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Effect of temperature change on CO_2 Flux in temperate mixed forest ecosystem

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ABSTRACT

Forest is the main carbon sink of terrestrial ecosystem. Due to the unique growth characteristics of plants, the response of their growth status and physiological activities to climate change will affect the carbon cycle process of forest ecosystem. Based on the local scale CO_2 flux and temperature observation data recorded by the FLUXNET registration site and Harvard Forest FLUX observation tower from 2000 to 2012, combined with the phenological model, this paper analyzes the impact of temperature changes on CO_2 flux in temperate forest ecosystems. The results show that: (1) the maximum NEE in 2000–2012 was 298.13 $g \cdot m^{-2} \cdot a^{-1}$, which occurred in 2010. Except in the 2010 and 2011, the annual NEE in other years was negative. (2) NEE, GPP, temperature and phenology models have good fitting effects ($R^2 > 0.8$), which shows that the stable period of photosynthesis in temperate mixed forest ecosystem is mainly concentrated in summer, and vegetation growth is the dominant factor of carbon cycle in temperate mixed forest ecosystem. (3) The linear fitting results of the change time points of air temperature (maximum point, minimum point and 0 point date) and the change time points of NEE and GPP (maximum point, minimum point and 0 point date) show that there is a significant positive correlation between air temperature and CO_2 flux ($P < 0.01$), and the change of air temperature affects the carbon cycle process of temperate mixed forest ecosystem.

Keywords: Mixed Forest; Ecosystem; Eddy Correlation System; CO_2 Flux; Phenological Model

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1. Introduction

In the context of global climate change, the process of surface urbanization, human industrial activities, the use of fossil fuels and the increase of the world population have led to the increase in the concentration of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) in the atmosphere, which has brought many environmental problems (mainly greenhouse effect). People began to pay attention to the research on the emission dynamics of greenhouse gases such as CO_2 and CH_4[1-5].

Forest and grassland ecosystems are the main carbon sinks of terrestrial ecosystems[6]. Photosynthesis of vegetation will absorb part of CO_2 in the atmosphere[7-10]. Due to the unique growth characteristics of plants, the response of plant growth status and physiological activities to climate change, the research on the carbon cycle process of forest and grassland system plays an important role in analyzing the global carbon cycle process and coping with and solving global climate problems[11-15].

Since the 1990s, with the application of eddy correlation (eddy covariance) technology (EC), a technical method has been provided for direct observation of CO_2 emission and absorption dynamics of different ecosystems[5]. Eddy correlation technology, as a technical means to observe the material circulation and energy flow between the underlying surface and the atmosphere within a certain ecological scale, was mostly used in the early stage to study the CO_2 exchange between natural ecosystems such as forests, wetlands, grasslands and the atmosphere[16-22]. In order to better study the carbon cycle process of terrestrial ecosystems, the application of eddy correlation technology in the study of CO_2 flux in forest ecosystems has become a hot spot. For the integration and analysis of global multi site flux data and the standardization of flux data processing, the regional-global flux observation data sharing networks such as FLUXNET and China flux network are carried out[22-27]. International flux network is a large flux data sharing platform. At present, there are more than 900 registered flux observation stations, and a considerable number of forest ecosystem flux observation stations are distributed in temperate regions, including Harvard Forest Station in Massachusetts, which carried out flux observation early[21-22]. Using flux data released by FLUXNET, there are also many studies on CO_2 exchange in global forest ecosystems, mainly including: dynamic characteristics of CO_2 flux in forest ecosystems, climatic characteristics of flux source footprint, CO_2 flux modeling and others[17,21], among which CO_2 flux modeling is an important content of CO_2 flux research in forest ecosystems, mainly including CO_2 flux prediction and extraction of CO_2 flux phenological characteristics etc.[17]. The phenological characteristics of CO_2 flux in forest ecosystem (characteristics of CO_2 flux change) provide help for understanding the response of CO_2 flux to climate change. In the past, the extraction of phenological characteristics of forest ecosystem was mostly based on vegetation products in remote sensing data (such as NDVI, EVI, GPP, etc.), and the calculation model used are mainly asymmetric Gaussian function, D-L fitting, S-G filtering, etc.[28-32]. With the popularization of eddy correlation system, high-precision and high-time resolution CO_2 flux observation data provide high-quality data support for CO_2 flux modeling of forest ecosystem. Gu *et al.*[17] developed a parameterized phenological model of photosynthesis in plant communities based on eddy correlation. The model is based on interannual scale CO_2 flux data to fit and extract the phenological characteristics of CO_2 flux. Richardson *et al.*[13] used the phenological model to analyze the phenological characteristics of net CO_2 exchange (NEE) and total primary productivity (GPP) of the multi site ecosystem of the international flux network and their relationship with climate change. It was believed that the productivity of evergreen coniferous forests was less sensitive to phenology. Yi *et al.*[16] applied the phenological model to the grassland flux site, and they believed that the model had the ability to analyze long-time series climate change and carbon feedback mechanism. Niu *et al.*[15] used the international flux network CO_2 flux data and phenological model to analyze the response of the Northern Hemisphere ecosystem CO_2 flux to the annual average temperature change, and they believed that the phenological characteristics of 68 flux stations were highly sensitive to the annual average temperature change.

Studying the carbon cycle process of forest ecosystem and its response to temperature change can provide reference for further understanding the carbon cycle mechanism of terrestrial ecosystem and rational layout of forest structure. This study uses the FLUXNET2015 data set provided by the international flux network, i.e. the CO_2 flux and temperature observation data etc. the Harvard Forest flux Observatory in Massachusetts (LTER, US-Ha1) garnered from 2000 to 2012[21,22]. Based on the phenological model of plant community photosynthesis, the variation characteristics of CO_2 flux in temperate forest ecosystem and its response to temperature changes are analyzed.

2. Overview of the study area

The study area is located in the Harvard Forest Area in pitsham, Massachusetts, USA. The temperature zone of this area is temperate, and the climate is temperate continental humid climate. The geographical coordinate of the positioning environmental observation tower (EMS) is

(42.53°N, 72.17°W). Located in the Harvard Forest long term ecological observation and research station, the flux observation tower is equipped with eddy related flux observation system and gradient micro meteorological observation system. The tower is 30 m above the ground (5 m higher than the canopy height), with an altitude of 340 m. The local wind direction is mostly southwest and northwest. Flux observation station was established by Harvard University in the United States. Since 1988, it has carried out meteorological and ecological environment observation and research on Harvard Forest. The registration ID of this forest station in FLUXNET is US-Hal[21]. It has accumulated flux data and micro meteorological data on a long time scale, including aboveground biomass, litter, soil temperature and humidity, leaf area index and other ecological data[21]. The annual average temperature in this area is 6.62 ℃, of which the highest monthly average temperature occurs in July and the lowest monthly average temperature occurs in January; the average annual precipitation for many years is 1,071 mm (see **Table 1**). The underlying surface of this area is mostly woody plants, mainly including deciduous broad-leaved forests such as Quercus rubra, Acer rubrum and Tsuga canadensis, with an average canopy height of about 20–24 m[21]. Due to the influence of observation height, wind speed, wind direction and other factors, the range of flux source area in this area can be extended to 1 km away from the upwind direction[21].

Table 1. Annual precipitation and average annual temperature of Harvard Forest ecosystem from 2000 to 2012

Year	Annual precipitation/mm	Annual average temperature/℃
2000	1,330.14	9.074 ± 7.08
2001	1,182.97	8.824 ± 8.73
2002	1,406.83	8.275 ± 8.13
2003	1,388.23	7.416 ± 9.37
2004	1,216.49	7.525 ± 9.48
2005	990.13	7.984 ± 9.19
2006	1,102.42	8.937 ± 7.59
2007	1,021.00	7.646 ± 9.28
2008	1,092.27	7.638 ± 8.31
2009	1,171.00	5.328 ± 10.01
2010	1,097.22	9.026 ± 9.31
2011	1,263.41	8.746 ± 9.10
2012	896.38	9.585 ± 7.93

3. Research methods

3.1 Sources of CO_2 flux and temperature data

The CO_2 flux and temperature data used in the research are the CO_2 flux data and temperature data (T_a) from 2000 to 2012 observed and recorded by the Harvard Forest long term ecological observation station (US-Hal) provided by the international flux network (FLUXNET). Among them, the CO_2 flux data has been removed from the pretreatment of flux data such as wild points, coordinate axis rotation and density correction. The CO_2 flux data mainly includes ecosystem net CO_2 exchange (NEE) and total primary productivity (GPP)[21,22]. When NEE is positive, it means that the ecosystem is in the state of releasing CO_2, that is, carbon source. When NEE is negative, it means that the ecosystem is in the state of absorbing CO_2, that is, carbon sink. GPP is the total amount of organic carbon fixed by plants through photosynthesis in unit time and unit area. It is also an important indicator to measure the intensity of vegetation carbon sink and study the carbon cycle of vegetation.

3.2 Parameterized phenological model of photosynthesis in plant communities

In order to analyze the change characteristics of NEE and GPP in Harvard Forest from 2000 to 2012, and discuss the response of CO_2 flux to temperature change, the phenological model[17] of photosynthesis of plant communities of total primary productivity (GPP) of the ecosystem is referred to the model uses the annual scale (1–365 days) of the maximum GPP per half an hour per day in Harvard forest ecosystem to quantify the seasonal change of photosynthetic capacity of plant characteristic communities. Therefore, this study applies the phenological model to the calculation of NEE, GPP and temperature changes in the Harvard Forest Ecosystem, and analyzes the characteristics of CO_2 flux and temperature changes. The diurnal sequence of the maximum, zero and minimum points of NEE and GPP changes is linearly fitted with the diurnal sequence of the maximum, zero and minimum points of temperature changes, and the response of CO_2 flux to temperature changes is analyzed.

4. Results and analysis

4.1 Characteristics of ecosystem CO_2 flux observations

It can be seen from **Table 2** that the maximum annual total amount of NEE in 2000–2012 was 298.13 g·m^{-2}·a^{-1}, which appeared in 2010, followed by 60.86 g·m^{-2}·a^{-1}, which appeared in 2011, indicating that the Harvard Forest Ecosystem was a carbon source in 2010 and 2011; the annual total amount of NEE in other years was negative, that is, it was a carbon sink, of which the intensity of carbon sink was the largest in 2008. The maximum annual total GPP appeared in 2010, 2023.18 g·m^{-2}·a^{-1}; the minimum value of GPP annual total appeared in 2005, which was l,345.68 g·m^{-2}·a^{-1}.

Table 2. NEE and GPP annual total characteristics of Harvard Forest ecosystem from 2000 to 2012

Year	NEE total exchange volume/g·m^{-2}·a^{-1}	GPP/g·m^{-2}·a^{-1}
2000	-238.56	1,522.71
2001	-396.21	1,582.75
2002	-204.73	1,475.74
2003	-191.97	1,473.79
2004	-435.19	1,716.59
2005	-325.50	1,345.68
2006	-474.53	1,639.00
2007	-527.41	1,627.78
2008	-631.62	1,609.13
2009	-160.51	1,400.89
2010	298.13	2,023.18
2011	60.86	1,671.72
2012	-381.19	1,750.79

According to **Figure 1**, there is a good correlation between CO_2 flux of Harvard Forest Ecosystem and temperature change in 2000–2012 ($P < 0.01$), in which the correlation coefficient (R^2) of linear fitting analysis between NEE and temperature is 0.65, which shows that NEE has a downward trend with the rise of temperature. The correlation coefficient (R^2) of linear fitting analysis between GPP and temperature is 0.81, which shows that GPP has an upward trend with the increase of temperature. The reason for this phenomenon is that the rise of temperature promotes the growth of woody plants in the Harvard Forest Ecosystem, enhances the photosynthesis of plant communities, and leads to the downward trend of NEE and the upward trend of GPP.

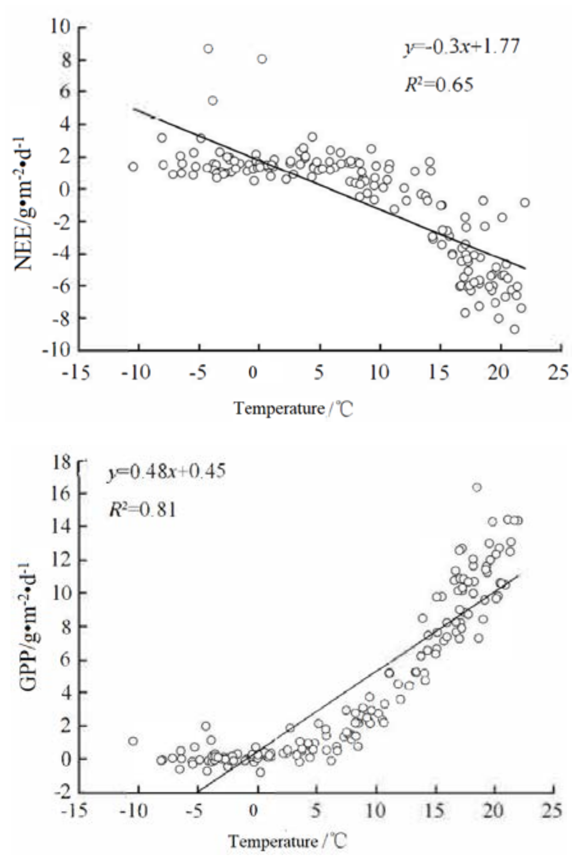

Figure 1. Relationship between CO_2 Flux and temperature in Harvard Forest Ecosystem.

4.2 Calculation of CO_2 flux change based on phenological model

4.2.1 Calculation of nee variation

It can be seen from **Table 3** that after fitting the NEE data from 2000 to 2012 with the phenological model, the correlation coefficient (R^2) of the fitting results is greater than 0.8 every year, which means that the fitting effect of applying the phenological model to the NEE data of the region is nice. The characteristics of annual NEE change are similar, but the minimum point, maximum point and zero point of NEE change have different diurnal sequences, and the change values are different. The daily sequence range of the minimum change point of NEE from 2000 to 2012 is 129–181 d. The daily sequence range of NEE change at 0 point is 169–221 d, and the daily sequence range of NEE change at maximum point is 225–294 d. Among them, the year of the earliest sequence at the point of the minimum change of NEE is 2010, and the change value is -0.50 $g \cdot m^{-2} \cdot d^{-1}$, that is, it is considered that the decline rate of NEE on that day in 2010 reached the maximum[17], which represents the time point at which the photosynthesis of plant communities increased the most. The year of the earliest sequence of NEE change at 0 point is 2012, which means that the total amount of NEE reached the lowest on that day in 2012, which can represent the time when plant photosynthesis was the strongest[17]. The year of the earliest sequence of the largest change in NEE is 2012, with a change value of 0.07 $g \cdot m^{-2} \cdot d^{-1}$, which means that the rise rate of NEE on that day in 2012 reached the maximum. From 2000 to 2012, the average value of the diurnal sequence at the minimum point of NEE change was 152 d, the average value of the diurnal sequence at the 0 point of NEE change was 194 d, and the average value of the diurnal sequence at the maximum point of NEE change was 255 d. According to the results of the dynamic characteristics analysis of NEE, it is inferred that the midpoint of the growth season of Harvard Forest ecosystem is 194 d[17]. The change values of the minimum point, 0 point and the maximum point of NEE change are different. From 2000 to 2012, the range of the minimum point of NEE change is -0.55 ~ -0.11 $g \cdot m^{-2} \cdot a^{-1}$, with an average of -0.27 $g \cdot m^{-2} \cdot d^{-1}$, and the range of the maximum point of NEE change is 0.07~0.16$g \cdot m^{-2} \cdot d^{-1}$, with an average of 0.11 $g \cdot m^{-2} \cdot d^{-1}$. Based on the analysis of the average daily sequence of the minimum point, 0 point and maximum point of NEE change in 2000–2012, it is inferred that the time of the strongest photosynthesis in the growth season of Harvard Forest Ecosystem starts at the end of spring and ends at the beginning of autumn, mainly in the three months in summer. This result is similar to the study of Richardson *et al.*[13] on the phenological characteristics of forest ecosystems at multi flux sites, and is more consistent with the study of Gu *et al.*[17] on the mid point of the growth season of temperate forest ecosystems in Finland at 200 d.

4.2.2 GPP variation calculation

It can be seen from **Table 4** that after fitting the GPP data from 2000 to 2012 with the phenological model, the correlation coefficient (R^2) of the fitting results every year is greater than 0.8, which means that the fitting effect of applying the phenological model to the GPP data in the region is better. The daily sequence range of GPP variation at the maximum point from 2000 to 2012 is 130–172 d. The daily sequence range of GPP variation at the zero point is 169–209 d, and the daily sequence range of the point with the smallest GPP variation is 215–305 d. Among them, the year of the earliest sequence of the point with the largest GPP change is 2007, and the change value is 0.23 $g \cdot m^{-2} \cdot d^{-1}$, that is, it is considered that the GPP rise rate reached the maximum on that day in 2007, which can represent the time when the plant photosynthesis increased the most. The year of the earliest sequence of GPP variation at zero point is 2006, which means that the total GPP reached the highest on that day in 2006, which can represent the time when plant photosynthesis was the strongest[17]. The year of the earliest sequence of the minimum point of GPP change is 2008, and the change value is -0.15 $g \cdot m^{-2} \cdot d^{-1}$, which means that the decline rate of GPP reached the maximum on that day in 2008. In 2000–2012, the average value of the daily sequence where the maximum point of GPP change is located is 150 d, and the average value of the day sequence of GPP variation at zero point is 191 d, and the average value of the day sequence at the point with the minimum change of GPP is 256 d, which is similar to the average value of the day sequence at the point with the minimum change of NEE (152 d), the average value of the day sequence at the point with the 0 change of NEE (194 d), and the average value of the day sequence at the point with the maximum change of NEE (255 d). Based on the analysis of the dynamic characteristics of GPP, it is speculated that the time plants in Harvard Forest Ecosystem entering the stable period of photosynthesis begins on the 150th day of the year, the midpoint is 191th day, and ends on the 256th day. The whole year lasts for about 106 days. Based on the analysis of GPP dynamic characteristics and the general division of seasons in the Northern Hemisphere, it is inferred that the stable period of photosynthesis in the growth season of Harvard Forest Ecosystem begins in the late spring and ends in the early autumn, and is mainly concentrated in the three months of summer, which is consistent with the analysis results of NEE dynamic characteristics.

Table 3. NEE change characteristics of Harvard Forest Ecosystem from 2000 to 2012

Year	NEE minimum value		NEE day sequence at 0/d	NEE Maximum value	
	Day sequence/d	Measured value/$g \cdot m^{-2} \cdot d^{-1}$		Day sequence/d	Measured value/$g \cdot m^{-2} \cdot d^{-1}$
2000	151	-0.28	186	225	0.07
2001	159	-0.14	206	256	0.13
2002	154	-0.24	189	245	0.10
2003	163	-0.12	209	259	0.13
2004	142	-0.34	183	289	0.16
2005	181	-0.11	221	265	0.13
2006	160	-0.55	173	262	0.12
2007	142	-0.32	216	262	0.13
2008	152	-0.17	194	240	0.10
2009	165	-0.12	210	257	0.10
2010	129	-0.50	178	294	0.08
2011	149	-0.16	199	241	0.10
2012	141	-0.49	169	225	0.07

Table 4. GPP change characteristics of Harvard Forest Ecosystem from 2000 to 2012

Year	GPP min		Daily sequence when GPP is 0/d	GPP Max	
	Day sequence/d	Measured value/$g \cdot m^{-2} \cdot d^{-1}$		Day sequence/d	Measured value/$g \cdot m^{-2} \cdot d^{-1}$
2000	147	0.16	200	256	-0.14
2001	153	0.30	179	288	-0.20
2002	149	0.21	196	245	-0.12
2003	162	0.42	180	275	-0.17
2004	138	0.16	200	262	-0.14
2005	164	0.19	209	255	-0.15
2006	164	0.59	169	233	-0.14
2007	130	0.23	172	305	-0.18
2008	172	0.23	197	215	-0.15
2009	147	0.13	204	265	-0.13
2010	133	0.21	184	236	-0.16
2011	151	0.18	205	260	-0.16
2012	144	0.25	188	234	-0.14

4.3 Response of CO_2 Flux to temperature change

It can be seen from **Table 5** that after fitting the temperature data in 2000–2012 with the phenological model, the correlation coefficient (R^2) of the fitting results every year is greater than 0.8, which means that the phenological model is applied to the fitting effect of temperature data in this region. The diurnal sequence range of the maximum temperature change from 2000 to 2012 is 79–151 d, with an average of 105 d. The daily sequence range of temperature change at 0 point is 201–270 d, with an average of 212 d. The daily sequence range of the minimum point of temperature change is 255–315 d, and the average value is 287 d.

It can be seen from **Table 6** that the correlation coefficient (R^2) of the daily sequence at the maximum point, 0 point and minimum point of temperature change fitting with the daily sequence of the maximum point, 0 point and minimum point of NEE and GPP change is 0.81, which means that there is a certain correlation between temperature change and CO_2 flux change ($P < 0.01$), and it is a positive correlation. That is, the delay or advance of the time point of temperature change will cause the delay or advance of the time point of CO_2 flux change. The analysis shows that temperature is one of the main factors affecting CO_2 flux of forest ecosystem, which is consistent with the research results of Niu *et al.*[15], Richardson *et al.*[13] and Bracho *et al.*[33]

Table 5. Temperature variation characteristics of Harvard Forest Ecosystem from 2000 to 2012

Year	**T_a max**		**Day sequence when T_a is 0/d**	**T_a min**	
	Day sequence/d	**Measured value/°C·d^{-1}**		**Day sequence/d**	**Measured value/°C·d^{-1}**
2000	123	0.25	201	315	-0.24
2001	96	0.29	217	285	-0.21
2002	151	0.26	205	274	-0.22
2003	101	0.22	213	268	-0.22
2004	79	0.23	213	297	-0.22
2005	107	0.22	215	296	-0.27
2006	112	0.22	202	255	-0.17
2007	99	0.28	208	315	-0.39
2008	107	0.24	201	306	-0.24
2009	95	0.22	270	273	-8.50
2010	85	0.19	206	297	-0.23
2011	98	0.24	206	282	-0.80
2012	118	0.16	207	278	-0.20

Table 6. Response of CO_2 flux to temperature change

Model type	**Fitting formula**	**R^2**	**P**
Temperature variation-GPP variation daily sequence	$y = 0.53x + 93.8$	0.81	<0.01
Temperature variation-NEEvariation daily sequence	$y = 0.54x + 88.5$	0.81	<0.01

5. Conclusion

Based on the CO_2 flux data and temperature data observed and recorded by the Harvard Forest flux observation station in the United States in 2000–2012 provided by the international flux network, this study uses a phenological model to analyze the variation characteristics of CO_2 flux in the temperate forest ecosystem in this region and the response of CO_2 flux to temperature changes. The forest ecosystem acted as carbon source in 2010 and 2011, and the total annual NEE in other years was negative, which was a relatively stable terrestrial ecosystem carbon sink. The vegetation growth status in the study area was the dominant factor in the ecosystem carbon cycle. The time when the photosynthesis of plant communities was strongest was mainly concentrated in summer. NEE, GPP and temperature had a certain correlation, that is, with the delay or advance of the time point of temperature growth, the time point of CO_2 flux change will be delayed or advanced.

Conflict of interest

The authors declared no conflict of interest.

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