Divergent drivers of the spatial and temporal variations of cropland carbon transfer in Liaoning province, China

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Spatial and temporal variations are important points of focus in ecological research. Analysing their differences improves our understanding on the variations of ecological phenomena. Using data from the Liaoning Statistical Yearbook, we investigated the spatial and temporal variations of cropland carbon transfer (CCT), an important ecological phenomenon in quantifying the regional carbon budget, in particular, the influencing factors and difference. The results showed that, from 1992 to 2014, the average CCT in Liaoning province was 18.56 TgC yr\(^{-1}\) and decreased from northwest to southeast. CCT spatial variation was primarily affected by the ratio of planting area to regional area (RPR) via its effect on the magnitude of carbon transfer (MCT), which depended mainly on fertilizer usage per area (FUA). From 1992 to 2014, CCT exhibited a significantly increasing trend with a rate of 0.48 TgC yr\(^{-1}\). The inter-annual variation of CCT was dominated by carbon transfer per planting area (CTP) through its effect on MCT, which significantly correlated with FUA but showed no significant correlation with climatic factors. Therefore, the factors affecting the spatial variation of CCT differed from those that affected its inter-annual variation, indicating that the spatial and temporal variations of ecological phenomena were affected by divergent factors.

Spatial and temporal variations have been a vital focus of ecological research and have attracted much attention\(^1\,^2\). Many studies have assumed that the drivers of spatial and temporal variations in ecology are similar and have investigated the temporal variation of ecological phenomena using spatial sampling\(^3\,^4\). However, recent studies have showed that the spatial variation of annual gross primary productivity (GPP) is strongly affected by annual mean air temperature (MAT) and annual mean precipitation (MAP)\(^5\,^6\), while MAT and MAP contribute little to the inter-annual variation of annual GPP in most ecosystems\(^7\,^8\). This highlights the need to illustrate whether drivers of spatial variation differ from those of temporal variation.

Cropland carbon transfer (CCT) is an important component of cropland carbon budget\(^9\) and is composed of the quantity of organic matter harvested from cropland\(^10\,^11\) including grains and straws but excluding residues. Investigating the spatiotemporal variations of CCT helps to accurately assess the cropland carbon budget, which is vital in regional carbon budget assessments aiming to mitigate climate change\(^9\). This is because cropland plays a key role in maintaining the global carbon budget\(^12\,^13\). In addition, CCT serves as a vital process of global carbon cycle, which is a key topic of ecological research. Analysing the spatiotemporal variations of CCT can also reveal whether there are differences in the drivers of spatial and temporal variations of ecological phenomena.

According to its definition, CCT is calculated from yield (Y), harvest index (HI), carbon content (C), and water content (W), where Y can be obtained from statistical yearbook and the remaining values are empirical parameters. In addition, CCT can be deemed as the product of the magnitude of carbon transfer per area (MCT, gC m\(^{-2}\) yr\(^{-1}\)) and regional area (RA, m\(^2\)), where RA can be obtained from available data. MCT, an important item in quantifying the regional carbon budget\(^14\), is thus calculated as the ratio of CCT to RA. Additionally, MCT is regarded as the product of carbon transfer per planting area (CTP, gC m\(^{-2}\) yr\(^{-1}\)) and the ratio of planting area to regional area (RPR, %), where the planting area is obtained from statistical yearbook. Furthermore, CTP, the quantity of carbon contained in grains and straws but excluding residues, can also be deemed as gross primary

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productivity (GPP) minus autotrophic respiration (AR). Therefore, CCT can be separated into many components (Fig. 1). Analysing the roles of these components in the spatiotemporal variations of CCT can help understand the differences between its spatial and temporal variations.

Although many studies have intensively analysed the spatial and inter-annual variations of CCT using data from the China Statistical Yearbook15–17, they have paid little attention to the roles of CCT components in its spatial and temporal variations. Therefore, whether the drivers of CCT spatial variation differ from its temporal variation remains a puzzle, which inhibits the full understanding of its spatiotemporal variations and thus the difference between the spatial and temporal variations of ecological phenomena.

Given its high yield18, Liaoning province, located in the northeast of China, is one of the country’s most important producers of commodity grains thus guaranteeing national food security. Additionally, due to its particular climate, its carbon budget assessment contains substantial uncertainties19. Investigating the spatiotemporal variations of CCT in Liaoning province and the dominating components would provide data to support the carbon budget assessment, which would also help to illustrate whether the drivers of spatial variation differ from those of temporal variation.

Therefore, we analysed the spatiotemporal variations of CCT and their drivers in Liaoning province from 1992–2014, based on the Liaoning Statistical Yearbook. In addition, the factor decomposition model was employed to clarify the roles of CCT components in its spatiotemporal variations. The aims of our study were to clarify: (1) How CCT spatially and temporally varied in Liaoning province? (2) Which components dominated the spatial and temporal variations of CCT? (3) Were there differences in the drivers of spatial and temporal variations? Our results provide a data foundation to assess the regional carbon budget in Liaoning province and a reference for calculating CCT in other regions. They also provide evidence for understanding the difference between spatial and temporal variations.

Results
The spatial variations of CCT and its components. From 1992–2014, the CCT of Liaoning province was 18.56 TgC yr$^{-1}$ and spatially varied, exhibiting a decreasing trend from northwest to southeast (Fig. 2a). The northwest and west region, represented by Shenyang, Tieling, and Jinzhou, had the highest CCT, which exceeded 2 TgC yr$^{-1}$, and each accounted for over 10% of Liaoning CCT. The CCT of the southeast and east region, represented by Fushun, Liaoyang, Benxi, Dandong, and Yingkou, were lower than 1 TgC yr$^{-1}$, and each accounted for no more than 5% of the Liaoning CCT.

Factor decomposition model results suggest that the spatial variation of CCT was dominated by MCT, which accounted for 69.42% of CCT and RA accounted for the remained 30.58% of CCT spatial variation. MCT also varied spatially, with a decreasing trend from the centre to the border of Liaoning province (Fig. 2b). The central region, represented by Tieling, Shenyang, Jinzhou, and Panjin, had a higher MCT exceeding 200 gC m$^{-2}$ yr$^{-1}$. However, the border regions, such as Benxi, Dandong, Fushun, Dalian, Huludao, and Chaoyang, had a lower MCT, almost lower than 100 gC m$^{-2}$ yr$^{-1}$.

In contrast with the small contribution of CTP, RPR, whose spatial variation followed a convex parabola from west to east (Fig. 2d), contributed 84.84% of the spatial variation of MCT. The highest RPR was found in
the central areas of Liaoning province, such as Panjin, Shenyang, and Jinzhou, which exceeded 40%. The lowest RPR occurred in the eastern areas of Liaoning province, such as Fushun and Benxi, which were lower than 10%.

The inter-annual variations of CCT and its components. CCT showed a significant increasing trend among years (Fig. 3a). From 1992 to 2014, CCT increased at a rate of 0.48 TgC yr$^{-1}$, accounting for 2.59% of annual CCT.

The given regional area (RA) varied little among years, and MCT dominated the pattern of CCT, exhibiting an increasing trend (Fig. 3b) at a rate of 3.34 gC m$^{-2}$ yr$^{-1}$.

Factor decomposition model results indicate that 62.64% of inter-annual MCT variation was contributed by CTP, which showed a significant increasing trend at a rate of 7.77 gC m$^{-2}$ yr$^{-1}$ from 1992 to 2014 (Fig. 3c). However, the contribution of RPR to inter-annual MCT variation was only 37.36%, though it also increased significantly at a rate of 0.22% (Fig. 3d).

Effects of factors on the spatiotemporal variations of CCT and its components. Climatic factors did not correlate significantly with the spatial variations of CCT and its components (Table 1). The correlation coefficients between the spatial variations of CCT, including its components, and climatic factors, such as sunshine duration (SD), annual mean air temperature (MAT), and annual mean precipitation (MAP), were lower than 0.4, indicating nonsignificant correlations at the level of 0.05. However, societal factors represented by fertilizer usage per area (FUA) correlated significantly with the spatial variations of CCT and its components. FUA had a positive correlation coefficient with CCT and its components, all exceeding 0.6, indicating a significant correlation at the level of 0.05.

The effects of various factors on the inter-annual variations of CCT and its components were similar to their spatial variation (Table 1). With the changes of climatic factors, such as MAT, MAP, and SD, CCT and its components showed no significant variations, while the societal factors represented by FUA also increased CCT and its components among years.

Discussion
In this study, we found CCT of Liaoning province decreased from northwest to southeast in spatial but obviously increased overall from 1992 to 2014. However, the components of CCT played different roles in the spatial and temporal variations of CCT (Fig. 4). RPR dominated the spatial variation of CCT through MCT, while CTP played a vital role in the inter-annual variation of CCT through MCT. This indicates that the roles of CCT components in its spatial variation differed from those in its inter-annual variation. Our findings were consistent with
studies focusing on the spatiotemporal variations of gross primary productivity: the spatial variation of gross primary productivity was controlled by climate\textsuperscript{5,6,20} while its inter-annual variation was affected by the response of ecosystems to the varying climate\textsuperscript{7,8,21}. This suggests that though substituting “temporal” with “spatial” has been an important practice in ecological studies, using conclusions from spatial analysis to infer temporal variation may overestimate the magnitude of temporal variation\textsuperscript{4}. Therefore, we may need to separate temporal variation from spatial variation to investigate the spatiotemporal variations of ecological phenomena.

In addition, though climatic factors were not found to correlate significantly with the spatial variation of CCT, FUA did affect it, which may be ascribed to the following aspects. First, the spatial variation of CCT was

| CCT and its components | Factors | Spatial variation | Inter-annual variation |
|-----------------------|---------|------------------|-----------------------|
|                       |         | \( r \)          | \( p \)               |
| CCT                   | SD\textsuperscript{3} | 0.22             | 0.44 \( \neq 0.17 \) | 0.43 |
|                       | MAT\textsuperscript{2} | 0.02             | 0.95 \( \neq 0.23 \) | 0.29 |
|                       | MAP\textsuperscript{2} | 0.39             | 0.17 \( \neq 0.24 \) | 0.28 |
|                       | FUA\textsuperscript{2} | 0.65\textsuperscript{5} | 0.01 | 0.84 |
| MCT\textsuperscript{1} | SD      | 0.33             | 0.24 \( \neq 0.17 \) | 0.43 |
|                       | MAT     | 0.28             | 0.33 \( \neq 0.23 \) | 0.29 |
|                       | MAP     | 0.36             | 0.21 \( \neq 0.24 \) | 0.28 |
|                       | FUA     | 0.89             | 0.00 \( \neq 0.84 \) | 0.00 |
| CTP\textsuperscript{1} | SD      | 0.18             | 0.55 \( \neq 0.35 \) | 0.10 |
|                       | MAT     | 0.23             | 0.44 \( \neq 0.12 \) | 0.60 |
|                       | MAP     | 0.10             | 0.73 \( \neq 0.22 \) | 0.30 |
|                       | FUA     | 0.65             | 0.01 \( \neq 0.66 \) | 0.00 |
| RPR\textsuperscript{1} | SD      | 0.38             | 0.18 \( \neq 0.28 \) | 0.19 |
|                       | MAT     | 0.31             | 0.28 \( \neq 0.26 \) | 0.22 |
|                       | MAP     | 0.42             | 0.13 \( \neq 0.09 \) | 0.67 |
|                       | FUA     | 0.90             | 0.00 \( \neq 0.76 \) | 0.00 |

Table 1. The correlations between cropland carbon transfer (CCT), including its components, and various factors. Note: \textsuperscript{1}MCT, CTP, and RPR were the abbreviations of the magnitude of carbon transfer per area, carbon transfer per planting area, and the ratio of planting area to regional area, respectively. \textsuperscript{2}SD, MAT, MAP, and FUA were the abbreviations of sunshine duration, annual mean air temperature, annual mean precipitation, and fertilizer usage per area, respectively. \textsuperscript{3}Significant correlations were indicated by bold numbers.

Figure 3. The inter-annual variations of cropland carbon transfer (CCT, Tgc yr\textsuperscript{−1}) (a) and its components (b–d) in Liaoning province from 1992 to 2014. (b–d) were the inter-annual variations of the magnitude of carbon transfer per area (MCT, gC m\textsuperscript{2} yr\textsuperscript{−1}), carbon transfer per planting area (CTP, gC m\textsuperscript{2} yr\textsuperscript{−1}) and the ratio of planting area to regional area (RPR, %), respectively.
dominated by that of RPR through its effect on MCT (Fig. 4). Second, climatic factors only significantly affected the spatial variation of GPP and AR and thus CTP, while CTP impacted a small portion of MCT and thus the spatial variation of CCT (Fig. 4). Third, FUA, the quantity of fertilizer used per area, can be deemed as the product of RPR and fertilizer usage per planting area, which made FUA correlate highly with RPR (Table 1) and thus CCT spatial variation through MCT (Fig. 4).

Though the effects of climatic factors and FUA on the inter-annual variation of CCT were similar to those on CCT spatial variation (Table 1), their effects may be ascribed to different aspects. First, the inter-annual variation of CCT was primarily affected by that of CTP through its effect on MCT (Fig. 4). Second, climatic factors may not be the direct factors driving the inter-annual variation of GPP7,8,21, which was the basis of CTP (Fig. 1). Third, the increasing FUA was accompanied by the increase in fertilizer usage per planting area, which made CCT increase from 1992 to 2014 through CTP, as fertilization may improve the crop yield.

**Conclusions**

Based on data from the Liaoning Statistical Yearbook, we investigated the spatiotemporal variations of CCT and the factors that affected them. The results showed that the CCT of Liaoning province was 18.56 TgC yr$^{-1}$ during 1992 to 2014, which showed a decreasing trend from northwest to southeast and increased at a rate of 0.48 TgC yr$^{-1}$ from 1992 to 2014. The spatial variation of CCT was affected by FUA through its effect on RPR and thus MCT, while FUA affected the inter-annual variation of CCT through its effect on CTP and thus MCT. Therefore, the factors affecting the spatial variation of CCT differed from those that affected its temporal variation, indicating divergent drivers in the spatial and temporal variations of ecological phenomena.

**Methods**

**CCT calculation.** In this study, we calculated CCT as the product of crop yield ($Y$, g yr$^{-1}$), harvest index ($HI$, g g$^{-1}$), water content ($W$, g H$_2$O g$^{-1}$), and carbon content ($C$, g C g$^{-1}$), since the statistical yearbook only reported the yield. Then, the CCT of Liaoning province was summed as CCT from all prefectural-level cities and all crops (Eq. (1)).

$$CCT = \sum_{i=1}^{14} \sum_{j=1}^{n}(Y_j \times (1 - W_j/\text{HI}_j) \times C_j)$$

where $i$ was the number of prefectural-level city and $j$ was that of crops (Table 2), while $Y$ of each prefectural-level city was obtained from the Liaoning Statistical Yearbook22–44.

HI, defined as the ratio of harvested grain to total dry matter45, differed among crops, which were listed in Table 2. The HI of paddy and maize were set as the average reported HI in Liaoning province, while for other crops, the average HI of that crop in China was selected, since little data was reported for Liaoning province.

$W$ also differed among crops and were listed in Table 2 with values from previous studies19,46. Though $C$ somewhat differed among crops, the difference in $C$ was small and little reported. We had no choice but to set $C$ as 0.45 following the previous study47.

**Calculating CCT components.** Given that CCT was the product of RA and MCT, MCT was calculated as:
where RA can be obtained from the raster calculator of ArcGIS. In addition, MCT was regarded as the product of CTP and RPR, such that CTP can be calculated as:

\[ \text{CTP} = \frac{\text{MCT}}{\text{RPR}} \]  

where RPR was calculated from the ratio of planting area, which can be found in the Liaoning Statistical Yearbook, to RA.

**Calculating the roles of CCT components in CCT spatiotemporal variations.** In this study, we employed the factor decomposition model to distinguish the roles of CCT components in the spatiotemporal variations of CCT, which helped to illustrate the difference in the drivers of spatial and temporal variations. The factor decomposition model separated specific variables, regarded as the multiplication of some parts, into its components using a logarithm way. Given that CCT was the product of RA and MCT, after taking the natural logarithm of the two sides, the relationship between CCT and its components was obtained as:

\[ \ln\text{CCT} = \ln\text{RA} + \ln\text{MCT} \]  

Therefore, the CCT of the benchmark region (CCT\(_0\)) or any region (CCT\(_i\)) can be expressed as:

| Crops          | Harvest Index (HI) | Water content (W) | References |
|----------------|-------------------|------------------|------------|
| Paddy          | 0.5               | 0.13             | 48–50      |
| Maize          | 0.51              | 0.13             | 51–54      |
| Wheat          | 0.46              | 0.13             | 16         |
| Other cereal\(^1\) | 0.31             | 0.13             | 16         |
| Millet         | 0.38              | 0.13             | 16         |
| Sorghum\(^1\)  | 0.31              | 0.13             | 16         |
| Soybean        | 0.42              | 0.13             | 16         |
| Yam\(^2\)      | 0.64              | 0.133            | 16         |
| Cotton         | 0.16              | 0.083            | 16         |
| Peanut         | 0.50              | 0.09             | 16         |
| Sesame         | 0.34              | 0.09             | 16         |
| Sunflower      | 0.26              | 0.09             | 16         |
| Other oil plants\(^3\) | 0.36          | 0.09             | 16         |
| Sugar beet     | 0.71              | 0.133            | 16         |
| Tobacco        | 0.61              | 0.082            | 16         |
| Vegetable      | 0.49              | 0.82             | 16         |

**Table 2.** The values of harvest index (HI) and water content (W) of different crops. Note: \(^1\)HIs of Other cereal and Sorghum were calculated as the average HI of oat, triticale, and Rye in China\(^{16}\). \(^2\)HI of Yam was calculated as the average HI of potato, sweet potato, and cassava in China\(^{16}\). \(^3\)HI of other oil plants was calculated as the average HI of peanut, rape, sesame, and sunflower in China (Table 2).

| Prefectural-level city | SD (hours) | MAT (°C) | MAP (mm) |
|------------------------|------------|----------|----------|
| Shenyang               | 2400.0     | 8.43     | 684.3    |
| Dalian                 | 2625.6     | 11.41    | 619.5    |
| Anshan                 | 2560.4     | 10.45    | 714.3    |
| Fushun                 | 2506.7     | 7.10     | 775.7    |
| Benxi                  | 2548.5     | 8.27     | 798.8    |
| Dandong                | 2387.7     | 9.33     | 1000.0   |
| Jinzhou                | 2648.4     | 10.23    | 557.1    |
| Yingkou                | 2648.2     | 9.96     | 627.3    |
| Fuxin                  | 2638.8     | 8.23     | 475.2    |
| Liao yang              | 2306.9     | 9.34     | 687.5    |
| Panjin                 | 2602.8     | 9.35     | 596.2    |
| Tieling                | 2623.0     | 8.37     | 633.9    |
| Chaoyang               | 2606.8     | 9.70     | 478.1    |
| Huludao                | 2573.5     | 10.03    | 564.9    |

**Table 3.** The mean climatic data of Liaoning province from 1992 to 2014. Note: SD, MAT, and MAP were the abbreviations of sunshine duration, annual mean air temperature, and annual mean precipitation, respectively.
\[ \ln C_{CT0} = \ln R_A + \ln M_{CT0} \]  
\[ \ln C_{CTi} = \ln R_A + \ln M_{CTi} \]

After integrating Eqs (5) and (6), we can get the expression of CCT changes (\( \Delta \ln C_{CTi} \)) as:

\[ \Delta \ln C_{CTi} = \ln C_{CTi} - \ln C_{CT0} = \ln R_A_i - \ln R_A_0 + \ln M_{CTi} - \ln M_{CT0} \]

The amount of CCT variation from RA (\( \Delta C_{CT_RA} \)) and MCT (\( \Delta C_{CT_MCT} \)) can thus be expressed as:

\[ \Delta C_{CT_RA} = \sum_{i=1}^{n} (C_{CTi} - C_{CT0}) \times (\ln R_A_i - \ln R_A_0)/\ln C_{CTi} - \ln C_{CT0} \]

\[ \Delta C_{CT_MCT} = \sum_{i=1}^{n} (C_{CTi} - C_{CT0}) \times (\ln M_{CTi} - \ln M_{CT0})/\ln C_{CTi} - \ln C_{CT0} \]

Therefore, the relative contribution of RA and MCT to CCT spatial variation can be expressed as \( \Delta C_{CT_RA}/\Delta C_{CT} \) and \( \Delta C_{CT_MCT}/\Delta C_{CT} \) respectively. For simplicity, we selected the largest CCT, for all prefectural-level cities as the benchmark value (CCT0).

The roles of CTP and RPR in the spatial and inter-annual variations of MCT were also investigated in the same way.

**Climatic and societal data.** In this study, we selected the climatic data of each prefectural-level city (Table 3) from the Liaoning Statistical Yearbook22–44, including sunshine duration (SD), annual mean air temperature (MAT), and annual mean precipitation (MAP). In addition, we calculated the climatic data of Liaoning province based on climatic data for each prefectural-level city to illustrate the inter-annual variation of CCT.

Furthermore, given that fertilization promoted crop yield and thus CCT, we selected fertilizer usage per area (FUA) as a societal factor affecting the spatiotemporal variations of CCT. FUA was calculated using the regional area and the quantity of fertilizer used in each prefectural-level city, as reported in the Liaoning Statistical Yearbook.

**Statistical analysis.** In this study, we created the spatial distributions of CCT, MCT, RPR, and CTP with ArcGIS 10.0. The trends of CCT, MCT, RPR and CTP were determined by Mann-Kendall trend analysis using MATLAB 2014 (MathWorks Inc., Natick, MA, USA). The correlation between CCT, including its components, and various factors, including climatic and societal variables, were investigated with correlation analysis using MATLAB 2014 at the significance level of 0.05.

**Data availability statement.** The datasets analysed during the current study are available from the corresponding author on reasonable request.

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Author Contributions
Xian-Jin Zhu and Hong Yin designed the methodology. Han-Qi Zhang collected the data. Xian-Jin Zhu drafted the manuscript, which was revised by Tian-Hong Zhao, Jian-Dong Li, and Hong Yin. All authors have read and approved the final manuscript.

Additional Information
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