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ORIGINAL ARTICLE

Temporal variation of soil carbon stock and its controlling factors over the last two decades on the southern Song-nen Plain, Heilongjiang Province

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Abstract Against the current background of global climate change, the study of variations in the soil carbon pool and its controlling factors may aid in the evaluation of soil's role in the mitigation or enhancement of greenhouse gas. This paper studies spatial and temporal variation in the soil carbon pool and their controlling factors in the southern Song-nen Plain in Heilongjiang Province, using soil data collected over two distinct periods by the Multi-purpose Regional Geochemical Survey in 2005–2007, and another soil survey conducted in 1982–1990. The study area is a carbon source of 1479 t/km^2 and in the past 20 years, from the 1980s until 2005, the practical carbon emission from the soil was 0.12 Gt. Temperature, which has been found to be linearly correlated to soil organic carbon, is the dominant climatologic factor controlling soil organic carbon contents. Our study shows that in the relevant area and time period the potential loss of soil organic carbon caused by rising temperatures was 0.10 Gt, the potential soil carbon emission resulting from land-use change was 0.09 Gt, and the combined potential loss of soil carbon (0.19 Gt) caused by warming and land-use change is comparable to that of fossil fuel combustion (0.21 Gt). Due to the time delay in soil carbon pool variation, there is still 0.07 Gt

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in the potential emission caused by warming and land-use change that will be gradually released in the future.

1. Introduction

Globally, two thirds of organic carbon in terrestrial ecosystems is stored in soils in the form of organic matter, and the total amount of organic carbon in soils is twice that of the atmospheric carbon pool. Therefore, the stability, increase, or release of soil organic carbon (SOC) all exerts significant influences on CO_2 concentration in the atmosphere. Soil carbon sequestration has become the most simple and effective method for reducing the atmospheric concentration of greenhouse gases and slowing down global warming (Pan et al., 2007; Sun et al., 2008). Studying soil organic carbon storage, its spatial distribution, and its dynamic changes is prerequisite to building a soil carbon pool inventory, assessing its historical deficit or surplus, and predicting the potential for soil carbon sequestration. These steps are also essential to the study of the carbon cycle and climate change as well as developing future land-use policies (Pan et al., 2000, 2007). In addition, because soil organic matter has an important relationship with soil quality and function, and because it is a natural resource, the yield of the study of temporal variation in the soil organic carbon pool and its controlling factors will also be of great relevance to agricultural production and national food security concerns (Pan and Zhao, 2005). For a long time a lack of data spanning different time periods has meant that the study of the soil carbon pool has been confined to carbon reserve estimates made at specific points in time (Wang et al., 2000; Li et al., 2003; Zhou et al., 2007), and there has, therefore, been a dearth of analyses of its changes. Additionally, although some researchers have studied the factors that control soil organic carbon change, they have only carried out qualitative analyses, leaving much quantitative research to be done (Su and Zhao, 2002; Jiang et al., 2007; Xu et al., 2007).

China carried out national soil surveys twice in the last century, and the second soil survey in particular, conducted in the early 1980s, provides a dataset ideal for research on soil carbon evolution. Another dataset used in this study is from the Multi-purpose Regional Geochemical Survey carried out by the China Geological Survey since 1999, which uses a scheme of double layer and grid sampling. As of 2008, this survey has covered 1.6 million km^2, and its data can be used to estimate the soil carbon pool in the early 21st century (Xi et al., 2009). The data from these two surveys serve as vast seas of information that are key to the study of temporal variations in the soil carbon pool. Using the southern part of Song-nen Plain in Heilongjiang Province as a representative model, and using soil organic carbon data from the two periods mentioned above, this article studies the distribution characteristics of the soil organic carbon pool. In particular we study change in the soil carbon pool in a recent 20 year period and its controlling factors, and quantitatively analyze the relative contribution of these factors to soil carbon pool variations.

2. Data and methods

The study area is located in the southern part of the Song-nen Plain in China's Heilongjiang Province, has an area of 81,500 km^2, is located at east longitude 122°20′–128°00′, north latitude 44°40′–48°00′, is administered by Harbin, Daqing, Qiqihaer, and Suihua, and altogether involves 28 counties and cities. The range of annual average temperature is 1.7–4.0 °C and there are four distinct seasons, with winter being long and cold and summer being short and hot. The annual average precipitation is 370–670 mm, with 500–600 mm falling on the eastern plain and less than 500 mm falling on the western and northern part of the region. April–September precipitation accounts for 83–94% of annual precipitation. Soil parent materials in the Song-nen Plain include residual deposits, slope wash, layered alluvial gravel, loess-like clayey soil, alluvium, and aeolian sand. Soil types in the Song-nen plain are mainly dark brown soil, white slurry soil, black soil, chernozem, meadow soil, swamp soil, alkaline earth, blown sandy soil, and paddy soil, amounting to a total of nine types. Black soil, chernozem, and meadow soil account for over 90% of the soil in the Song-nen Plain area.

2.1. Data for 1982–1990

This data comes from the Second National Soil Survey, conducted from 1982 to 1990, and represents the local soil carbon pool of the 1980s. Data is from "Chinese Soil Species, vol. 2". The organic and inorganic carbon densities of surface (0–20 cm) soil were calculated using Microsoft EXCEL software and the calculation method is described in the relevant literature (Pan, 1999; Xi et al., 2009). Data on carbon density was imported to a soil map as the attribute value in ArcGIS software, and raster data was formed by inverse distance weighted interpolation.

2.2. Data for 2005–2007

This data represents the soil organic carbon pool in the early 21st century. The data's sampling density is one sample per km^2, and four samples for each 4 square kilometers were mixed together for chemical analysis, which included analysis of soil total carbon and organic carbon. Sampling points were made in the form of point shape files in ArcGIS, and raster dataset files were formed by inverse distance weighted interpolation. Using map algebra methods, we carried out subtraction calculations with carbon pool grid data from the two periods, and then obtained the map of increased organic carbon density. Overlay analysis was made between the raster data and the polygon data on soil type and land-use types.

3. Results and discussion

3.1. Proportion and distribution of soil carbon

The soil carbon pool is composed of two parts: the organic and inorganic carbon pools. Soil organic carbon (SOC) comes from the bodies of animals, plants, and microorganisms; their excreta, secretion, and degradation products; and humus, the organic matter in soil science. Soil inorganic carbon (SIC) generally exists in the

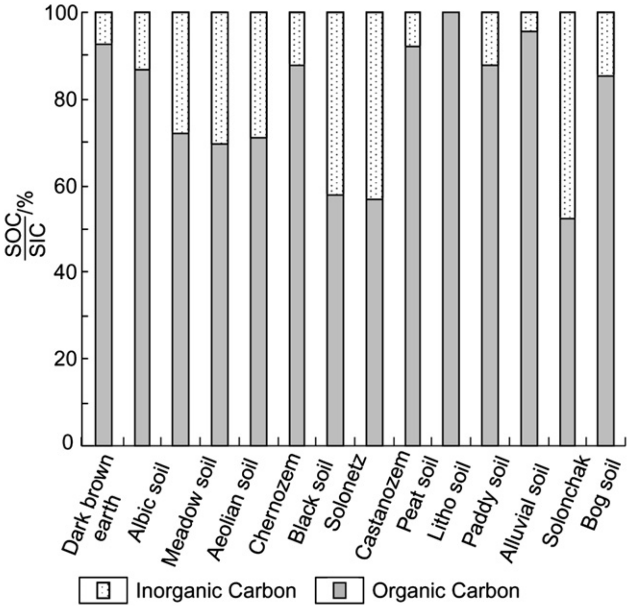

Figure 1 Proportions of SOC and SIC pool in the various soil types.

form of $CaCO_3$ produced by the weathering of parent rock or soil illuviation; in alkaline soil types it comes mainly in the form of HCO_3^- (Chen, 2004). Fig. 1 shows the relative proportions of SOC and SIC in the surface soil (0—20 cm) of different soil types. The data are from the Multi-purpose Geochemical Survey. In the study area, SOC is the dominant form (comprising more than 50%) of soil carbon for all soil types. However, the proportion of SOC in the total carbon pool also depends on the soil types. For example, saline, alkaline earth, and chestnut soil all have relatively low levels of SOC when compared to other soil types, with SIC in the form of calcium or HCO_3^- comprising a greater proportion of the soil (close to 50% of the total carbon pool) than it does in other soils. Conversely, in rocky soil, alluvial soil, dark brown soil, and peat soil, SIC contents are very low and organic carbon is predominant.

Table 1 displays various soil types' SOC and SIC density and overall storage. Swamp land has the highest SOC density of all the soil types, followed by rocky soil, dark brown soil, and paddy soil. However, from the perspective of SOC storage, meadow soil, followed by chernozem and black soil, has the greatest SOC storage capacity due to its relatively larger area.

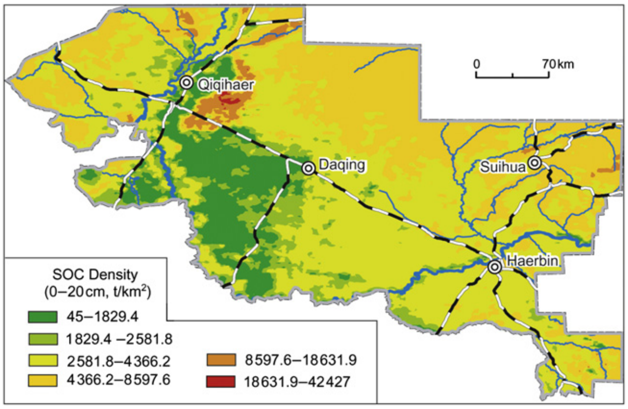

Figure 2 Sketch map for soil organic carbon density (0—20 cm, 2005).

3.2. Temporal variation in the SOC pool

Compared to absolute amounts of soil carbon, the temporal variation of the soil carbon pool yields much more information of value to the study of global climate change. In the study area, there was a time interval of 20 years between samplings. This time period represents an era of rapid economic development and dramatic land-use changes in China. During this short period, human activities made unprecedented impacts on nature, and the global climate changed significantly.

Fig. 2 is a map of SOC density in the early 21st century from the Multi-purpose Regional Geochemical Survey dataset. This raster data was subtracted from that of the 1980s, and data on the distribution of soil organic carbon sources and sinks over the last 20 years were obtained (Fig. 3). Positive values represent the increases in SOC during the 20 years, i.e. soil carbon sink values; negative values represent decreases in SOC, i.e. soil carbon source values. It can be seen from the map that most of the study

Table 1 Soil organic carbon density (0—20cm) and storage for various soil types.

	Density of SOC ($t\ km^{-2}$)	Density of SIC ($t\ km^{-2}$)	Bulk density ($t\ m^{-3}$)	Area (km^2)	Reserve of SOC (10^5 t)	Reserve of SIC (10^5 t)
Dark brown soil	4813.8	369.1	1.05	3328	160.2	12.3
Lessive soil	4176.2	631.3	1.04	1688	70.5	10.7
Meadow soil	3794.7	1476.5	1.19	37232	1412.8	549.7
Aeolian sandy soil	1953.3	848.7	1.41	5464	106.7	46.4
Chernozem	3923.5	1607.2	1.20	19808	777.2	318.4
Black soil	4053.1	572.8	1.14	11692	473.9	67.0
Solonetz	2139.1	1551.3	1.20	220	4.7	3.4
Castanozem	2711.8	2072.0	1.14	128	3.5	2.7
Peat soil	792.7	69.7	0.17	148	1.2	0.1
Litho soil	5801.1	0.0	1.20	28	1.6	0.0
Paddy soil	4852.4	666.0	1.18	1108	53.8	7.4
New plot soil	3199.8	154.9	1.31	92	2.9	0.1
Saline soil	1932.7	1742.8	1.26	300	5.8	5.2
Marsh soil	6193.9	1072.9	0.95	2480	153.6	26.6

area's soil has served as a source of carbon in the last 20 years, in particular the vast meadow soil zone located to the south of the line of Qiqihaer—Daqing—Harbin; large carbon source areas also exist in the black soil area of Tailai County, between Hulan County and Bayan County, in the meadow soil north of Longjiang County, in the dark brown soil area in the west of Longjiang County, and in the dark brown soil areas in western Shuangcheng County and in the north side of Niuhe in northern Wuchang County. Soil in most of the carbon source areas lost over 2600 t/km^2 of carbon during the 20 years in question. The chernozem area along the line of Lindian County—Mingshui County—Qinggang County—Wangkui County is a soil carbon sink. Other SOC sink areas are generally related to river and lake systems, such as the area around the Zhalong Wetland, on both sides of the Alun and Wuyu'er rivers in north Fuyu County, and upstream of Gemuke River in Qing'an County. These carbon sink areas have the characteristics of being of small areas, having large carbon sink values. The quantities of carbon sequestered within them during the 20 year study period are generally greater

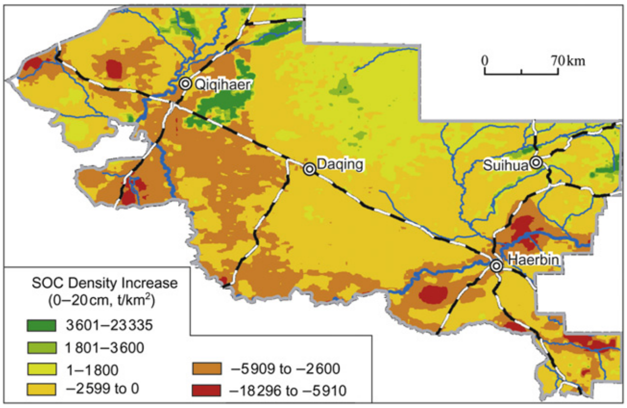

Figure 3 Increase of soil carbon density in the last two decades (1985—2005).

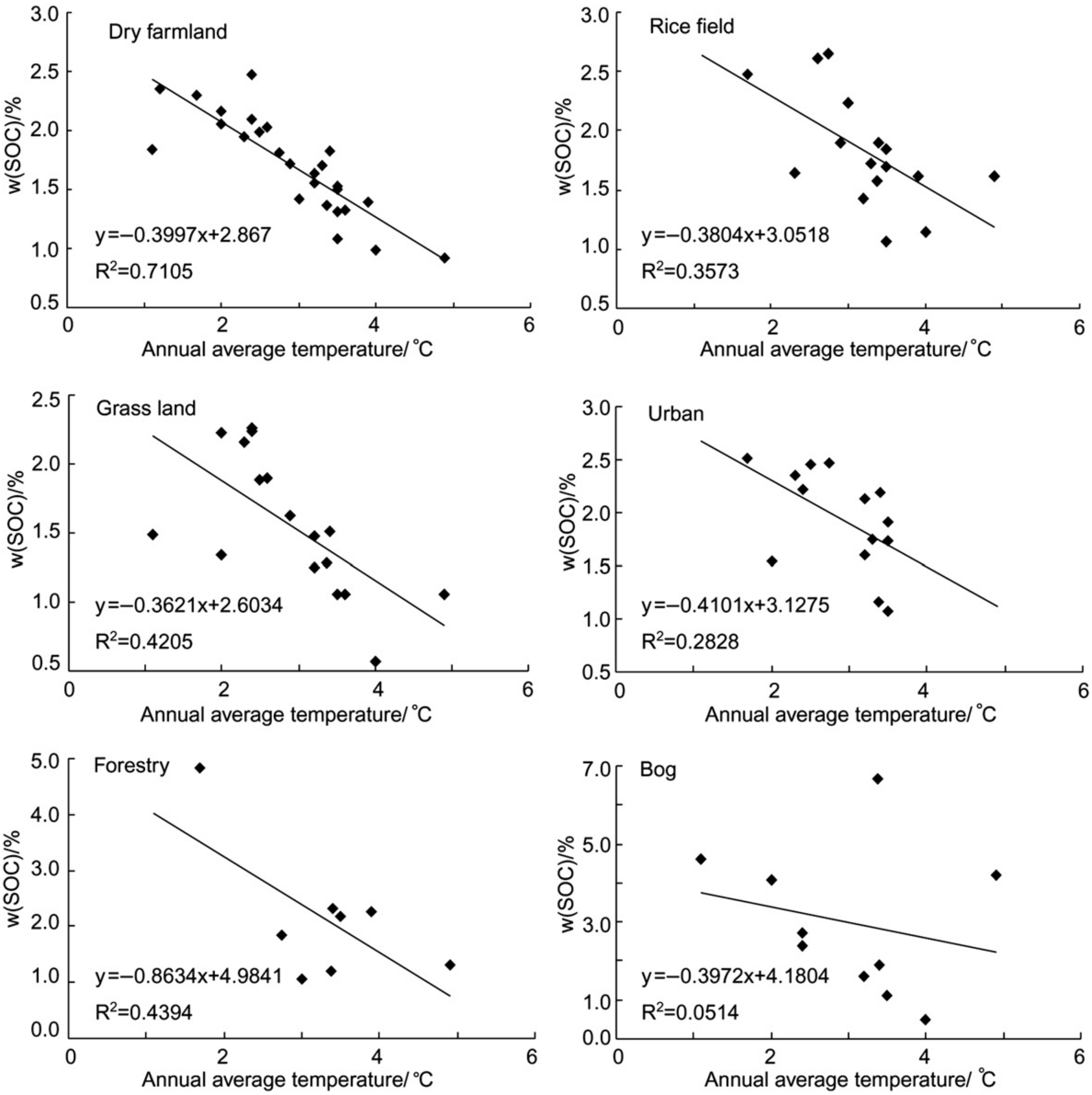

Figure 4 Soil organic carbon vs. average annual temperature for the various ecosystems.

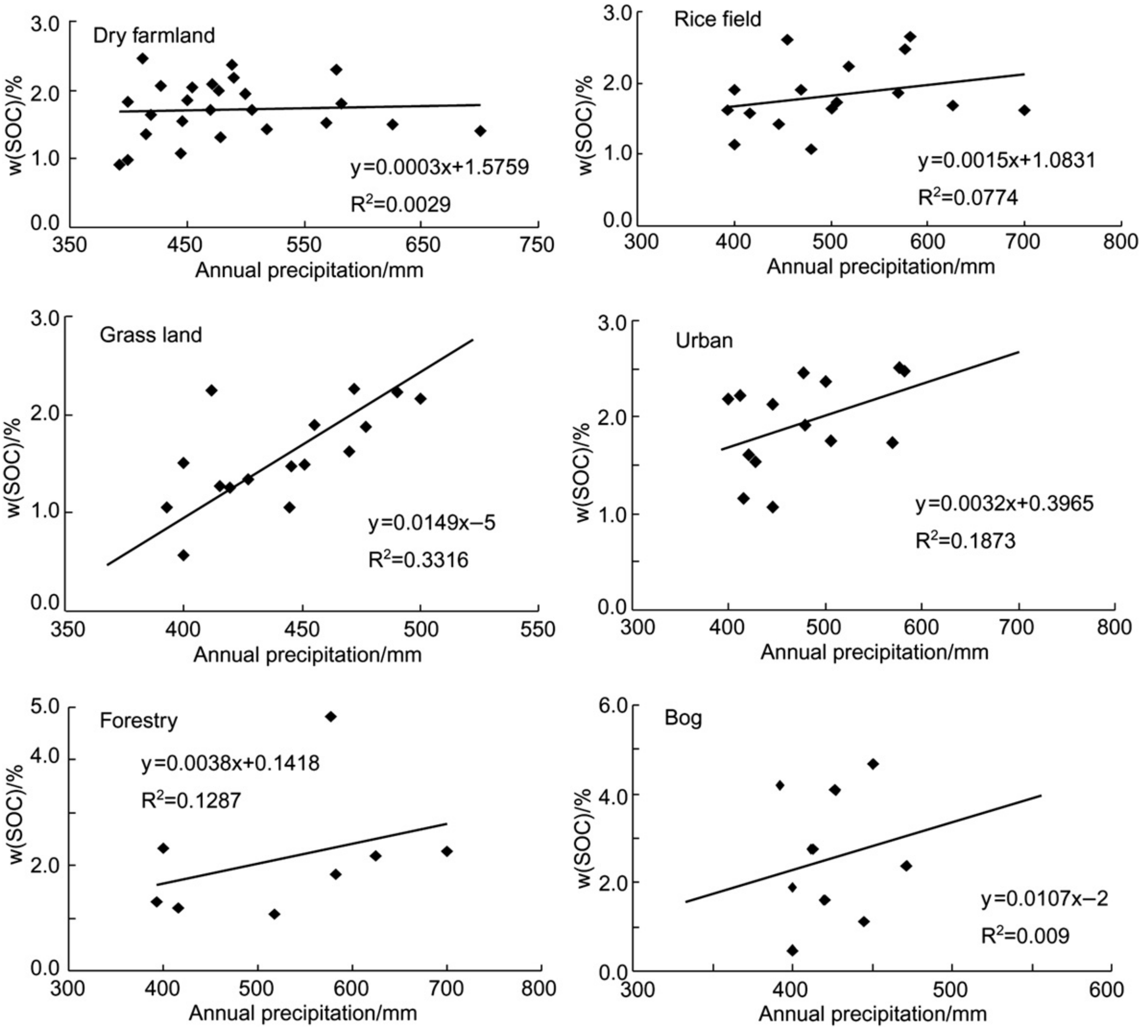

Figure 5 Soil organic carbon vs. annual precipitation for the various ecosystems.

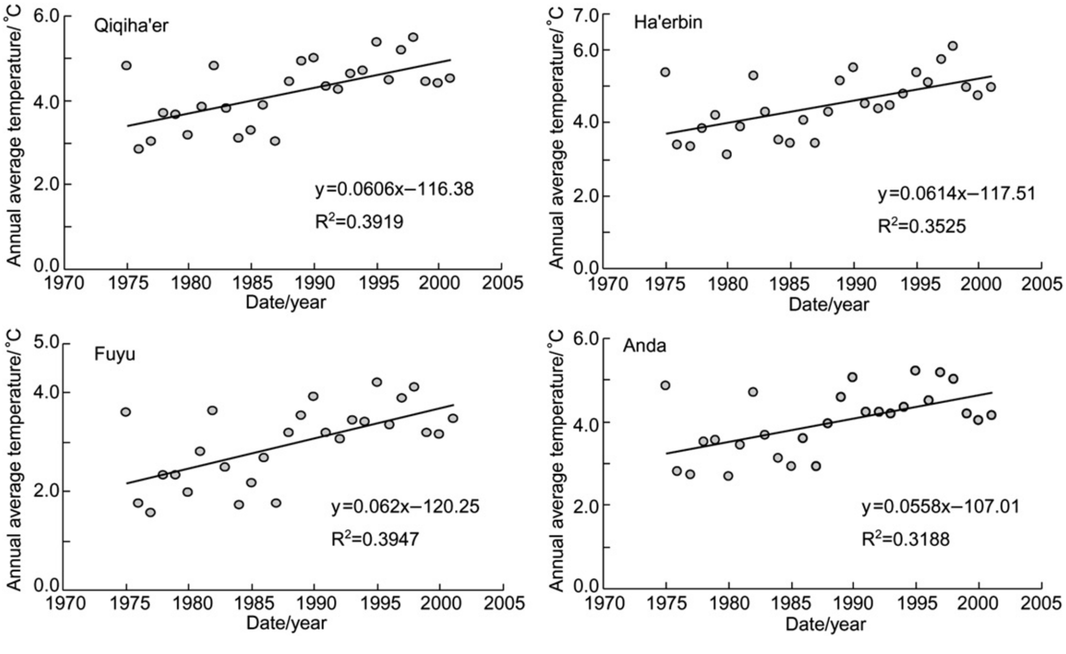

Figure 6 Increasing average annual air temperature in the last 3 decades.

Table 2 Potential soil carbon loss caused by the warming climate in the last two decades.

Ecosystem	Area (km^2)	Density of SOC ($t\ km^{-2}$)	Unit release ($t\ km^{-2}$)	Total release (10^6 t)
Grassland	16,861	2807.31	1045.61	17.63
Dry farmland	50,425	3824.53	1110.65	56.00
Paddy field	7430	4305.28	1059.25	7.87
County	1456	3084.58	1165.80	1.70
Forest	2904	5383.05	2323.82	6.75
Swamp	2423	8967.90	4279.27	10.37
Total	81,500	–	–	100.32

3600 t/km^2. Formation of these local carbon sinks is caused by low-lying land and blocked water drainage, which results in the slow decomposition of organic matter and long-term accumulation of soils rich in organic carbon.

In Fig. 3, it can be seen that the average value of all grids is −1479, meaning that the region is a 1479 t/km^2 carbon source on average. The study area is about 81,500 km^2, so our results show a total carbon source of 0.12 Gt, which is the carbon emission to the atmosphere from the whole area for the 20 year period. Our finding that the study area is a large carbon source is consistent with Liu et al.'s (2004) earlier results.

3.3. Factors controlling soil carbon loss

Organic carbon input to soil mainly comes in the form of plant residues. Relatedly, organic carbon in soil is released into the atmosphere mainly in the form of CO_2 released by decomposition performed by soil microbes. SOC content is the result of the long-term balance of the carbon input and output in the soil carbon circling system. A number of physical, biological, and anthropogenic factors including climate, vegetation, soil properties, and agricultural management affect the soil carbon balance by changing carbon input and output rates, and thus have an impact on SOC densities (Su and Zhao, 2002; Xu et al., 2007). The variation of SOC pool in the southern Song-nen plain is mainly the result of soil carbon release, which is the result of many natural and anthropogenic factors, generally including climate change and land-use changes.

3.3.1. Climate change

Previous studies (Kirschbaum, 2000) have shown that temperature is the most important climate factors affecting SOC content, followed by moisture. We calculated the average SOC content of various ecosystems county by county. Using climate data from weather stations in each county, we carried out correlation analysis between SOC and annual average temperature and annual precipitation respectively (Figs. 4 and 5). It can be seen from our calculations that temperature significantly affects SOC contents, particularly in dry farmland and grassland ecosystems; conversely, the impact of precipitation on SOC is much less than that of temperature, and every ecosystem showed relatively lower correlation coefficients when precipitation was calculated.

We collected recent decades' temperature data observed daily by weather stations in the study area and calculated annual average temperatures from 1975 to 2002. The linear regression of the temperature data shows that the slopes of the regression equations are all positive (Fig. 6), indicating the long-term increasing trend of annual average temperature and climate warming. The slopes of the regression equations are between 0.0558 and 0.0620, meaning that the range of temperature change within three decades is between 1.67 and 1.86 °C. That value equates to 0.0558–0.0620 $°C\ a^{-1}$, which is much higher than the average global temperature increase considered most probable by the Intergovernmental Panel on Climate Change (Houghton et al., 1990).

SOC's sensitivity to temperature can be expressed by the slopes calculated with the equations used in Fig. 4. We estimated the loss of SOC caused by temperatures rising in the past 20 years according to the total area and temperature sensitivity of each ecosystem. In Table 2, we calculated the SOC losses in each ecosystem with the assumption that temperatures have risen by about 1.2 °C in the past 20 years. The total carbon loss due to ecosystem temperature rise is 0.10 Gt. It is noteworthy that the result given here is the potential emission caused by rising temperatures, rather than the actual amount that has been released. Temperature affects the soil carbon pool by adjusting the input and output of carbon in soil, so it will take a long time (measured in

Table 3 Soil carbon loss caused by land use transformation ($t\ km^{-2}$).

	Paddy field	Dry farmland	Woodland	Grassland	Construction land	Unused land
Paddy field	–	−480.74	1077.77	−1497.97	−969.89	4662.62
Dry farmland	480.74	–	1558.51	−1017.22	−489.14	5143.36
Woodland	−1077.77	−1558.51	–	−2575.74	−2047.66	3584.85
Grassland	1497.97	1017.22	2575.74	–	528.08	6160.59
Construction land	969.89	489.14	2047.66	−528.08	–	5632.51
Unused land	−4662.62	−5143.36	−3584.85	−6160.59	−5143.36	-

The type before transformation is in the far left of the same row of the figure and the land use type after transformation is in the far up of the column; Negative values mean carbon release of that land use change and vice versa.

Table 4 Increasing of soil carbon storage caused by land use transformation in the study area (t).

	Paddy field	Dry farmland	Woodland	Grassland	Construction land	Unused land
Paddy field	0.00	−9908018.24	23654.92	−334598.02	−4492.11	359037.13
Dry farmland	174010.15	0.00	166906.41	−844069.99	−10331.26	211926.41
Woodland	−33640.29	−54155322.67	0.00	−10488250.40	−99018.79	481961.68
Grassland	240020.68	26729656.56	424389.96	0.00	5693.18	3127594.24
Construction land	40164.07	2150279.50	33339.03	−219107.25	0.00	642742.38
Unused land	−1213422.28	−25866028.51	−182517.35	−22785900.81	−132026.35	0.00

The type before transformation is in the far left of the same row of the figure and the land use type after transformation is in the far up of the column; Negative values mean carbon release of that land use change and vice versa.

tens, hundreds, or even thousands of years) to achieve balance after a change in input and output occurs. The data displayed in Table 2 actually refers to the entire release that will have occurred when the temperature has risen by 1.2 °C and balance has been achieved. Studies have shown (Lin et al., 2008) that in contrast to temperature, rainfall in the study area did not change significantly in recent decades; in addition, the impact of rainfall on SOC content is not obvious (Fig. 5). We have, therefore, ignored the impact of precipitation changes on SOC.

3.3.2. Land-use change

Another factor causing the release of soil carbon is land reclamation and land-use change. In general, after agricultural irrigation and fertilization, the SOC content in drought-stricken and barren land will increase. On the other hand, in land such as the Song-nen plain, natural soil is already fertile with high organic carbon content, and SOC shows a trend toward decrease in response to tillage and a reduction of natural organic debris input caused by agriculture (Cui et al., 2003). A decrease in both the quantity and quality of grassland caused by land-use change is one of the main causes of carbon release (Almaz and Duan, 2009). In addition, the conversion of dry land, paddy fields, and woodlands into construction sites also forces a release of soil carbon into the atmosphere. Table 3 shows the quantity of the carbon exchange between soil and atmosphere for the various land-use type changes based on the Multi-purpose Regional Geochemical Survey dataset.

Using remote sensing data, Zhang (2006) estimated the conversion of land-use types from the mid-1980s to the early 21st century in the Song-nen Plain. As the range of the study area has a slight deviation, we used the relative proportion to calculate the matrix of land-use change in the study area (Table 3), and on this basis the quantity of carbon exchange between soil and atmosphere was calculated (Table 4). The sum of all values in Table 4 is −91,465,368.01 t, which means that the potential release of soil carbon caused by land-use change in the study area is about 0.09 Gt in the last 20 years.

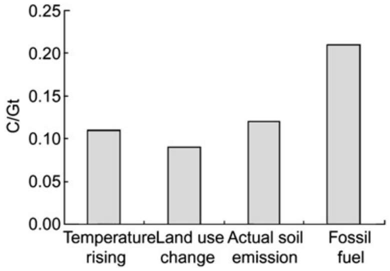

Figure 7 Carbon emission from the various sources in the last two decades.

3.3.3. Discussion of the carbon sources

In the above analysis, the potential amount of carbon emission caused by rising temperatures is estimated to be 0.10 Gt in the study area, and that caused by land-use change 0.09 Gt. Thus, the soil carbon source is formed by both natural and anthropogenic factors, each of which accounts for about one half of the total.

As the amount of soil carbon emission resulting from climactic warming in the past 20 years is 0.10 Gt, and that caused by land-use change is 0.09 Gt, the sum of these figures is 0.19 Gt. However, according to our analysis of the data from the Multi-purpose Geochemical Survey and the second soil survey, the value of the carbon source in the study area is 0.12 Gt within the 20 years, meaning there is a difference of 0.07 Gt between predicted and observed values. We explain this discrepancy as follows: 0.12 Gt is the actual value observed from investigation and reflects what has already been released; 0.19 Gt is the potential total amount of emission due to warming and land-use change; the difference of 0.07 Gt reflects the amount of soil carbon that should be released in the future. Soil carbon release and carbon balance are long-term processes; the release of carbon caused by warming and land-use change is still in process, and has not yet reached a state of balance.

Fossil fuel combustion is another anthropogenic source of carbon dioxide emission into the atmosphere. The consumption of fossil fuel for each year in Heilongjiang is given in the "China Statistical Yearbook database" (Cnki Cajeph, 2010). During 1985−2005, the estimated amount of carbon dioxide produced by fossil fuel combustion in Heilongjiang Province was 4,519,770,280 t, or an amount of carbon equivalent to 1.23 Gt.

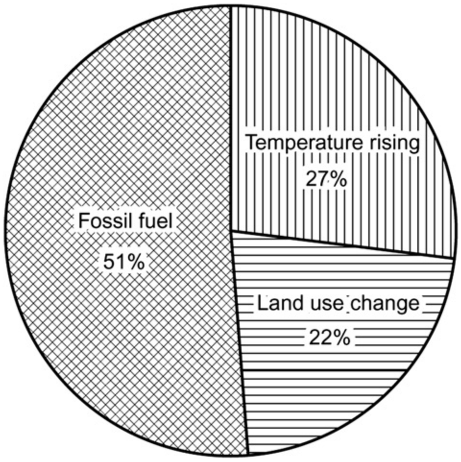

Figure 8 Proportions of the carbon sources.

The study area accounts for approximately 17.7% of the total area of Heilongjiang, and according to this proportion we estimate that carbon emission from fossil fuel in the study area in this period was 0.21 Gt.

Fig. 7 shows the estimated value of released carbon in the study area from the 1980s until the early 21st century from the four sources discussed above. It should be noted that the emission value resulting from rising temperatures and land-use change is a potential value greater than the actual emission value observed during this period. This discrepancy rests on the fact that the abruptness of land-use and temperature changes requires the passage of a long period of time before a state of balance in terms of soil carbon circulation will be reached—the difference between the predicted and observed values will eventually be released in the future. Fig. 8 shows the proportions of the three factors causing carbon emission, from which it can be seen that fossil fuel emission is the most influential cause, accounting for about a half of total emission, while soil carbon change resulting from rising temperatures and land-use changes combined account for the other half.

4. Conclusions

1) The soil organic carbon density has decreased by about 1479 t/km^2 on average in the Southern Song-nen Plain during the two decades from the 1980s until the early 21st century. The soil in the study area has released about 0.12 Gt of carbon into the atmosphere.
2) SOC content decreases with increases in temperature. Over the past 20 years, the potential loss of SOC due to rising temperatures is 0.10 Gt, and the potential loss due to land-use change is 0.09 Gt.
3) The soil carbon source of the study area was attributed to both natural and human factors. About 55% of the carbon source is attributable to rising temperatures, and 45% comes from land-use change.
4) In the study area, the potential amount of carbon emission from soil that has occurred in response to increasing temperatures and land-use changes is roughly equivalent to that which has been emitted because of fossil fuel combustion during the same period of the 1980s to the early 21st century.

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