Grassland Carbon Budget and Its Driving Factors of the Subtropical and Tropical Monsoon Region in China During 1961 to 2013

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The southern grasslands are an integral part of the grassland ecosystems of China and play an essential role in the terrestrial carbon cycle of the country. We reproduced the spatiotemporal dynamics of the carbon budget of southern grasslands from 1961 to 2013 using the Terrestrial Ecosystem Model and our results showed that the annual carbon budget varied from $-8.12$ to $6.16 \text{Tg} \; \text{C} \; \text{y}^{-1}$ with an annual average of $0.45 \text{Tg} \; \text{C} \; \text{y}^{-1}$ during the study period. Overall, southern grasslands acted as a weak carbon sink and sequestered $23.83 \text{Tg} \; \text{C}$ from 1961 to 2013. At the seasonal scale, southern grasslands acted as a carbon sink in wet seasons but as a carbon source in dry seasons. During the study period, temperature and precipitation were the main factors driving carbon budget dynamics at the seasonal scale, while soil moisture was the main driving factor at the annual scale. Over the entire study region, $71.81\%$ of the area switched to being a carbon sink while only $5.90\%$ remained stable and the strong carbon sinks were mainly found in the southern, northern and western areas of the southern grasslands.
In this work, we calibrated and verified the Terrestrial Ecosystem model using information about nitrogen and carbon fluxes and pools acquired from field observation and the literature. We then simulated and analyzed the spatiotemporal dynamics of the carbon budget and its control mechanisms in southern grasslands from 1961 to 2013.

Results

Model Verification. We verified the TEM results with the observed vegetation and soil organic carbon density data sets from 2011 to 2013 (Fig. 1). First, we removed unreasonable values from the observation data, such as above- or below-ground vegetation densities or soil carbon densities in all soil layers equal to zero, as well as the data for parameter calibration, and we then used the Pauta criterion (3δ method) to exclude the observation data that were more than 3-fold greater than the standard deviation of the observation data and their average. Finally, we used the remaining observation data to verify the TEM simulation results. The parameterized TEM-simulated vegetation carbon ($R^2 = 0.50$, $n = 215$) and soil organic carbon ($R^2 = 0.44$, $n = 127$) data matched the observation data well, exceeding the confidence level of 99%. The average measured vegetation and soil organic carbon density values were 572.70 g C m$^{-2}$ and 1564.60 g C m$^{-2}$, respectively, which were close to the corresponding simulated values of 574.94 g C m$^{-2}$ and 1604.56 g C m$^{-2}$.

Temporal Dynamics of Precipitation and Temperature. The average annual temperature in southern grasslands increased remarkably ($R^2 = 0.44$, $P < 0.001$, $N = 53$; Fig. 2a) during 1961 to 2013, and the annual precipitation varied greatly from year to year, with an annual average of 1057.35 mm (Fig. 2a). The study region was seriously affected by the Asian Monsoon and experienced considerable seasonal changes in precipitation with obvious wet (April to September) and dry seasons in one year (Fig. 2b). During wet seasons, the total precipitation accounted for 77.16% of the annual precipitation, on average, from 1961 to 2013. The mean temperature was 21.10 °C during wet seasons, which was approximately twice that in dry seasons (10.71 °C). Therefore, the climate was wetter and warmer during wet seasons, especially during the summer season of June to August.

Temporal Dynamics of the Carbon Budget. In the TEM, net ecosystem production (NEP) was defined as the difference between net primary production (NPP) and heterotrophic respiration (RH). The annual NEP in southern grasslands ranged from $-8.12$ to 6.16 Tg C y$^{-1}$ from 1961 to 2013, with an annual average of 0.45 Tg C y$^{-1}$ (Fig. 3a). Thus, the entire study region ($0.29 \times 10^6$ km$^2$) acted as a weak carbon sink and fixed 23.83 Tg C during the study period with large inter-annual variations. Compared with NEP, the annual NPP and RH showed different temporal dynamics (Fig. 3b); both showed significantly increasing trends from 1961 to 2013 ($R^2 = 0.35$, $P < 0.001$, $N = 53$ and $R^2 = 0.68$, $P < 0.001$, $N = 53$, respectively). The rate of increase of NPP (0.18 Tg C y$^{-1}$) was greater than that of RH (0.17 Tg C y$^{-1}$), and the difference between these rates was the basis for the annual
fluctuations in NEP in southern grasslands from 1961 to 2013. The average annual NPP was 93.63 Tg C y$^{-1}$ during 1961 to 2013, and the annual RH ranged from 89.9 to 97.1 Tg C with an annual average of 93.2 Tg C y$^{-1}$.

The seasonal variations in monthly NPP and RH exhibited the same pattern, decreasing from July to December and increasing from January to July (Fig. 3d), and the differences in the monthly NPP and RH led to the seasonal variation in NEP. The seasonal variation in monthly NEP showed a distinct bimodal pattern with the maximum appearing in May and October (Fig. 3c). The NEP in summer was close to zero because almost all the carbon fixed by grasslands from the atmosphere was released by the soil under high temperature and high moisture conditions. Therefore, the southern grasslands acted as a carbon sink in wet seasons and as a carbon source in dry seasons.

Response of NEP to Climate Variables. Climatic variables, such as precipitation, air temperature, soil temperature and so on, could affect the NEP of grasslands through their influence on NPP and RH. At the seasonal scale, southern grasslands were strongly affected by the monsoon climate and characterized by high temperature and precipitation in wet seasons (Fig. 3b), and the differences in the monthly NPP and RH led to the seasonal variation in NEP. The seasonal variation in monthly NEP showed a distinct bimodal pattern with the maximum appearing in May and October (Fig. 3c). The NEP in summer was close to zero because almost all the carbon fixed by grasslands from the atmosphere was released by the soil under high temperature and high moisture conditions. Therefore, the southern grasslands acted as a carbon sink in wet seasons and as a carbon source in dry seasons.

Spatial Dynamics of Grassland NEP in Southern China. From 1961 to 2013, TEM simulations indicated that southern grasslands acted as a carbon sink with a high standard deviation (3.38 Tg C y$^{-1}$), which was the difference between the average annual NPP and RH of the total vegetated area of 0.29 $\times$ $10^6$ km$^2$. Therefore, the annual NEP of southern grasslands in China was 1.53 g C m$^{-2}$ y$^{-1}$ with significant spatial variation; large
carbon sinks were in the southern, western and northern portions of the southern grasslands (e.g., Guangxi, Hubei, and Sichuan Provinces), which experienced high precipitation and high temperatures. Central Yunnan Province, which has low temperatures and low precipitation mainly acted as a carbon source (Fig. 4a).

The spatial distribution of the areas with increasing NEP indicated that 71.81% of the study area tended to be a carbon sink from 1961 to 2013 (Fig. 4b). These areas are mainly in most areas in southern grasslands. Less than 22.26% of the total grasslands area acted as carbon sources. These areas were distributed mainly in the central of Yunnan province. Only approximately 5.93% of the study area was in a steady condition (0.00–0.01 g C m\(^{-2}\) y\(^{-1}\)).

**Discussions**

Only a few studies have been conducted on the carbon budget of southern grasslands (Table 2). For instance, Sun *et al*.\(^4^4\) estimated that southern grasslands sequestered carbon at a rate of 3.25 to 81.98 g C m\(^{-2}\) y\(^{-1}\) during 2001 to 2010 using an improved BIOME-BGC model. In contrast, we estimated a much lower carbon sink of 1.53 g C m\(^{-2}\) y\(^{-1}\) from 1961 to 2013, which was much lower than that of other types of grasslands, e.g., 158.00 g C m\(^{-2}\) y\(^{-1}\) for the temperate grasslands of northern China during the growing season\(^4^6\), 11.25 g C m\(^{-2}\) y\(^{-1}\) for the temperate grasslands of China\(^4^9\) by TEM from 1961 to 2007, 88.21 g C m\(^{-2}\) y\(^{-1}\) for the grasslands of Inner Mongolia\(^6^0\) and 4.00–192.50 g C m\(^{-2}\) y\(^{-1}\) for the grasslands of the Tibetan Plateau\(^3^9\). The estimates of Sun *et al*.\(^4^4\) were quite different from those of this study due to the large difference in the scopes of the two studies. The research by Sun *et al*.\(^4^4\) was based on samples from three typical grasslands (mountain steppe meadow, typical grassland mountain and slope and typical mountain meadow) in southern China, while this study covered all grasslands in southern China.

The TEM-simulated NPP of southern grasslands was 318.15 g C m\(^{-2}\) y\(^{-1}\), which was within the range of previous estimates\(^4^0,4^1,4^4,4^5\) of 191.96–389.14 g C m\(^{-2}\) y\(^{-1}\). In comparison, our estimated average regional NPP was lower than that simulation by Sun *et al*.\(^4^2\) (1081.78 g C m\(^{-2}\) y\(^{-1}\)) using the Global Production Efficiency Model, by Sun *et al*.\(^4^3\) (656.30 g C m\(^{-2}\) y\(^{-1}\)) using the improved comprehensive and sequential classification system (CSCS) and by Sun *et al*.\(^3^9\) (471.62 g C m\(^{-2}\) y\(^{-1}\)) using a new climate productivity model. Our estimated annual NPP increased (0.88 g C m\(^{-2}\) y\(^{-1}\)) from 1981 to 2000 and decreased (1.01 g C m\(^{-2}\) y\(^{-1}\)) from 2000 to 2011 and Sun *et al*.\(^4^0\) similarly found an increasing trend from 1981 to 2000 with the GLO-PEM model and a decreasing trend from 2000 to 2011 by the improved CASA model. Earlier studies reported the NPP of different grasslands types. For instance, the simulated NPP ranged from 259.90 to 290.23 g C m\(^{-2}\) y\(^{-1}\) in Inner Mongolian grasslands,\(^4^7\),\(^5^3\),\(^5^6\),\(^5^7\),\(^5^8\) and from 92.50 to 334.45 g C m\(^{-2}\) y\(^{-1}\) in Tibetan Plateau grasslands,\(^3^9,4^0,4^6,5^1,5^2,5^7,5^8\). In general, the NPP of southern grasslands was similar to that of Inner Mongolian grasslands and slightly higher than the NPP of Qinghai-Tibet Plateau grasslands per unit area.

Our simulated RH ranged from 300.90–339.00 g C m\(^{-2}\) y\(^{-1}\) from 1961 to 2013 with an annual average of 317.16 g C m\(^{-2}\) y\(^{-1}\), which was similar to that estimated by Liu\(^4^5\) with a range from 79.61 to 719.14 g C m\(^{-2}\) y\(^{-1}\) of the grasslands of the Qinghai-Tibetan Plateau,\(^5^3,5^4,5^5\) and 132.00–866.00 g C m\(^{-2}\) y\(^{-1}\) for temperate grasslands,\(^5^3,5^5\) but lower than 470.00–900.00 g C m\(^{-2}\) y\(^{-1}\) for tropical grasslands.\(^5^4\)

The differences of in the grassland carbon budgets of these studies\(^3^7–4^5\) probably resulted for the following reasons. (1) The study regions and areas were different. The studies by Sun *et al*.\(^4^1\) and Liu\(^4^5\) were administered in south China and eastern Tibet, respectively, and the study by Sun *et al*.\(^4^4\) was administered in southern China, which had a grassland area of 0.6 × 10^6 km\(^2\) of grasslands area. (2) The data sources in previous studies were also quite different. For example, Sun *et al*.\(^3^8\) and Liu\(^4^5\) used data from the moderate-resolution imaging spectroradiometer (MODIS) to estimate grassland NPP, and Sun *et al*.\(^4^1,4^4\) used observation data from 2009 to 2010 and data from the 1980 Chinese grassland resource inventory, respectively. (3) Different estimation methods were used. For example, Sun *et al*.\(^3^8\) estimated the NPP of grasslands based on the relationship between NPP and the normalized difference vegetation index (NDVI); Liu\(^4^5\) estimated NPP and carbon storage with the improved Comprehensive Sequence Classification System (CASA) model; Sun *et al*.\(^4^4\) estimated NPP and NEP based on the BIOME-BGC model and Sun *et al*.\(^4^2\) used the Global Production Efficiency Model to simulate NPP. (4) Different study periods were used. Liu\(^4^5\), Sun *et al*.\(^4^1,4^4\) performed their studies from 2001 to 2010; Sun *et al*.\(^4^2\) analyzed the temporal and spatial dynamics from 1981 to 2000; Sun *et al*.\(^3^8\) worked in 2011; and Sun *et al*.\(^3^8\) performed research from 2000 to 2011.
In this study, the area of the southern grasslands was approximately $0.29 \times 10^6$ km$^2$, with an annual mean NEP of $0.45$ Tg C y$^{-1}$, an annual mean NPP of $93.63$ Tg C y$^{-1}$ and an annual mean RH of $93.20$ Tg C y$^{-1}$. The annual mean NEP, NPP and RH of the grasslands of China were $8.44$–$54.40$ Tg C$^{-1}$, $490.40$–$1392.00$ Tg C$^{-1}$ and $320.00$–$3068.40$ Tg C$^{-1}$, respectively, based on the results of previous studies (Table 3). Therefore, our results showed that southern grasslands accounted for $0.83$–$5.33\%$ of the NEP, $6.73$–$19.09\%$ of the NPP and $3.04$–$29.13\%$ of the RH of the grasslands of China.

The seasonal variation in NEP indicated that the dry season was a key period for annual net carbon emissions. In the wet season (June to August), southern grasslands acted as a weak carbon sink and were close to carbon neutral because the carbon fixed by the vegetation was equal to the amount released from the soil under warm and moist conditions. In contrast, the maximum monthly NEP was observed in May and October. Our study showed that the seasonal and annual variations in NEP were mainly driven by NPP.

Our analyses suggested that temperature (air temperature and soil temperature) was a key factor influencing the NEP of southern grasslands at the seasonal scale, accounting for 45% of the total variance in NEP. Future warming will tend to obviously positively correlate with the NEP of southern grasslands. Meanwhile, the results from our study suggested that water conditions (precipitation and soil moisture) also had strongly positive effects on the NEP of southern grasslands at the seasonal scale. Overall, all selected climatic variables could explain approximately 94.7% ($P < 0.001$) of the seasonal variation in NEP.

| Study area                     | Time          | g C m$^{-2}$ y$^{-1}$ | references |
|-------------------------------|---------------|-----------------------|------------|
| NEP                           |               |                       |            |
| Southern grasslands           | 1961–2013     | 1.53                  | This study |
|                               | 2001–2010     | 3.25–81.96            | 44         |
| Temperate grasslands in northern China | 2000–2010 | 158.00                | 46         |
| Temperate grasslands in China  | 1961–2007     | 11.25                 | 24         |
| Inner Mongolia grasslands     | 2001–2012     | 88.21                 | 47         |
| Tibetan plateau grasslands    | 1961–2010     | 10.03                 | 20         |
|                               | 1990s         | 28.00                 | 48         |
|                               | 2002–2004     | 78.50–192.50          | 49         |
|                               | 1981–2012     | 4.00                  | 51         |
|                               | 2000–2001     | 55.47                 | 52         |
| NPP                           |               |                       |            |
| Southern grasslands           | 1961–2013     | 318.15                | This study |
|                               | 2000–2011     | 471.62                | 39         |
|                               | 2010          | 389.14                | 40         |
|                               | 2001–2010     | 320.00                | 41         |
|                               | 1981–2000     | 1081.78               | 42         |
|                               | 2001–2010     | 656.30                | 43         |
|                               | 2001–2010     | 191.96–357.17         | 44         |
|                               | 1982–2012     | 356.79                | 45         |
| Inner Mongolia grasslands     | 2001–2012     | 278.83                | 47         |
|                               | 2001–2010     | 281.30                | 53         |
|                               | 1982–2002     | 290.23                | 54         |
|                               | 2002          | 259.90                | 55         |
|                               | 2002–2006     | 262.05                | 56         |
| Tibetan plateau grasslands    | 1961–2010     | 193.70                | 20         |
|                               | 1982–2009     | 120.80                | 19         |
|                               | 1990s         | 334.45                | 48         |
|                               | 1981–2002     | 199.00                | 51         |
|                               | 2001          | 161.12                | 57         |
|                               | 1982–1999     | 122.00                | 58         |
|                               | 2000–2001     | 92.50                 | 52         |
|                               | 1980–1990     | 233.00                | 59         |
| RH                            |               |                       |            |
| Southern grasslands           | 1961–2013     | 317.16                | This study |
|                               | 1982–2012     | 314.46                | 45         |
|                               | —             | 719.14                | 18         |
| Qinghai-Tibetan plateau grasslands | 1990s   | 306.32                | 48         |
|                               | 2000–2001     | 79.61                 | 52         |
| Temperate grasslands          | 1998–2000     | 390.00–866.00         | 60         |
|                               | —             | 132.00–830.00         | 61         |
| Tropical grasslands           |               | 470.00–900.00         | 61         |

Table 2. Carbon budget of different study regions from different studies.
At the annual scale, the results indicated a positive relationship between the annual NEP and the annual soil moisture, but we found no remarkable relationship between annual NEP and any of other climatic variables. In contrast, Sun et al. found a negative correlation between annual NEP and annual mean temperature, but correlation analysis detected no significant relationship between precipitation and NEP in southern grasslands.

**Methods**

**Study Region.** The study region, which accounts for 24.60% of the total terrestrial area of China, covers approximately 2.36 × 10⁶ km² and is located in southern China. Administratively, southern China includes 17 provinces and municipalities, e.g., Yunnan (excluding the Qinghai-Tibet Plateau), Sichuan (excluding the western portion of the Qinghai-Tibet Plateau), Guangxi, Hunan, and Hubei (Fig. 5). The southern grasslands cover an area of approximately 0.29 × 10⁶ km², which accounts for 12.50% of southern China and 7.50% of the grasslands of China. The southern grasslands are mainly characterized by tropical tussock and tropical shrub-tussock vegetation based on the second grassland investigation in China, and the altitude varies by two or three staircases over complicated terrain. The eastern region is mainly composed of plains and hills, while the western region is mainly composed of basins and plateaus. Furthermore, the study area is mainly characterized by temperate monsoon, subtropical monsoon, and tropical monsoon climates. The summer is hot and humid and the winter is warm in the tropical monsoon climate region and cold in the subtropical monsoon climate region, although the air is relatively warm and moist. The frost-free period is more than 300 d with abundant precipitation; the precipitation ranges from 800 mm to 1600 mm in most areas that are suitable for growing forage.

**Data Source.** The Terrestrial Ecosystem Model (TEM 5.0) requires input of monthly climate data sets (precipitation, temperature, cloud cover, and solar radiation) and longitude and latitude location information as well as soil texture. The study region, which accounts for 24.60% of the total terrestrial area of China, covers approximately 2.36 × 10⁶ km² and is located in southern China. Administratively, southern China includes 17 provinces and municipalities, e.g., Yunnan (excluding the Qinghai-Tibet Plateau), Sichuan (excluding the western portion of the Qinghai-Tibet Plateau), Guangxi, Hunan, and Hubei (Fig. 5). The southern grasslands cover an area of approximately 0.29 × 10⁶ km², which accounts for 12.50% of southern China and 7.50% of the grasslands of China. The southern grasslands are mainly characterized by tropical tussock and tropical shrub-tussock vegetation based on the second grassland investigation in China, and the altitude varies by two or three staircases over complicated terrain. The eastern region is mainly composed of plains and hills, while the western region is mainly composed of basins and plateaus. Furthermore, the study area is mainly characterized by temperate monsoon, subtropical monsoon, and tropical monsoon climates. The summer is hot and humid and the winter is warm in the tropical monsoon climate region and cold in the subtropical monsoon climate region, although the air is relatively warm and moist. The frost-free period is more than 300 d with abundant precipitation; the precipitation ranges from 800 mm to 1600 mm in most areas that are suitable for growing forage.

**NEP**

| Time     | Total (g C m⁻² y⁻¹) | Proportion (%) | references |
|----------|---------------------|----------------|-------------|
| 2005     | 271.00              | 8.64           | 63          |
| 1995     | 236.04              | 9.92           | 64          |
| 1981–1998| 348.00              | 6.73           | 65          |
| 1995     | 240.79              | 9.72           | 66          |
| 2000     | 178.23              | 13.13          | 66          |
| 1989–1993| 298.65              | 7.84           | 68          |
| 1979–2008| 279.4               | 8.38           | 69          |
| 2001     | 122.60              | 19.09          | 70          |
| 1989–2008| 13.60               | 0.83           | 69          |
| 1981–2000| 2.11                | 5.33           | 70          |

**Table 3.** Southern grasslands contribute to carbon budget in China’s grasslands.
At the monthly scale, the TEM defined the difference between net primary production (NPP) and soil heterotrophic respiration (RH) as net ecosystem production (NEP), and the difference between gross primary production (GPP) and plant autotrophic respiration (RA) was defined as NPP. These algorithms have been described in many previous studies.\textsuperscript{48,77,79,80}

Model Parameterization, Verification and Simulation. TEM parameterization requires monthly climate data sets and vegetation- and soil-specific parameters related to the nitrogen and carbon processes in vegetation and soil. For TEM calibration, the required parameters and their sources are shown in Table 5. The parameterization must follow three criteria within a certain tolerance (1%): (1) the simulated annual NPP and

| Type         | Data Name  | Code | Unit     | Time                      | Data Characteristics                  | Source                                      |
|--------------|------------|------|----------|---------------------------|----------------------------------------|---------------------------------------------|
| Location     | Longitude  | Lon  | degree   | —                         | constant                              | Longitude and latitude of meteorological stations |
|              | Latitude   | Lat  | degree   | —                         | constant                              | Longitude and latitude of meteorological stations |
| Altitude     | Above sea surface | ELEV | m       | —                         | constant                              | Altitude above sea surface of Meteorological Stations |
| Climate      | Precipitation | PRECIP | mm | 1961–2013 | monthly | Meteorological data sharing network |
|              | Temperature | TAIR  | °C       | 1961–2013                 | monthly | Meteorological data sharing network |
|              | Cloud Amount | CLDS  | %        | 1981–2010                 | monthly | Meteorological data sharing network |
|              | Radiation   | NIRR  | W m−2   | 1961–2013                 | monthly | Meteorological data sharing network |
|              | CO2 Concentration |  | ppm   | 1961–2013                 | annual | NOAA published |
| Soil         | Sand       | PCTSAND | %     | multi-year | constant | Second soil investigation |
|              | Clay       | PCTSILT | %      | multi-year | constant | Second soil investigation |
|              | Silt       | PCTCLAY | %     | multi-year | constant | Second soil investigation |
| Vegetation   | Vegetation Type | TEMVEG | —     | multi-year | constant | Grassland investigation |

Table 4. Environmental Variables for the TEM.
GPP are close to the measured values; (2) the simulated annual nitrogen uptake matches the measured value; and (3) the simulated annual NEP is close to zero.

After TEM calibration, we used the soil and vegetation carbon density field observation data from the 2011 to 2013 grassland survey to verify the simulated results by comparing the average simulated results for 2011–2013 with the observations. When multiple sample sites located in one grid cell, we calculated the mean value of these sample sites.

We then extrapolated the parameterized and verified TEM to southern China for 1961 to 2013. For zone modeling, we first ran the TEM at each grid cell to equilibrium using the long-term average monthly meteorological data sets of 1961–2013. Then, to explain the impact of inter-annual climate variability, we used the 1961–1975 climate data to spin up 45 years of the model of the undisturbed ecosystem. Finally, we used atmospheric CO2 concentrations and monthly climate data for 1961–2013 to run the model.

Lastly, after model simulation, we aggregated the simulated results from each grid to the whole study region by multiplying the grasslands area data and the simulated results grid by grid.

Data availability statement. The datasets used during the current study such as vegetation and soil carbon density are available from grasslands investigation during 2011 to 2013 (this project was funded by the Strategic Priority Research Program—Climate Change: Carbon Budget and Related Issues of the Chinese Academy of Sciences [grant number XDA05050408]), climate data sets are available from National Meteorological Information Center, China Meteorological Administration (CMA), the elevation data sets are available from the National Fundamental Geographic Information System of China, the soil texture data sets are available from Nanjing Institute of Soil, the Chinese Academy of Sciences (CAS), the vegetation data sets are available from the national grassland resource survey, and the atmospheric CO2 data is available from National Oceanic and Atmospheric Administration (NOAA), United States Department of Commerce (www.esrl.noaa.gov/gmd/ccgg/trends).

Table 5. Southern grassland ecosystem parameterization method.

| Variables   | Values | Sources and notes                      |
|-------------|--------|----------------------------------------|
| CV          | 490    | Average observational values from 2011 to 2013 |
| NV          | 12     | Estimated value                        |
| CS          | 1000   | Average observational values from 2011 to 2013 |
| NS          | 120    | Estimate based on the soil C:N and Cs values in the southern regions |
| Nav         | 1.032  | Estimate based on the average Nav:NS = 0.86% |
| GPP         | 370    | Estimate based on GPP:NPP at approximately 1.5–2 |
| NPP         | 185    | See Sun et al.                        |
| NPPSAT      | 277.5  | Estimate based on NPPSAT:NPP at approximately 1.2–1.5 |
| NUPTAKE     | 4.4    | See Melillo et al. in Table 2          |

Figure 6. Distributions for 10 select meteorological stations in southern grasslands (a) and investigation stations to verified the model (b) (This picture was made by ArcGIS 10.2, http://esri.uconn.edu/).
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Zhang L. and Zhou G.S. wrote the main manuscript text, Ji Y.H. and Bai Y.F. prepared data and drew figures. All authors reviewed the manuscript.

Additional Information
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