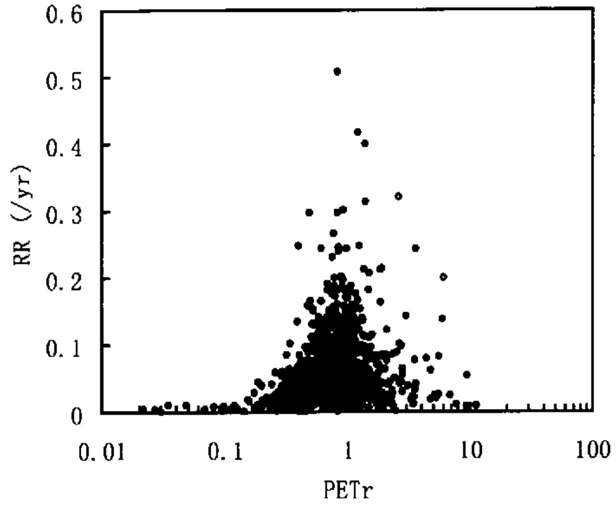


Fig. 1. The relationship between soil respiration rate $R_r$ and PETr.

over the world. We chose the natural vegetation and undisturbed sites from the data set, and calculated the averaged value of the carbon density on $0.5^\circ \times 0.5^\circ$ grid for sites located in the same grid (this is done due to the same resolution of climate data we used). In so doing, total 975 grid–averaged soil carbon data were obtained. The respiration rate $R_r$ for each soil carbon data can be calculated by using the NPP model.

Among the climate variables, we found $R_r$ is closely related with potential evapotranspiration rate (PETr) (Holdridge, 1947). PETr can be expressed as (Post et al., 1982)

$$\mathrm{PETr} = 58.93 T_b / P \,, \tag{4}$$

where $P$ is annual precipitation (mm) and $T_b$ annual mean biotemperature (°C). Figure 1 shows the relationship between $R_r$ and PETr, and the peak value of $R_r$ appears at PETr $\approx$ 0.8. These calculated $R_r$ data were divided into two groups based on its PETr value. Figure 2a shows the regression function of $R_r$ for PETr< 1.0 (representing wet soil condition: $R_w$ ), while Fig. 2b for PETr > 1.0 (representing dry soil condition: $R_d$ ).

$$R_w = 0.061\mathrm{PETr}^{0.7521} \quad \text{when} \quad \mathrm{PETr} < 1 \,, \tag{5}$$

$$R_d = 0.0476\mathrm{PETr}^{-0.3305} \quad \text{when} \quad \mathrm{PETr} > 1 \,. \tag{6}$$

They are significant at 99% and 95% confidence level, respectively. Combining these two equations into one, we have

$$R_{wd} = \min(R_w, R_d) \,. \tag{7}$$

$R_{wd}$ reaches its highest value of 0.05 ($\mathrm{yr}^{-1}$) at PETr $\approx$ 0.8. Temperature effects on soil respiration rate can be obtained by dividing $R_r$ by $R_{wd}$. Figure 3 shows the relationship between temperature effect $F$ and annual mean temperature MAT. Equation (8) is the regression function:

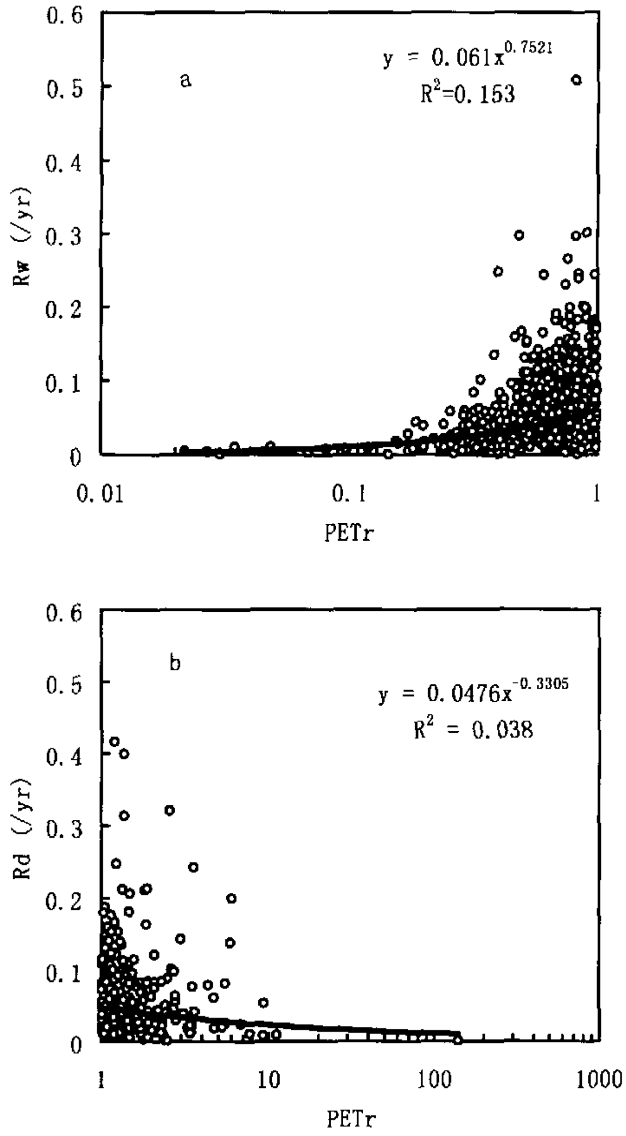


Fig. 2. The relationship between $R_r$ and PETr for (a) PETr< 1.0 and (b) for PETr> 1.0. Repression functions are given in the figures.

$$F = 0.6323\exp(0.0512\mathrm{MAT}) \ . \tag{8}$$

Then, the soil respiration rate can be expressed as

$$R_r = FR_{wd} \ , \tag{9}$$

$$R_r = 0.6323\exp(0.0512\mathrm{MAT})\min(R_w, R_d) \ . \tag{10}$$

The net soil carbon flux NEP can be changed into

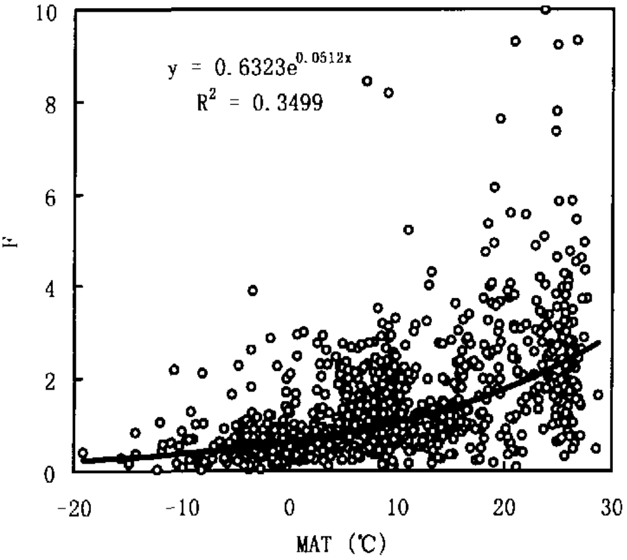


Fig. 3. The relationship between temperature effect $F$ and annual mean biotemperature $T_b$. Regression function is given in the figure.

$$\mathrm{NEP} = \mathrm{NPP} - 0.6323\exp(0.0512\mathrm{MAT})\min(R_w, R_d)C_0 \quad . \tag{11}$$

The positive value denotes the net carbon flux from the atmosphere to land biosphere, vice versa. It should be noted that the net carbon flux is dependent on $C_0$ and further on the climate period used in calculating $C_0$. In this paper we use a mean climate condition during the period of 1920–1949 as done by Dai and Fund (1993). However, another long time mean data from 1901 to 1990 were also used in order to make a comparison.

According to Eq.(8), the temperature effect on carbon decomposition is evident, as $Q_{10} = 1.7$. This $Q_{10}$ value is a little lower than some estimated values of 2.0–2.4 (Raich and Schlesinger, 1992; Esser, 1993).

## 4. Model Results and analysis

Figure 4 shows the global map of modeled soil carbon density. It can be found that the lowest carbon density ($< 2$ kgC / m$^2$) appears in extremely dry climate condition, such as in desert / desert bush. The soil carbon density in the tropical areas is not so high as in most of mid– to high–latitude areas reflecting the evident temperature effects on soil carbon decomposition. However under very wet condition, such as in some regions of Southeast Asia, the soil carbon density is even larger than 20 kgC / m$^2$. The higher carbon density in the southeast part of the Tibet an Plateau is mainly due to high terrain effects on both rainfall and temperature. The total soil carbon pool is about 1150 PgC which is a little lower than the previous estimated values of 1200–1500 PgC (Schlesinger, 1977; Post et al., 1982, 1985).

Figure 5 shows the relationship between observed (Post et al., 1985) and modeled mean carbon density in 38 vegetation types of Holdridge life system. The correlation coefficient between them is very high with $R^2 = 0.6$ (significant at 99.9% level), indicating that our model has a good ability in describing the soil carbon density at various vegetation types under

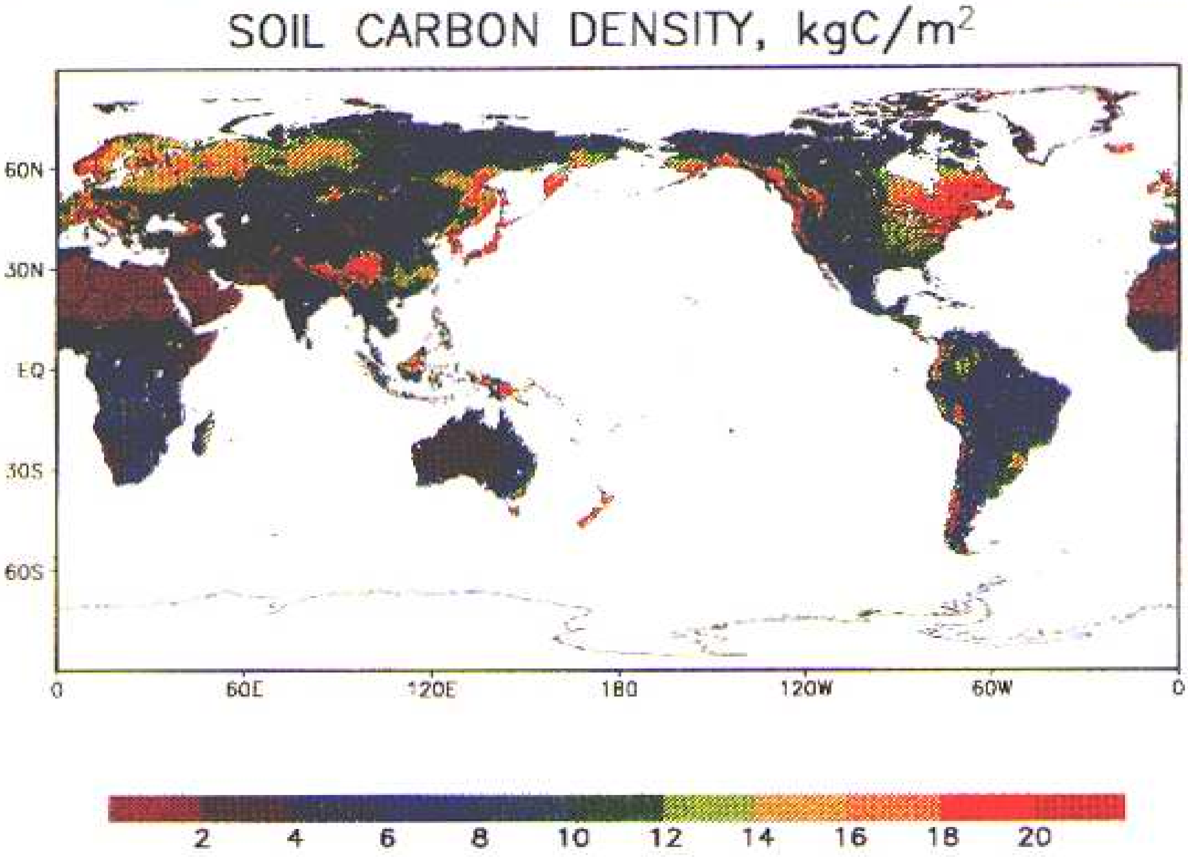


Fig. 4. The world map of simulated soil carbon density (kgC/m²). Values larger than 20 kgC/m2 is set 20 kgC/m² in the figure.

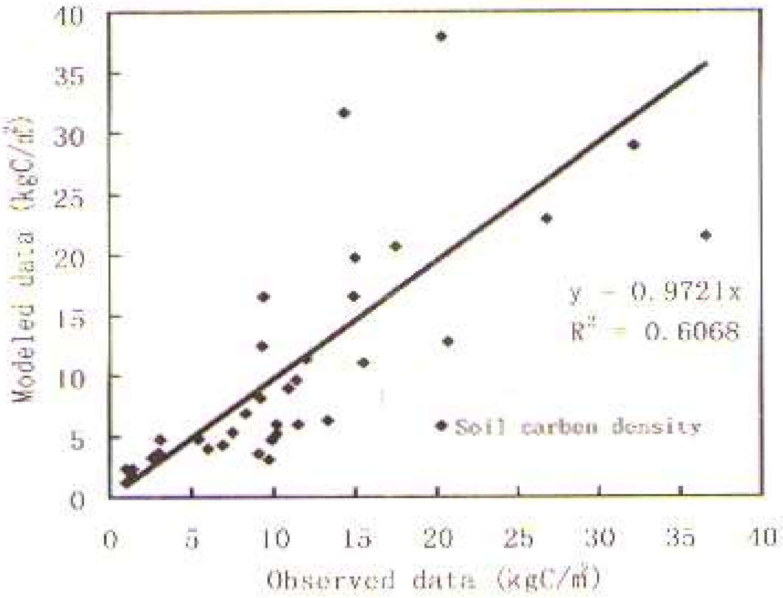
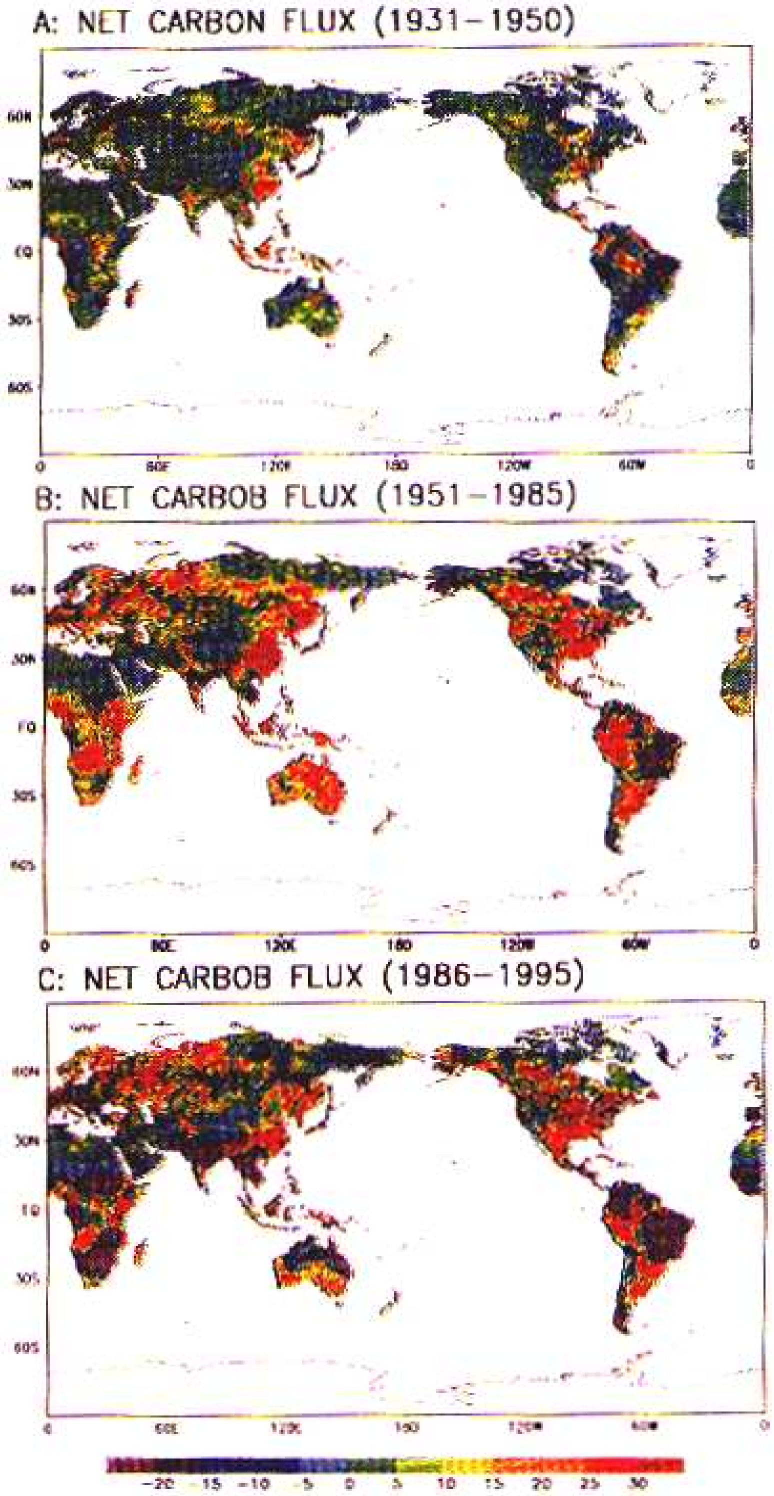


Fig. 5. The relationship between observed and modeled mean carbon density in 38 vegetation types of Holdridge life system.



A: NET CARBON FLUX (1931–1950)

B: NET CARBOB FLUX (1951–1985)

C: NET CARBOB FLUX (1986–1995)

Fig. 6. The distribution of annual averaged net carbon flux during periods of 1931–1950, for 1951–1985 and for 1986–1995, respectively. Positive value means net carbon sink to atmosphere (in g C m⁻² yr⁻¹).

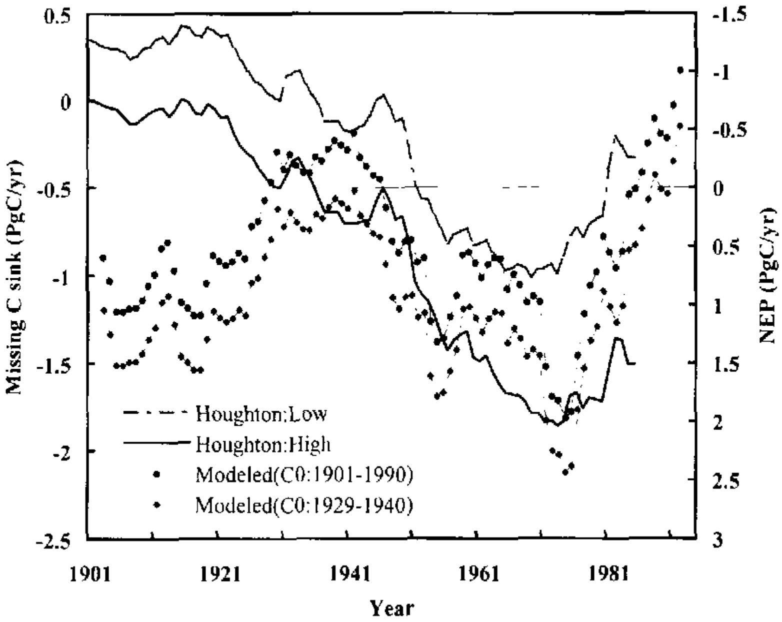


Fig. 7. The simulated net carbon flux NEP with 5 years running mean (right axis, positive value means net carbon sink in land), and estimated " missing sink" from deconvolution analysis (left axis, negative value means missing carbon sink).

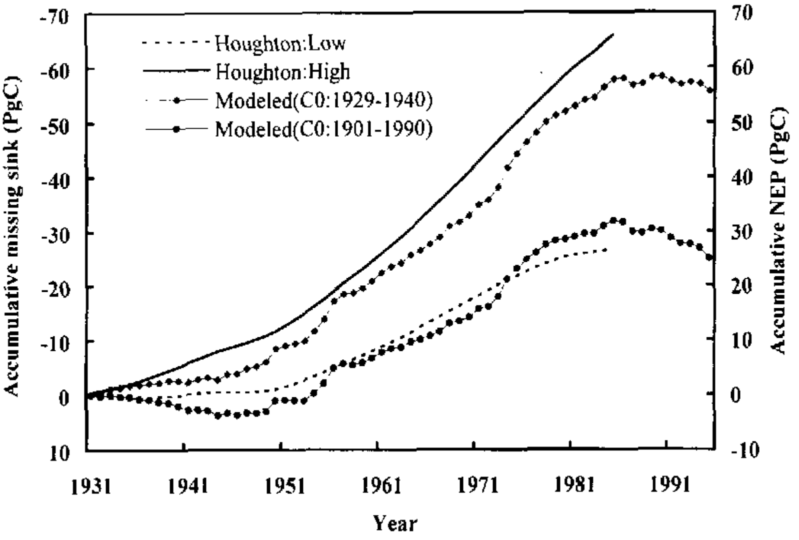


Fig. 8. The accumulative net carbon flux of and accumulative " missing sink" over the period of 1931-1995.

different climate conditions.

Figures 6a, 6b, and 6c show the geographic distributions of mean net carbon fluxes of three periods: 1931–1950, 1951–1985 and 1986–1995 respectively (using mean climate data of 1929–1949 in calculating $C_0$). Figure 6a shows that terrestrial biosphere exists as a weak carbon sink from 1931 to 1950, with a total accumulative carbon sink of 9 PgC (0.45 PgC / yr). A near zero net carbon flux (−1 PgC) was obtained based on the mean climate data of 1901–1990 in calculating $C_0$.

Figure 6b shows that most of terrestrial biosphere served as carbon sinks during the period of 1950–1985. Over these 35 years, about total carbon of 50 PgC (equal to 1.4 PgC / yr) was absorbed, which is larger than Dai and Fung's (1993) estimated value of 20 PgC. If we used mean climate data of 1901–1990 in calculating $C_0$, the total sink reduces to 33 PgC (equal to 0.9 PgC / yr). It can be found that there are some regions, such as the tropical areas (Amazon, Southeast Asia), Northern middle latitudes (eastern Asia and south part of North American) and most of the Southern Hemisphere (< 40°S), absorbing more carbon from the atmosphere. These results indicated that the tropics are important regions in determining the global carbon cycles, especially for Amazon basin and tropical southeastern Asia.

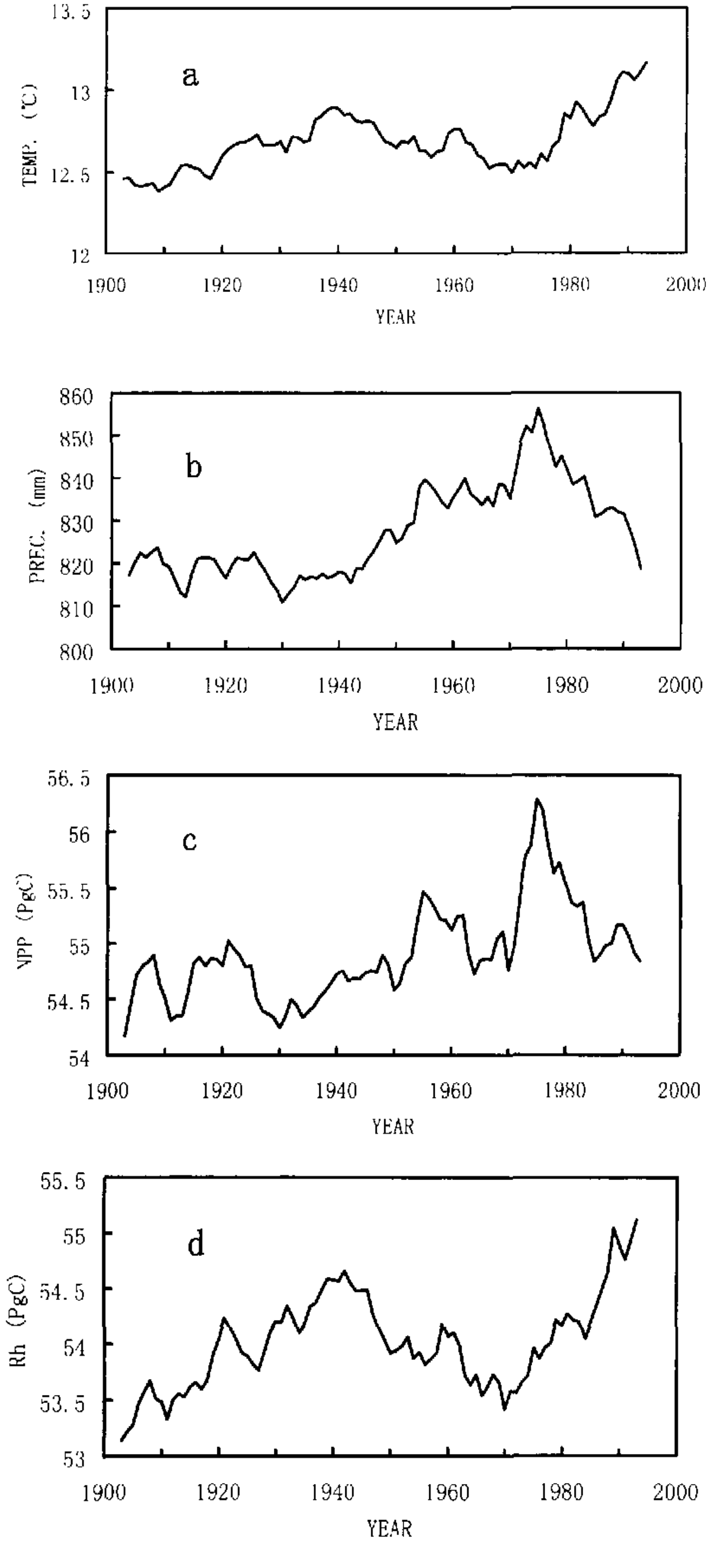
There are some evident discrepancies between Dai and Fung's (1993) results and our modeled results, these differences are likely due to the different expression of soil respiration rate used in models, although both of then used the same NPP model. In South America, our results showed a large net sink, however Dai and Fung (1993) gave a net source. Another evident difference appeared in Eurasia, our model showed that eastern Asia was a major carbon sink, whereas Dai and Fung's (1993) result did not show the similar conclusion instead they found a significant sink located to the north of 45°N.

The tropical regions play an important role in balancing the global carbon budget. Woodwell (1998) pointed out that a sink of 0.6 PgC / yr in the tropical forests was needed in order to balance global carbon budget over the period of the 1980s. These estimates were consistent with previous measurements and model studies showing that Amazon absorbed carbon by 0.2–0.4 PgC / yr (Grace et al., 1995; Tian et al., 1998; Prentice and Lloyd, 1998; Phillips et al., 1998). Our model showed that the total carbon sink in tropical areas (10°S–10°N) over the period of 1951–1985 and 1980–1989 was about 0.4 and 0.2 PgC / yr respectively ($C_0$: 1929–1940). The large sink in tropical areas may be due to the evident increasing in precipitation but little variation in temperature. In low latitude band, precipitation increased with a rate of 5% per century, but temperature showed near zero increasing trend ouer the past century (IPCC, 1996).

The carbon fluxes in Northern mid–latitudes (30°–60°N) were about 0.6 PgC / yr for 1951–1985 and 0.5 PgC / yr for 1980–1989 respectively ($C_0$: 1929–1940). These value is consistent with direct measurements in Northern temperate and boreal zones (Woodwell et al., 1998; Dixon et al., 1994; Houghton, 1996). The net flux in Southern subtropical (10°–40°S) band was about 0.3 PgC / yr for 1951–1985 and 0.3 PgC / yr for 1980–1989 respectively ($C_0$: 1929–1940).

The total accumulative carbon sink during 1986–1995 was about −2 PgC ($C_0$: 1929–1940) and −7 PgC ($C_0$: 1901–1990). Figure 6c shows that during this period most of regions had changed to sources except for Northern mid–latitudes. This result is consistent with the recent studies indicating that current terrestrial ecosystem were changing from net carbon sinks to net sources (Houghton, 1995; Woodwell et al., 1998). This changing may be due to the alternation of climatic situation.

Figure 7 shows that our modeled net carbon flux is in good agreement with the estimated


a
TEMP. (℃)
13.5
13
12.5
12
1900
1920
1940
1960
1980
2000
YEAR
b
PREC. (mm)
860
850
840
830
820
810
800
1900
1920
1940
1960
1980
2000
YEAR
c
NPP (PgC)
56.5
56
55.5
55
54.5
54
1900
1920
1940
1960
1980
2000
YEAR
d
Rh (PgC)
55.5
55
54.5
54
53.5
53
1900
1920
1940
1960
1980
2000
YEAR

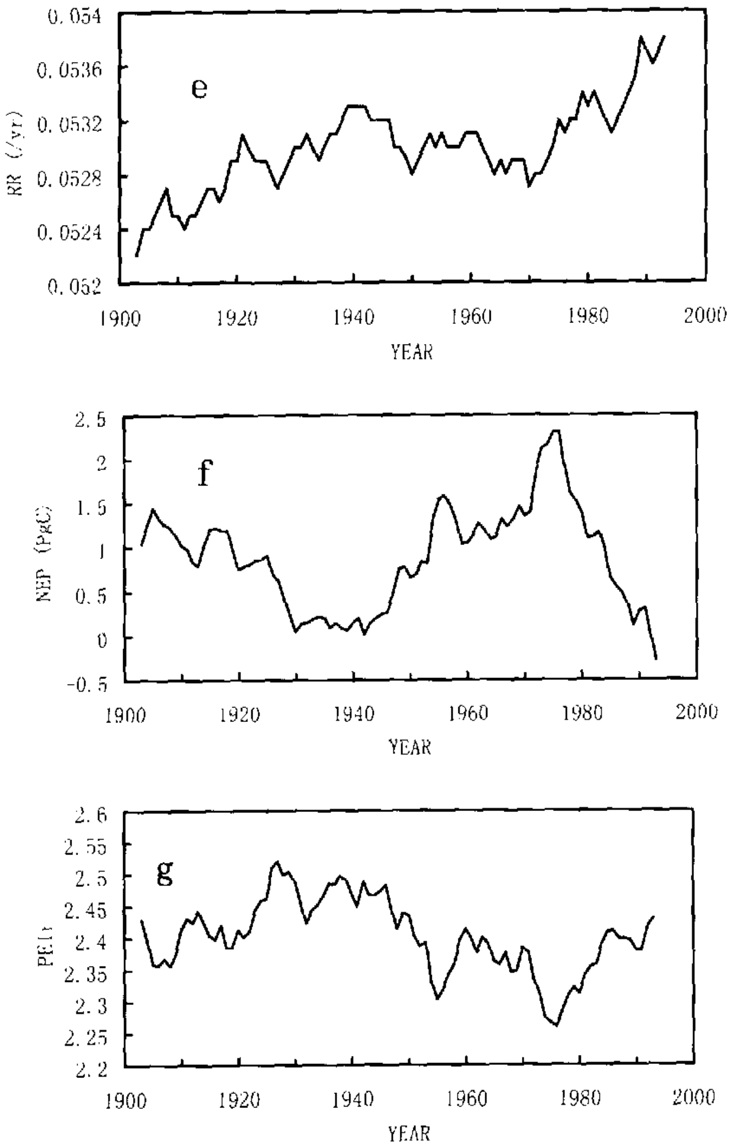


Fig. 9. 5-year running mean of (a) annual mean temperature, (b) annual precipitation, (c) net primary production NPP, (d) soil heterotrophic repiration ($R_h$), (e) soil respiration rate ($R_r$), (f) net carbon flux (NEP), and (g) potential evapotranspiration rate (PETr) over global land ecosystem.

"missing sink" values by Houghton (1993) except before the 1930s. Net carbon sinks by terrestrial ecosystem increased during the 1940s–mid–1970s, and decreased sharply after the mid–1970s. These variations resulted from the alternation of climatic situation before and after the mid–1970s. Since the 1940s, temperature decreased and precipitation increased until the mid–1970s, while after the mid–1970s, an opposite climate situation occurred with evident increasing in temperature and decreasing in precipitation (Figs. 9a and b). Usually, warmer and dryer climate condition is not favorable for net carbon absorption by biosphere and even causes net carbon release from soil, while cooler and wetter condition may induce ecosystem to absorbe more carbon from air.

The large discrepancy between our model results and estimated " missing sink" values before the 1930s may stem from the inaccuracy in the climate data owing to the less valid observation data (especially for precipitation). Errors may also occur when using the two empirical models (calculating NPP and soil respiration rate) in time dependent condition as they are for equilibrium situation and are invalid for evident changes in climatic conditions as happened before and after the 1920s.

The total accumulative carbon sink during 1901–1995 is 89 PgC ($C_0$: 1929–1940) and 49 PgC ($C_0$: 1901–1990) respectively, which is very close to the low level of " missing sink". Figure 8 shows the accumulative values of modeled net carbon flux and that of " missing sink" during the period of 1931–1995. It can be found that our model results are consistent with the estimated " missing sink" . Over the 65 years, a high accumulative value of 56 PgC (0.9 PgC / yr) ($C_0$: 1929–1940) and a low value of 25 PgC (0.4 PgC / yr) ($C_0$: 1901–1990) was obtained. A large part of these sinks happened during the period of 1951–1985 as mentioned before.

Figures 9 (a–g) show the 5–year running mean values of 6 different parameters (as to the model output, $C_0$: 1929–1940). The relationship between NPP (Fig. 9c) and temperature (Fig. 9a) is not significant with a small correlation coefficient of 0.2, while NPP is significantly related to precipitation (Fig. 9b) with a large coefficient of 0.83. They imply that the productivity of most terrestrial ecosystem is limited by wate, which is consistent with Esser's (1993) conclusion. Soil heterotrophic respiration $R_h$ (Fig. 9d) and soil respiration rate $R_r$ (Fig. 9e) are closely related to temperature with correlation coefficients of 0.85 and 0.84 respectively indicating that temperature has large effects on soil carbon decomposition. The opposite sign of correlation coefficients between net carbon flux NEP (Fig. 9f) and temperature (−0.51) and between NEP and precipitation (0.69) indicates that the same variation trends of temperature and precipitation will offset their individual effects on the carbon flux. Increases in precipitation together with decreases in temperature will enhance more carbon sink. So, the combined effects of temperature and precipitation on carbon cycles are complicated and greatly depend on their relative importance. PETr is a useful index in description of the combined effects of temperature and precipitation. PETr (Fig. 9g) shows a significant negative correlation with NEP with a coefficient of −0.71 indicating that warmer and dryer conditions are not more favorable for carbon sink than cooler and wetter conditions do.

## 5. Discussion

It is hard to say that the terrestrial biosphere will continue to release carbon dioxide to the atmosphere in the next decades. The net flux between the biosphere and the atmosphere is highly dependent on the combined effects of temperature and precipitation but not individual one. Precipitation plays an important role in determining the net carbon flux. If the warm and dry climate condition existing in recent decades continued, more soil carbon would release to air and greatly enhanced the " greenhouse effect". However, if there were sufficient precipitation with temperature increasing, land biosphere would serve a net carbon sink as a result.

Only two basic climatic variables, annual precipitation and biotemperature were used in our model. In real situation, NPP and soil respiration are controlled by many factors in addition to the above two factors, and the interactions between them are complicated (Cao and Woodward, 1998). Our one–compartment model calculating soil respiration rate and Miami model are just empirical models and not suitable for time dependent variation. At least two parts of soil pool (one for the active soil with rapid respiration rate and another for inactive part with relatively long turnover time) are needed in order to describe short time soil carbon variation.

Although our model result showed that the simulated net carbon flux after the 1930s was well similar to the " missing sink", it did not mean that we solved the missing sink problem. In fact, our model results just had qualitative meaning. However, our model results together with Dai and Fung's (1993) results indicated that climatic changing is a potential factor causing terrestrial ecosystem serving as net carbon sink, in addition to the possible $CO_2$ and $N$ fertilization effects.

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# 1901—1995年气候变化导致陆地生态系统净吸收碳

杨 昕 王明星 黄 耀

## 摘 要

利用所建立的直接计算土壤呼吸速率的简单模型，对近一百年来陆地生态系统碳通量的变化进行了模拟。结果显示，1901—1995年间整个陆地生态系统表现为一个碳汇。这期间总碳吸收量的低估计值为44Pg(0.5Pg碳／年)。而高高估计值为89Pg(0.9Pg碳／年)。其中大部分碳的吸收发生在30年代以后，1931−1995年间共吸收碳的低估计值为25Pg，高估计值为56Pg。另外模拟出的净碳通量与利用其他方法估计出的"丢失汇"十分接近。在空间分布上，三个主要碳汇分别在热带(10°S−10°N)，北半球的中高纬度(30°−60°N)以及南半球(10°−40°S)。40年代至70年代的气候状况(温度下降而降水增加)十分接近。在空间分布上，三个主要碳汇分别在热带(10°S−10°N)、北半球的中高纬度(30°N−60°)以及南半球(10°S−40°)。40年代至70年代的气候状况(温度下降而降水增加)十分有利于陆地生态系统对碳的吸收；但70年代期后的气候条件(即温度上升而降水下降)则不利于陆地生态系统对碳的吸收，甚至导致净释放碳。模式结果显示：净碳通量受温度影响很大，而湿度和降水对它的的影响也不能忽视。除了二氧化碳和氮素的"施肥效应"外，过去的气候变化可能是造成陆地生态系统成为碳汇的另外一个重要原因。

**关键词**：气候，陆地生态系统，丢失的碳汇，模型