Spatiotemporal Variation of Net Carbon Sink Function in Aksu Oasis Cropland over the Past 17 Years: Postprint

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Abstract

Based on remote sensing, meteorological data, and related statistical data on agricultural inputs in the Aksu region from 2001 to 2017, the net carbon sink capacity of Aksu oasis farmland was estimated. The results indicate that: (1) Over the past 17 years, the Net Ecosystem Productivity (NEP) of Aksu oasis farmland has exhibited a year-by-year increasing trend, with a relatively uniform overall spatial distribution. Higher values were primarily concentrated in the southern part of Wensu County, the central part of Aksu City, and the junction area of Xinhe, Kuqa, and Shaya counties. (2) Carbon emissions from agricultural production inputs increased from 39.94$\times10^{4}$ t in 2001 to 106.73$\times10^{4}$ t in 2017, with an average annual growth rate of 25.14%, exhibiting a spatial distribution pattern of high in the southeast and low in the northwest. (3) Over the past 17 years, the net carbon sink of Aksu oasis farmland demonstrated a fluctuating upward trend, characterized by a gradual increase from northwest to southeast spatially. Overall, Aksu oasis farmland possesses a strong net carbon sink capacity, yet significant regional differences exist in the net carbon sink among counties and cities. The net carbon sink capacity of oasis farmland can be enhanced through measures such as optimizing field management and reducing carbon emissions from agricultural production.

Full Text

Spatial and Temporal Variation of Net Carbon Sink Function in Aksu Oasis Farmland over the Past 17 Years

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Abstract: Based on remote sensing, meteorological data, and agricultural input statistics from 2001 to 2017, this study estimated the net carbon sink of Aksu oasis farmland. The results show that: (1) The net ecosystem productivity (NEP) of Aksu oasis farmland exhibited an increasing trend during the study period, with an average annual growth rate of 7.43%. Spatially, the distribution was relatively uniform, with higher values concentrated in the southern part of Wensu County, central Aksu City, and the intersection of Xinhe, Kuqa, and Shaya counties. (2) Carbon emissions from agricultural production inputs increased from 39.94$\times10^{4}$ t in 2001 to 106.73$\times10^{4}$ t in 2017, with an average annual growth rate of 25.14%. The spatial distribution pattern showed high values in the southeast and low values in the northwest. (3) The net carbon sink of Aksu oasis farmland showed a fluctuating upward trend, increasing from 61.45$\times10^{4}$ t in 2001 to 147.39$\times10^{4}$ t in 2017, with an average annual growth rate of 78.16%. Spatially, it gradually increased from northwest to southeast. Overall, Aksu oasis farmland has a strong net carbon sink capacity, but significant regional differences exist among counties and cities. The net carbon sink capacity can be enhanced through optimized field management and reduced carbon emissions from agricultural production.

Keywords: Net Ecosystem Productivity (NEP); oasis; farmland; carbon emission; net carbon sink; Aksu

1.1 Study Area Overview

The Aksu region is located between 39°30 -42°41 N and 78°03 -84°07 E, situated in the central Tianshan Mountains and the northeastern Tarim Basin, belonging to a warm temperate arid climate zone with topography that slopes from high in the north to low in the south. The main soil types in oasis farmland include fluvo-aquic soil, irrigation-silt soil, brown desert soil, meadow soil, and brown calcic soil. The total oasis farmland area is 1.44$\times10^{4}$ km^2, accounting for 11.2% of the total area of Aksu region. The primary economic crop is cotton, with a sown area accounting for 54.5% of total farmland sown area, followed by corn and wheat.

1.2 Data Sources and Processing

The photosynthetically active radiation data were obtained from MOD15A3H products (https://lpdaacsvc.cr.usgs.gov/appeears/task/area) with a spatial resolution of 500 m. Normalized Difference Vegetation Index (NDVI) data were derived from MOD13A1 products with a spatial resolution of 500 m and temporal resolution of 16 days. Temperature and precipitation data were obtained from GLDAS (https://search.earthdata.nasa.gov/search) with a spatial resolution of 0.25° and monthly temporal resolution. Land use data with 500 m spatial resolution were sourced from https://www.usgs.gov. All data with different resolutions were resampled using ArcGIS 10.2 to ensure they were on the same baseline. The boundary between plains and mountains was delineated using a relief amplitude of 200 m, with areas having relief amplitude greater than 200 m classified as mountains. Areas with relief amplitude less than 200 m were classified as oasis or desert based on land use type. The spatial distribution of mountains, desert, and oasis in Aksu region is shown in [Figure 1: see original paper]. Agricultural management data for each county and city, including sown area, crop yield, and irrigation area, were obtained from the *Xinjiang Statistical Yearbook* and *Aksu Statistical Yearbook* for 2001–2017.

1.3 Research Methods

1.3.1 NEP Calculation Method

NEP is an important indicator for estimating vegetation carbon sources and sinks, often used as a measure of carbon sink magnitude. The calculation formula is:

$$NEP = NPP - R_h$$

where NPP represents net primary productivity and R_h represents soil microbial respiration.

NPP estimation adopts the modified Carnegie-Ames-Stanford Approach (CASA) model, expressed through absorbed photosynthetically active radiation (APAR) and actual light use efficiency (ε):

$$NPP(z,t) = APAR(z,t) \times \varepsilon(z,t)$$

where z represents a pixel, t represents month, $APAR(z,t)$ is the photosynthetically active radiation absorbed by pixel z in month t, and $\varepsilon(z,t)$ is the actual light use efficiency of pixel z in month t.

For R_h estimation, temperature and precipitation are the main influencing factors. This study employs an empirical model that estimates R_h through a regression relationship between temperature, precipitation, and carbon emissions:

$$R_h = 0.22 \times T + 1 \times R + 30 \times 46.5\%$$

where T is monthly average temperature (°C) and R is monthly total precipitation (mm).

The interannual variation trend of NEP was calculated using unary linear regression analysis:

$$Slope = \frac{n \times \sum_{i=1}^{n} i \times NEP_i - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} NEP_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where *Slope* is the trend line slope, n represents the study time span, and i represents the year variable. A positive *Slope* indicates an increasing trend, while a negative value indicates a decreasing trend.

1.3.2 Carbon Emission Estimation Method

The main sources of carbon emissions from farmland ecosystems include chemical fertilizers, pesticides, agricultural film, agricultural machinery, irrigation, diesel fuel, and tillage. The estimation formula is:

$$E_t = E_f + E_p + E_m + E_e + E_i + E_s + E_g$$

where E_t is the total carbon emission from farmland ecosystems; E_f, E_p, E_m, E_e, E_i, E_s, and E_g represent carbon emissions from chemical fertilizers, pesticides, agricultural film, agricultural machinery, irrigation, diesel fuel, and tillage, respectively.

The specific calculation formula is:

$$E_t = \sum G_i \times A_i + G_p \times B + G_m \times C + A_e \times D + W_e \times F + L_i \times G + G_s \times J + S_i \times H$$

where G_i, G_p, G_m, A_e, W_e, L_i, G_s, and S_i represent the specific usage amounts of each agricultural production input; A, B, C, D, F, G, J, and H represent various carbon emission coefficients for agricultural production inputs ().

1.3.3 Net Carbon Sink Estimation Method

By calculating the difference between NEP and carbon emissions from agricultural production inputs over the past 17 years, a mathematical model for estimating the net carbon sink of oasis farmland was established:

$$N_c = NEP - E_t$$

$$N_u = \frac{N_c}{S_a}$$

where N_c is the net carbon sink of oasis farmland; N_u is the net carbon sink per unit sown area; S_a is the crop sown area.

2.1 Spatiotemporal Variation of NEP

From 2001 to 2017, the interannual variations of NEP in mountains, desert, and oasis farmland in Aksu all showed upward trends ([Figure 2: see original paper]). The average annual growth rates were 3.04% for mountains, 2.09% for desert, and 7.43% for oasis farmland, indicating that the carbon sequestration capacity of vegetation in the study area is continuously strengthening. The monthly average NEP of oasis farmland showed a fluctuating trend of first increasing and then decreasing, which is generally consistent with the growth patterns of crops in oasis farmland ([Figure 2: see original paper]). From March to April, temperatures began to rise and snow melted, resulting in crop carbon sequestration exceeding soil respiration carbon emissions (NEP > 0). From May to June, increasing temperatures and tillage operations enhanced soil respiration carbon emissions, but crop carbon sequestration capacity remained greater than soil respiration emissions (NEP > 0). From July to August, with substantially rising temperatures and continuous irrigation reaching optimal conditions for crop growth, NEP reached its peak. From September to October, decreasing temperatures slowed crop growth and most crops were harvested, causing soil respiration carbon emissions to exceed crop carbon sequestration (NEP < 0).

Spatially, the average annual NEP distribution of oasis farmland was relatively uniform over the 17-year period, with peak values concentrated in southern Wensu County, central Aksu City, and the intersection of Xinhe, Kuqa, and Shaya counties ([Figure 3: see original paper]). The multi-year average NEP of oasis farmland was 143.47 $g \cdot m^{-2} \cdot a^{-1}$. Areas with NEP > 0 (carbon sink status) covered 9,360.94 km^2, accounting for 92.85% of total oasis farmland area. Areas with NEP values of 0–100 $g \cdot m^{-2} \cdot a^{-1}$, 100–200 $g \cdot m^{-2} \cdot a^{-1}$, and >200 $g \cdot m^{-2} \cdot a^{-1}$ covered 1,807.04 km^2, 9,136.69 km^2, and 1,417.21 km^2, respectively, accounting for 17.76%, 89.74%, and 13.91% of total oasis farmland area. Overall, the 100–200 $g \cdot m^{-2} \cdot a^{-1}$ NEP range occupied the largest proportion of oasis farmland, distributed mainly within the oasis areas of each county and city.

The interannual variation trend of NEP from 2001 to 2017 was calculated using unary linear regression and T-test significance testing. The area showing a significant increasing trend was 1.44$×10^{4}$ km^2, accounting for 97.7% of total oasis farmland area and distributed in oasis regions of all counties and cities. The area showing a significant decreasing trend was 339 km^2, accounting for 2.3% of total area, mainly distributed in the oasis areas of Wensu, Awati, Aksu City, and Kuqa County. The decreasing trend may be attributed to urban expansion due to population growth, resulting in reduced oasis farmland area. Overall, the carbon sequestration capacity of crops in oasis farmland has been continuously improving over the past 17 years, with only a very small portion showing decline.

2.2 Analysis of Carbon Emission Changes in Oasis Farmland

Carbon emissions from oasis farmland showed distinct spatiotemporal variations. Temporally, total carbon emissions from oasis farmland increased annually from 2001 to 2017 ([Figure 5: see original paper]), rising from 39.94×10^{4} t to 106.73×10^{4} t with an average annual growth rate of 25.14%. Carbon emissions per unit area increased from 0.31 $t \cdot hm^{-2}$ to 1.21 $t \cdot hm^{-2}$ with an average annual growth rate of 15.86%. The primary reason for this growth was increased input of agricultural materials and expanded use of agricultural machinery.

Spatially, carbon emissions from oasis farmland in each county and city showed a pattern of low values in the northwest and high values in the southeast ([Figure 5: see original paper]). Kuqa County had the highest carbon emissions (17.76×10^{4} t), while Keping County had the lowest (1.55×10^{4} t), representing an 11.5-fold difference. Kuqa County' s crop sown area was 12.6 times that of Keping County. Aksu City had the highest carbon emissions per unit sown area (1.66 $t \cdot hm^{-2}$), while Kuqa County had the lowest (0.97 $t \cdot hm^{-2}$). Among the main carbon emission pathways in oasis farmland, chemical fertilizers, agricultural machinery, and agricultural film accounted for the largest proportions at 28%, 26%, and 24%, respectively, showing annual increasing trends (). Notably, carbon emissions from agricultural film decreased after 2015, with its proportion declining from 24% to 15% and cotton planting area proportion decreasing from 73.13% to 54.50%. This may be because lower cotton prices or higher agricultural film prices led local farmers to switch from cotton to other crops like rice, reducing agricultural film usage.

2.3 Analysis of Net Carbon Sink Changes in Oasis Farmland

From 2001 to 2017, the net carbon sink of oasis farmland showed an overall upward trend despite fluctuations ([Figure 6: see original paper]), increasing from 61.45×10^{4} t to 147.39×10^{4} t with an average annual growth rate of 78.16%. Net carbon sink per unit area increased from -0.07 $t \cdot hm^{-2}$ to 0.69 $t \cdot hm^{-2}$ with an average annual growth rate of 49.24%. These results indicate that with improved production technology and stable crop yield growth, oasis farmland in Aksu possesses a high net carbon sink capacity.

Spatial variation was significant, showing a general pattern of increase from northwest to southeast ([Figure 7: see original paper]). The multi-year average spatial distribution of net carbon sink revealed that high-value areas (Nc $> 1.0\times10^{4}$ t) were concentrated in the southern part of Wensu County, the western part of Aksu City, the entire Alar City, and the eastern part of Xinhe County. Low-value areas (Nc $< 0.1\times10^{4}$ t) were mainly in the southwestern part of Wensu County and the periphery of Aksu City. Keping County had the smallest Nc (-0.03×10^{4} t), while Shaya County had the largest (4.08×10^{4} t). These differences likely reflect varying development levels and production conditions among counties and cities. Overall, significant regional differences exist in the net carbon sink of oasis farmland among counties and cities. Areas like Awati County and Keping County should improve their farmland ecosystem net carbon sink capacity through optimized field management measures.

3 Discussion

By constructing a mathematical model for the net carbon sink of farmland ecosystems, this study found that the net carbon sink of oasis farmland in Aksu region showed a fluctuating upward trend from 2001 to 2017, indicating that oasis farmland has strong carbon sequestration capacity. This study integrated previous research methods to comprehensively consider carbon emissions from farmland tillage, soil respiration, and diesel fuel consumption by agricultural machinery. Some carbon emission coefficients were derived from foreign studies that are frequently cited domestically but may not be entirely suitable for Aksu region. Therefore, field observations are needed to estimate local carbon emission coefficients and provide more accurate data for regional carbon emission accounting.

For R_h estimation, this study adopted the empirical model method from Pei Zhiyong et al. This method has been applied to carbon sink estimation in the arid regions of Central Asia and Northwest China, and our study area falls within these regions, making the approach appropriate. The magnitude of net carbon sink is primarily regulated by natural and anthropogenic factors. Natural factors (temperature and precipitation) indirectly regulate NEP by influencing NPP and R_h to achieve net carbon sink regulation. Previous studies indicate that NPP is more sensitive to precipitation than temperature, while R_h is more sensitive to temperature than precipitation. In this study, the annual contribution rates of temperature and precipitation to NEP were 28.79% and 23.23%, respectively.

Anthropogenic factors refer to carbon emissions from human production activities in farmland ecosystems, such as emissions from producing fertilizers, pesticides, and agricultural film, as well as fossil fuel and electricity consumption by agricultural machinery. Among these pathways, chemical fertilizers account for the largest proportion of carbon emissions. Therefore, fertilizer application rates should be determined based on crop requirements, or the proportion of organic fertilizer should be increased to reduce pollution from livestock manure and achieve resource recycling. In Aksu City and Awati County, where carbon emissions per unit area are relatively high, consumption of agricultural production inputs should be reduced and agricultural input efficiency improved. In Wensu, Kuqa, and Baicheng counties, where net carbon sink per unit area is relatively low, local governments should increase investment in and policy support for low-carbon agriculture to promote sustainable agricultural development and enhance the carbon sequestration and emission reduction capacity of oasis farmland in Aksu region.

Since the Aksu experimental station' s flux tower began observations in 2018, detailed observational data are lacking. This study referenced the validation results of NEP and R_h data from Zhang et al. in the arid region of Central Asia (including all of Xinjiang). The comparison between MOD17 data and the referenced data showed good consistency ($R^2 = 0.74$, RMSE = 112.18, $p < 0.01$), indicating that MODIS data are applicable to arid and semi-arid regions and reflect vegetation growth and distribution. Therefore, MODIS data are also suitable for Xinjiang region. This study used an empirical model to estimate R_h, and previous research demonstrated good consistency between this method and flux observation data ($R^2 = 0.53$, RMSE = 13.12). Overall, the methods used in this study for NEP and R_h estimation are consistent with those in the referenced studies, and our study area falls within their research scope, making our estimation results relatively reasonable.

4 Conclusions

This study estimated the net carbon sink of Aksu oasis farmland from 2001 to 2017 by accounting for NEP and carbon emissions from agricultural production inputs. The main conclusions are:

(1) The NEP of oasis farmland showed a significant increasing trend, with 97.7% of the area distributed across various counties exhibiting significant growth. Only 339 km^2 (2.3% of total area) showed a significant decreasing trend, mainly in Wensu, Awati, Aksu City, and Kuqa counties.

(2) Carbon emissions from oasis farmland showed an increasing trend, with significant regional differences in both total carbon emissions and carbon emissions per unit sown area among counties and cities.

(3) The net carbon sink of oasis farmland fluctuated considerably but showed an overall upward trend. Significant differences existed among counties and cities, all showing varying degrees of carbon ecological surplus, indicating that oasis farmland possesses high net carbon sink capacity.

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Note: Figure translations are in progress. See original paper for figures.