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Carbon cycle in the Arctic terrestrial ecosystems in relation to the global warming

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Abstract The relationship between the global warming and carbon cycle in the Arctic terrestrial ecosystem was discussed based on a literature survey. As a result, atmospheric carbon dioxide (CO_2) and methane (CH_4) concentrations increased markedly during the past few centuries. The increase in concentration of these greenhouse gases was coupled with the global warming. Summer temperature in the Arctic regions showed a rapid rising. The Arctic soil is a huge organic carbon pool, with a mean estimate of 355×10^9 tC, being 23.7% - 32.3% of global soil carbon pool. At present the Arctic terretrial ecosystem is functioning as a sink of atmospheric CO_2. The rising global temperature resulting from an increase in atmospheric CO_2 would influence markedly the Arctic soil carbon and CO_2 source/sink relation of the Arctic ecosystems.
Key words Arctic, terrestrial ecosystem, carbon cycle, global warming, soil carbon pool.

1 Introduction

In a long history of the globe evolution, atmospheric CO_2 concentration oscillates because of changes in atmospheric composition and effect of other natural factors (such as the glacial-interglacial cycles). In order to clarify the role of atmospheric CO_2 in the evolution of climate system and to explore its influence on the global carbon cycling, it is important to expound mechanism of changes in air CO_2 concentration (Kira 1976). In the 1950's scientists found that a marked increase of atmospheric CO_2 concentration was mainly caused by human activities. The conclusion was firmly approved by data from the global observation network and from the ice-core of the Arctic and Antarctic (Boden and Johnsen 1992; Ferguson 1992). The region with higher latitudes, especially the Arctic, is a good field for testing the global climate change and its ecological effects because of its huge terrestrial carbon pool and sensitivity to climate change (GRIP 1993; IPCC 1990; Oechel and Billings 1992). In this paper, we discuss the carbon cycle of the Arctic terrestrial ecosystem and its role in the global change through a literature survey.

2 Increasing greenhouse gases in relation to Arctic warming

Carbon dioxide (CO_2) and methane (CH_4) are two of main greenhouse gases,

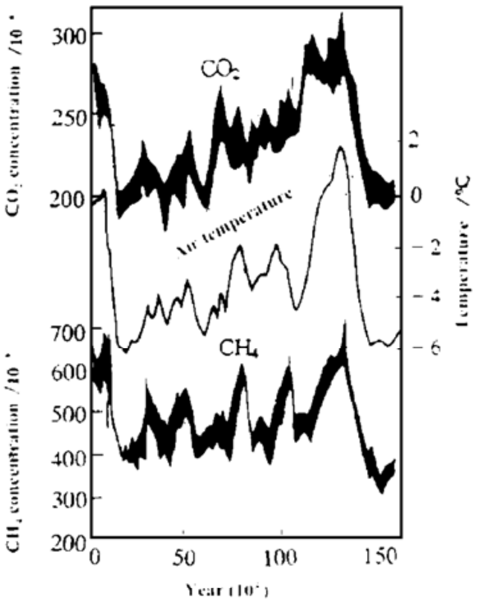

Fig. 1. CO_2 and CH_4 concentration and estimated Vostok atmospheric temperature changes during the past 160 ka, as determined on the ice cores.

which are closely associated with atmospheric temperature change. Fig. 1 shows the changes in CO_2 and CH_4 concentration and in temperature during the past 160 ka which was determined based on the ice-cores in Vostok, Antarctic (Barnola *et al.* 1987; Chappellaz *et al.* 1990). As illustrated in the figure, mean temperature in the late-glacial period (about 10 ka) and in the previous interglacial period (around 130 ka B. P.) was about 10℃ higher than in the glacial. Corresponding to such a change, CO_2 concentration was reduced by about 80×10^{-6}(80 ppm) from 280×10^{-6} in the interglacial period to 200×10^{-6} in the glacial period; CH_4 concentration changed from 700×10^{-9}(700 ppb) in the interglacial to 300×10^{-9} in the glacial.

A series of studies in Greenland and in other Arctic places have showed that during the past hundreds of years to thousands of years, there was a good correlation between the temperature changes and the atmospheric greenhouse gases in the Arctic areas (e. g. , Boden and Broecker 1993; Chappellaz *et al.* 1993; Taylor *et al.* 1993; Wahlen *et al.* 1991). Fig. 2 was drawn from data measured from the ice-core in Greenland, the Antarctic, and a direct 35 a observation at Mauna Loa, Hawaii (Keeling *et al.* 1989; Raynaud *et al.* 1993; Neftel *et al.* 1985). It illustrates clearly that the atmospheric CO_2 concentration rises abruptly since industrial revolution, especially since the 1950's.

Fig. 3 indicates the change in CH_4 concentration during the past few hundred years (Etheridge *et al.* 1988, Pearman and Fraser 1988). Antarctic CH_4 concentration was about 800×10^{-9} about two hundred years ago, while it rose to 1700×10^{-9} in the 1990's. It rises at a rate of 15×10^{-9} per year from the 1980's.

The increase in greenhouse gases is generating global warming. The Arctic area is one of the most sensitive areas to global change (GRIP 1993). Based on measure-

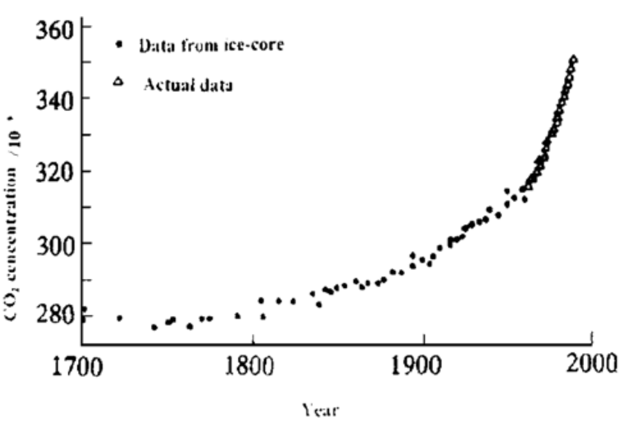

Fig. 2. Atmospheric CO_2 increase during the past 250 a.

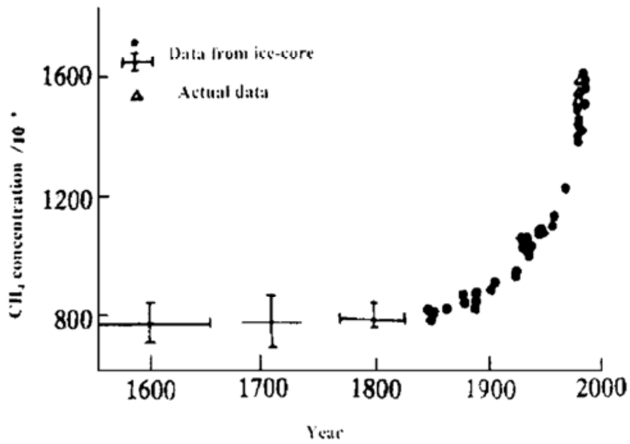

Fig. 3. Atmospheric CH_4 increase during the past few centuries measured from air in dated ice core.

ment of temperature at Alaskan tundra, Luchebruch and Marshall (1986) found that during the past dozens of years, mean temperature rose by about 2 – 4 ℃.

Such a change is clearly shown in Fig. 4, which illustrates summer temperature at Barrow and at the Prudhoe Bay in Alaska (Oechel, in press). Before the 1970's, summer temperature in Barrow had a warm-cold cycle of about 10 –15 a. However, since the 1970's the temperature rose linearly (Although there was a drop in the beginning of the 80's). In the Prudhoe Bay, the tendency is more striking, rising by 2.8 ℃ in 21 a from 4.1 ℃ in 1969 to 6.9 ℃ in 1990, with a rising rate of 0.13 ℃/a.

3 Carbon cycle of the Arctic terrestrial ecosystem

The main elements of the carbon cycling of the terrestrial ecosystem consist of five parts: plant photosynthesis, plant respiration, litterfall production and accumulation, soil organism accumulation, and soil respiration.

3.1 Plant biomass and productivity

Plant biomass and net production in the Arctic terrestrial ecosystem are listed in Table 1. Total Arctic terrestrial area is 20×10^{12} m^2(taiga plus tundra), being 13.4% of global terrestrial area (Schlesinger 1991). Total biomass is (80.0 – 113.8)× 10^9 tC, which constitutes 12.1% to 16.5% of global terrestrial biomass. Thereby, mean biomass density of the Arctic terrestrial ecosystems is similar to that of global mean, while mean net production in the Arctic is lower than global average, constituting only 6.1% to 10.1% of the global terrestrial production.

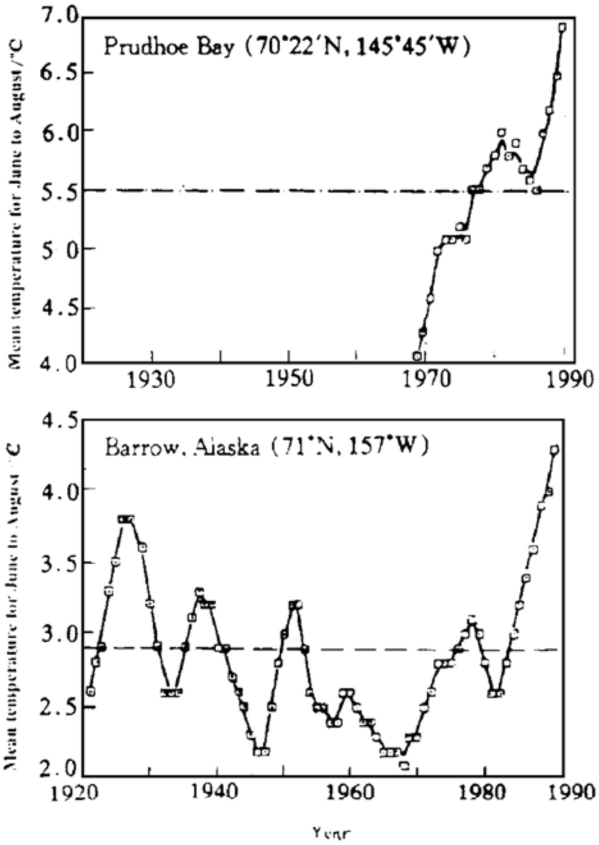

Fig. 4. Annual changes of summer air temperature in the Arctic regions.

Table 1. Biomass and plant net production in the Arctic terrestrial ecosystems [based on Moore *et al.* (1989), Oechel and Billings (1992) and Schlesinger (1991)]

Ecosystem	Area /10^{12} m^2	Biomass /10^9 tC	Ratio of Arctic biomass to global/%	Net production /(10^9 tC·a^{-1})	Ratio of Arctic net production to global/%
Taiga	12	80 – 108	11.6 – 15.7	2.5 – 4.3	5.2 – 8.9
Tundra	8	3.4 – 5.8	0.5 – 0.8	0.5 – 0.6	1.0 – 1.2
Total	20	83 – 114	12.1 – 16.5	3.0 – 4.9	6.2 – 10.1
Global sum	149	550 – 827	100	48.3	100

3.2 Soil organic carbon pools

It is well-known that the Arctic region is a huge soil carbon pool. The carbon pool is an important factor for the Arctic terrestrial ecosystem contributes to the global changes, but different authors estimate the pool much differently (Table 2).

According to recent estimates, total global carbon pool ranges from 1100×10^9 tC to 1500×10^9 tC (Adams *et al.* 1990; Fang *et al.* 1996; Moore *et al.* 1989; Schlesinger 1991). The Arctic and sub-arctic soil carbon are about 355×10^9 tC, constituting 23.75% – 32.3% of global soil carbon (Table 2).

Table 2. Estimates of the Arctic soil carbon pool by various authors

Author	Carbon/10^9 tC	Author	Carbon/10^9 tC
Ajtay and Hastings(1979)	200	Adams *et al.* (1990)	330
Post *et al.* (1982, 1985)	400	Gorham (1991)	455
Miller *et al.* (1983)	265	Schlesinger (1991)	380
Schlesinger (1984)	410	Oechel and Billings (1992)	265
Total mean	355		

In Table 2, estimated soil carbon includes litterfall amount. Because litterfall plays a very important role in carbon cycle, some detailed analyses are made hereafter. Analyzing the litterfall production all over the world (Bray and Gorham 1964; Kira 1976; Raich and Nadekhoffer 1989), we found that litterfall production decreases with increasing latitude as expressed in Eq. 1 (Fig. 5).

$$L_f = -0.1297X + 10.022 \qquad (r^2 = 0.90) \qquad (1)$$

where L_f is litterfall production (t/(hm^2·a)), and X is latitude.

According to the relationship, the litterfall production is zero at 77.3° in latitude. Obviously, it is not logical theoretically because even in the Arctic, there is still a little litterfall to be produced. However, most of lands with over 75° in latitude is ocean-covered. And, even if there are land plants, they grow very slowly. This is to say, their litterfall is neglectable.

Change in temperature along the geographical latitude generates such litterfall-latitude relationship mentioned-above. A graph showing the relationship between annual mean temperature and latitude is plotted (Fig. 6) by using climatic data from the North Hemisphere (Tokyo Astronomical Observatory 1985). In the figure, data with an altitude of over 500 m were not used. The relationship between annual mean temperature and latitude is expressed by the following function (Eq. 2).

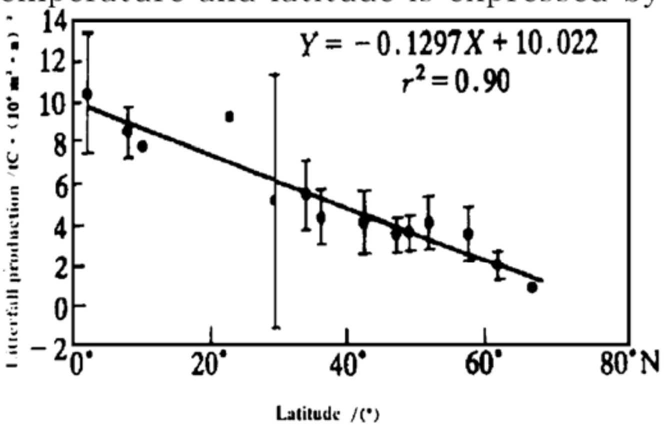

Fig. 5. Relationship between forest litterfall production and latitude.

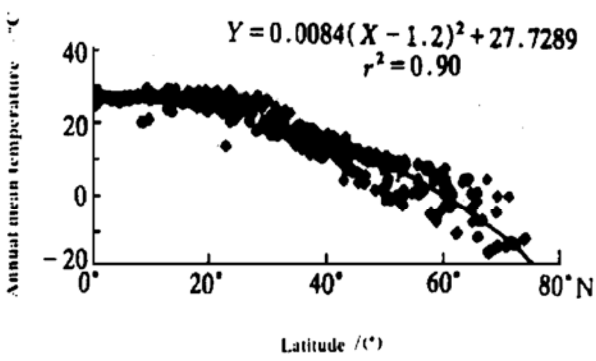

Fig. 6. Relationship between annual mean temperature and latitude in the North Hemisphere.

$$T = -0.0084(X - 1.2)^2 + 27.7267 \qquad (r^2 = 0.90) \qquad (2)$$

where T expresses annual mean temperature, and X is latitude.

Relationship between litterfall production and temperature was easily obtained from Eqs. 1 and 2 (Eq. 3).

$$L_f = -1.42\sqrt{27.73 - T} + 9.87 \qquad (3)$$

Eq. 3 is helpful for understanding litterfall production and its global distribution. According to the equation, litterfall production is zero at a mean temperature of −20.6 ℃; plants produce litterfall of 2.39 $t/(10^4\ m^2 \cdot a)$ at mean temperature of 0 ℃.

The litterfall in the Arctic derives from two parts, taiga forest and tundra. The litterfall production from tundra plants is approximately similar to their net production, namely, 0.5×10^9 t/a (Table 1). The litterfall production from taiga forests was estimated at $2.06 \times 10^9\ t/(10^4\ m^2 \cdot a)$, based on data from 29 sites of different regions in the world. Therefore, a total litterfall of 2.47×10^9 t/a was produced in taiga forests with multiplying total taiga area ($12 \times 10^{12}\ m^2$) (Table 1) by $2.06 \times 10^9\ t/(10^4\ m^2 \cdot a)$. This means that litterfall of 2.97×10^9 tC/a produced by the Arctic and sub-arctic plants enters into the Arctic soils.

3.3 Soil respiration and its change

CO_2 released from soils (soil respiration) is a very important source of atmospheric CO_2 concentration. Fig. 7 shows that soil respiration rate decreases linearly with an increase of latitude (Eq. 4).

$$S_R = -18.626X + 1405.3 \qquad (r^2 = 0.94) \qquad (4)$$

where S_R is soil respiration rate [$g/(m^2 \cdot a)$], and X is latitude.

Eq. 4 is generated by change in temperature along the latitudinal gradient. The relationship of soil respiration rate to annual mean temperature was easily obtained from Eqs. 2 and 4, and given in Eq. 5.

$$S_R = -203.21\sqrt{27.73 - T} + 1382.95 \qquad (5)$$

According to the equation, when temperature is −18.6 ℃, soil respiration rate equals to zero; when the temperature is 0 ℃, carbon of 312.9 $g/(m^2 \cdot a)$ is released from the Arctic soils.

It is possible to analyze the relationship between soil respiration rate and temperature at the global scale by using Eq. 5 and Q_{10} Law (law of Van Hoff). The Q_{10} value is just larger than 2 by each rising 10 ℃ in an area with lower temperature, while it becomes gradually smaller as temperature decreases.

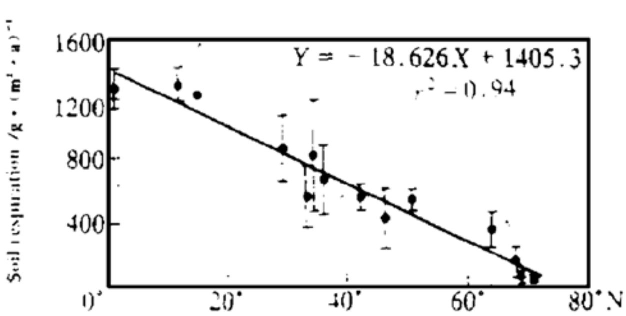

Fig. 7. Relationship between annual soil respiration rate in forest ecosystems and latitude.

In order to estimate soil respiration amount from the Arctic regions, data of soil respiration measured in various places of the Arctic were collected and re-calculated. As shown in Table 3, average soil respiration rate is 332 $gC/(m^2 \cdot a)$ for taiga forests and 61 $gC/(m^2 \cdot a)$ for tundra, and total carbon released from whole Arctic soil is $68 \times 10^9 C/a$, being 6.53% of total carbon released from global soils.

Table 3. Carbon released from the Arctic soils and its global significance

Ecosystem	Respiration rate $/g(m^2 \cdot a)^{-1}$	Annual emission$/10^9$ $tC \cdot a^{-1}$	Ratio of C released from Arctic to C released from global/%
Taiga	332	3.96	5.82
Tundra	61	0.49	0.71
Total	-	4.45	6.53
Global	-	68	100

3.4 *Carbon cycle and it's contribution to global change*

Fig. 8 illustrates the carbon cycle diagram of the Arctic terrestrial ecosystems. In this figure, total carbon of 29.8×10^9 tC in the Arctic atmosphere was estimated based on an atmospheric CO_2 concentration of 350×10^{-6} and a total area of Arctic region in Table 1. A total of 13.5×10^9 tC was annually absorbed by the land plants, and of 8.7×10^9 tC was released back to atmosphere by soil respiration. In 4.8×10^9 t carbon stored in the Arctic terrestrial ecosystems, 2.47×10^9 tC became soil organic matter of soil. An amount of 0.07×10^9 tC/a was transferred into oceans from lands through rivers (Schlesinger and Melack 1981). Carbon released to atmosphere from the Arctic soils by soil respiration (including respiration of plant roots) was 4.45×10^9 tC/a. Plant respiration includes respiration of roots. Therefore, soil respiration excluding root respiration is 3.0×10^9 tC/a if following an assumption that respiration of plant roots is 1/3 of total soil respiration (Raich and Schlesinger 1992).

According to Fig. 8, a total of $(0 - 1.9) \times 10^9$ tC is restored annually in the Arctic terrestrial ecosystems. It means that the Arctic terrestrial ecosystems are functioning as a sink of atmospheric CO_2. Moore *et al*. (1989) reported that $(5 - 6) \times 10^9$ tC was released annually to the atmosphere due to fossil fuels. This is to say, the Arctic terrestrial ecosystems may absorb 0 - 35% of it. This is agreement with D'Arrigo's study, who pointed out that taiga forests might slow the increase rate of atmospheric CO_2 concentration. A simulation study by Tans *et al*. (1989, 1990) also proved that the Arctic and subarctic terrestrial ecosystems are acting as air CO_2 sink. A physiological study by Vaisanen *et al*. (1994) also obtained the similar results to studies mentioned-above.

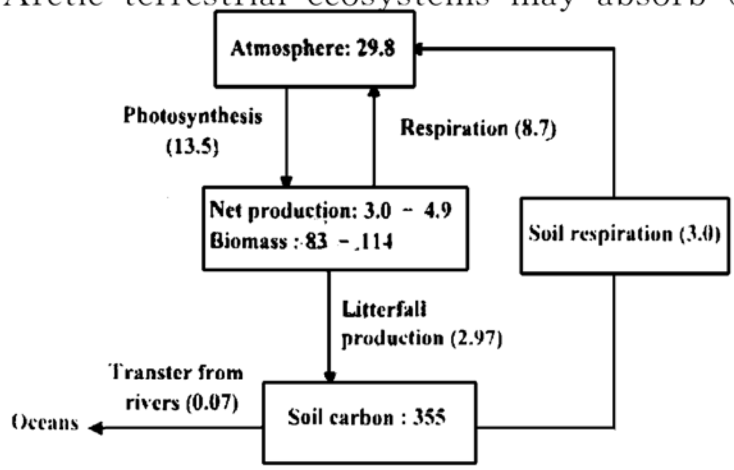

Fig. 8. Carbon cycle in the Arctic terrestrial ecosystems. All pools are presented in unit of 10^9 tC and annual fluxes in unit of 10^9 tC/a (parenthesized numerals).

In conclusion, although plant net production of the Arctic terrestrial ecosystems is rather small, the Arctic soils hold a huge carbon pool because of a cold climate and a low decomposition rate of organic matter. Meanwhile, a little amount of CO_2 is released to the atmosphere because of a low decomposition rate, and accordingly the Arctic terrestrial ecosystems play an important role in keeping air CO_2 concentration relatively stable. Once the Arctic terrestrial ecosystem is destroyed, it may increase the release of CO_2 from the Arctic soils and thus accelerate global warming.

3.5 Influence of doubled CO_2 concentration on the Arctic soil carbon pool

The Arctic soil is a huge carbon pool. Although CO_2 released to the atmosphere from the Arctic soils is not striking at present, it is an exponential huge source of atmospheric CO_2 if global warming remains. We hypothesis:

(1) CO_2 released to atmosphere by soil respiration (excluding root respiration) is 3×10^9 tC in the Arctic area (Table 1 and Fig. 8).

(2) The Q_{10} value is 2.4, namely, soil respiration increases by 2.4 times per increasing 10 ℃.

(3) According to forecast, at doubled CO_2 concentration condition, the global temperature rises by 1.5 – 4(5) ℃ (IPCC 1990), and the Arctic region rises by 11 ℃ (Mitchell 1990; Schlesinger and Mitchell 1987).

(4) The physiological characteristics of plants and the patterns of ecosystems remain unchanged at the global warming condition.

Then, the following conclusion can be obtained at a doubled CO_2 concentration condition:

(1) 6.8×10^9 t carbon will be annually released to the atmosphere from the Arctic soils, which is larger than a value of $(5-6)\times10^9$ tC/a released from fossil fuel.

(2) A total carbon (T_C) in the global atmosphere is obtained on the basis of the following calculation:

$$T_C = A_C \times (12/29) \times m \times S = 700 \times (12/29) \times 1.03 \times (5.1 \times 10^8)$$
$$= 1521.56 \times 10^9 \text{ t}C$$

where symbols A_C, m and S express atmospheric CO_2 concentration (ppmv), mean quality of atmosphere (kg/cm^2), and global area (km^2), respectively.

Interestingly, the T_C value is close to present global soil carbon $(1100-1500)\times10^9$ tC. If it is true, the carbon released from the Arctic soils will be 4.5 ‰ – 6.2 ‰ of the global atmospheric carbon. Although our results are based on some hypotheses, huge carbon pool in the Arctic soils will be a very important factor in balancing the global climate change and global carbon cycle in a doubled CO_2 concentration condition. In fact, early at the beginning of the 1980's based on a simulation study, Billings *et al.* (1982) concluded that the Arctic tundra would change to atmospheric CO_2 source from present CO_2 sink at increasing CO_2 concentration condition. Recently, Oechel *et al.* (1995a, b) pointed out that some of Alaskan tundra ecosystems were functioning as CO_2 source because of increasing global warming.

4 Conclusions

(1) Studies of the Arctic and Antarctic ice-core show that the global atmospheric CO_2 and CH_4 concentration are increasing. The increase in these greenhouse gases

is closely associated with the global temperature change. Under such a background, the air temperature in the Arctic regions is rising markedly, especially since the 1970's.

(2) Litterfall production and soil respiration rate of the Arctic terrestrial ecosystems decrease, with an increase of latitude. The Arctic terrestrial ecosystem is characterized by a huge soil carbon pool, whose estimate is 355×10^9 tC, being 1/4 to 1/3 of the total global carbon soil pools.

(3) The net production of Arctic terrestrial ecosystems is greater than its respiration; this suggests that the Arctic terrestrial ecosystem is functioning as atmospheric CO_2 sink.

(4) The rising in air CO_2 concentration will influence CO_2 release from the Arctic soils, and change CO_2 source/sink relation of the ecosystems. Under some hypotheses, 6.8×10^9 t carbon will be released annually from the Arctic soils at a doubled CO_2 concentration condition; this will generate a change of 4.5‰ to 6.2‰ of atmospheric CO_2 concentration.

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