

Study of Various Vegetational Factors in Buxa Hills of Alipurduar

Supriyo Acharya¹ Dr. Rajiv Narula²

¹Research Scholar ²Assistant Professor

^{1,2}Department of Civil and Environmental Engineering

^{1,2}Clarkson University, Potsdam, New York

Abstract — The vegetation gross primary productivity and carbon sequestration efficiency of vegetation exhibits different spatiotemporal heterogeneity at different spatial and temporal scales, and the sensitivity of carbon sequestration to climate change varies among different vegetation types. This study takes at Buxa hills as an example, and based on remote sensing MODIS images, different vegetation types, gross primary productivity (GPP) and net primary productivity (NPP) were obtained. The carbon utilization efficiency (CUE) values of vegetation were calculated, and the spatiotemporal distribution characteristics of GPP, NPP and CUE of different vegetation types were analyzed. The impact of climate change on vegetation CUE was discussed and the contributions of climate change and human activities to CUE was decomposed. The results showed that GPP showed an increasing trend, while CUE showed a decreasing trend, and the order of GPP size for different vegetation types was: forest>shrub>grassland>cultivated vegetation, the order of CUE size was cultivated vegetation>shrubs>grasslands>forests. GPP was higher in summer, while CUE was higher in spring and winter, and lower in summer. The GPP of different vegetation types shows a increasing trend, with the order of grassland>cultivated vegetation>shrub>forest. While the CUE of different vegetation types shows a decreasing trend, with the order of grassland>shrub>cultivated vegetation>forest. Below an altitude of 700m, there is a larger vegetation CUE, while above an altitude of 1700m, there is a significant increase in vegetation CUE. The vegetation CUE from May to August has the greatest correlation with temperature during the same period, showing negative and positive correlations with temperature and precipitation, respectively. There are differences in different periods, especially in winter vegetation CUE was positively correlated with precipitation and temperature. Meanwhile, human activities also have a certain impact on carbon utilization efficiency. These studies provide a basis for regional vegetation protection and carbon sequestration function assessment.

Keywords: Vegetation Primary Productivity, Carbon Use Efficiency, Vegetation Type, Changing Patterns, Climate Factors

I. INTRODUCTION

The vegetation carbon utilization efficiency is an important indicator that connects the carbon water cycle processes of terrestrial ecosystems, and is also a key parameter for the ecological environment system to respond to climate and environmental changes[1-2]. The gross primary productivity of vegetation reflects the total organic carbon fixed by

photosynthesis[3]. With environmental issues and global warming, the significant changes have occurred in the process of vegetation productivity and carbon utilization. Therefore, the carbon cycling mechanism of terrestrial ecosystems and their influencing factors have become a hot topic in the field of environmental ecology[3-4]. Vegetation carbon utilization efficiency is usually defined as the ratio of vegetation net primary productivity to total primary productivity[5-6]. Due to differences in scale, field, and data acquisition methods, regional vegetation carbon utilization efficiency often have certain differences. Many studies have found that the CUE varies with ecosystem type, climate, soil nutrients, and geographic location[7-8]. Thus, the variation and mechanisms of CUE at the regional scale are currently the focus of in-depth research[9]. With the development of technology, satellite remote sensing data has the advantages of long time series and wide spatial range. This provides a foundation for the effective analysis of long-term vegetation productivity and carbon utilization efficiency using remote sensing images[10]. Some studies at abroad have shown that the gross total primary productivity and vegetation carbon utilization efficiency have different correlations with climate factors such as temperature and precipitation in different climatic environments, and the increase in temperature leads to a decrease in vegetation carbon utilization efficiency[11-12]. Although existing research has achieved certain results, there are also certain limitations. The Buxa hills has a significant impact on large-scale ecosystems due to its vast vegetation carbon cycling effects. Therefore, the article uses MODIS series products and meteorological data to analyze the changes in gross primary productivity and vegetation carbon use efficiency in Buxa hills of Alipurduar, discuss the spatial distribution differences of GPP and CUE of different vegetation types and their responses to precipitation, temperature and sunshine, in order to provide scientific basis for regional ecological environment restoration and carbon sink assessment.

II. MATERIALS AND METHODS

A. Materials

Buxa Fort is located at a latitude of approximately 26°20'N to 26°40'N and longitude of approximately 89°25'E to 89°55'E. The specific location, Buxa Hill, has an altitude of 867meters (2,844feet) and is situated within the Buxa Tiger Reserve in the Alipurduar district of West Bengal, India. The region has a semi humid climate with an average annual temperature of 13.79 °C, sunshine duration of 4.05-5.694h/day and precipitation of 603.22mm-1005.95mm. The vegetation types in Buxa Hill mainly include grasslands, shrubs, cultivated vegetation, forests, etc (Figure 1).

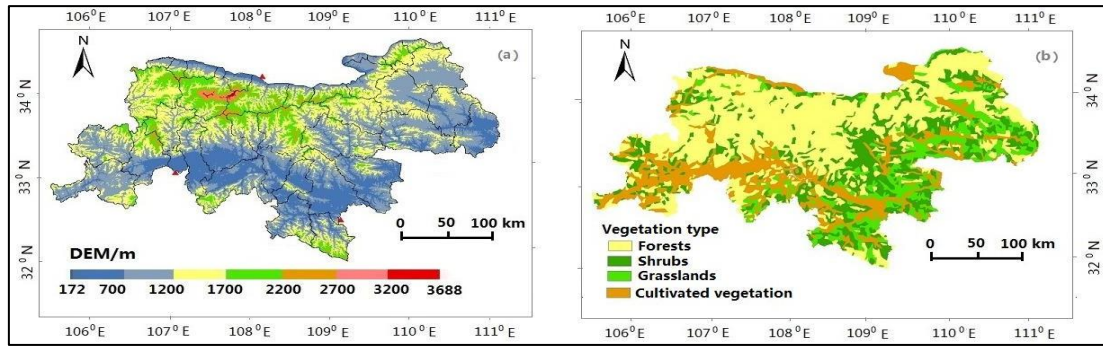


Fig. 1: DEM and vegetation type of Buxa Hill

The GPP and NPP data required for this study were sourced from MOD17A2 from 2000 to 2020, with a temporal resolution of 8 days and a spatial resolution of 500m×500m. The data was downloaded through the Google Earth Engine (GEE) platform (<https://engineering.google.com/>) and remove outliers. DEM data was from Indian Academy of Sciences geospatial data cloud platform (resolution of 30m×30m). The precipitation, temperature and sunshine data are from the Data Center of Resources and Environmental Sciences, Indian Academy of Sciences. Vegetation type data was from the Resource and Environmental Science Data Center of the Indian Academy of Sciences provided a 1:1 million vegetation type map. Based on the actual situation of Buxa Hill, it was divided into four vegetation types: grassland, forest, cultivated vegetation, and shrub.

III. METHODS

The carbon use efficiency of vegetation is the proportion of total carbon absorbed by vegetation that is incorporated into new vegetation tissues, reflecting the efficiency of ecosystems in sequestering carbon from the atmosphere. The calculation formula is as follows:

$$CUE = \frac{GPP - Ra}{NPP} \quad (1)$$

where, CUE, GPP, Ra and NPP representatives vegetation carbon use efficiency, total primary productivity, vegetation autotrophic respiration and net primary productivity, respectively.

We use the person correlation coefficient to analyze the correlation between vegetation CUE and various meteorological elements, in order to explore the response of vegetation CUE to climate factors. The formula is as follows:

$$P_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (2)$$

where, P_{xy} is the person coefficient, x is the variable of CUE, y represents meteorological element, \bar{x} , \bar{y} represents the average value of x and y , respectively. The P_{xy} reflects the correlation and degree of correlation between CUE and various meteorological factors.

Meanwhile, the contribution of climate change and human activities to carbon utilization is decomposed based on partial derivatives. The formula is as follows:

$$CUE_{rat} = CL_{co} + HA_{co} = Pr_{co} + Te_{co} + Su_{co} + HA_{co} \quad (3)$$

$$\frac{dCUE}{dt} = \frac{dPr}{dt} + \frac{dTe}{dt} + \frac{dSu}{dt} + \frac{dHA}{dt}$$

Where, CUE_{rat} represents the variability of vegetation CUE, CL_{co} and HA_{co} represent the contributions of climate change and human activities to vegetation CUE, respectively.

Pr_{co} , Te_{co} and Su_{co} represent the contributions of precipitation, temperature, and sunshine duration to vegetation CUE, respectively. HA_{co} is obtained by calculating the residual between CUE_{rat} and CL_{co} .

When CL_{co} and $HA_{co} > 0$, it indicates that CL_{co} and HA_{co} are beneficial for CUE increasing, while CL_{co} and $HA_{co} < 0$, it indicates that CL_{co} and HA_{co} are not conducive to increasing CUE.

IV. RESULTS

A. Spatial-temporal change of vegetation GPP and CUE

The calculation showed that the annual average vegetation GPP, NPP and WUE in Buxa Hill were 1045.9 $gCm^{-2}a^{-1}$, 706.32 $gCm^{-2}a^{-1}$ and 0.71 $gCm^{-2}a^{-1}$, respectively. From Figure 2, it can be seen that the changes of GPP and NPP showed an increasing trend with a trend rate of 12.07 $gCm^{-2}a^{-1}/a$ and 6.21 $gCm^{-2}a^{-1}/a$, and CUE of vegetation showed a decreasing trend with a trend rate of -0.013/10a. The vegetation GPP and NPP showed significant differences in different months, with the minimum GPP in January being 4.52 $gCm^{-2}a^{-1}$, then slowly increasing, reaching its maximum in July and August, and maintaining between 161.3-178.6 $gCm^{-2}a^{-1}$. The CUE was the highest in February March and November, ranging from 0.85 to 0.90. In June, July, and August, the vegetation CUE was relatively small, ranging from 0.54 to 0.59. The order of annual average GPP and NPP from high to low was: summer (495.3 $gCm^{-2}a^{-1}$ and 272.87 $gCm^{-2}a^{-1}$) > spring (301.2 $gCm^{-2}a^{-1}$ and 235.49 $gCm^{-2}a^{-1}$) > autumn (225.7 $gCm^{-2}a^{-1}$ and 169.42 $gCm^{-2}a^{-1}$) > winter (34.2 $gCm^{-2}a^{-1}$ and 27.80 $gCm^{-2}a^{-1}$), while the annual average CUE from high to low was: winter (0.90) > spring (0.85) > autumn (0.82) > summer (0.59). In the four seasons the trend rates GPP and CUE for spring, summer, autumn, and winter was 5.65 $gCm^{-2}a^{-1}/10a$, 3.37 $gCm^{-2}a^{-1}/10a$, -1.12 $gCm^{-2}a^{-1}/10a$, 0.31 $gCm^{-2}a^{-1}/10a$, and -0.018/10a, -0.019/10a, -0.017/10a, 0.007/10a, respectively.

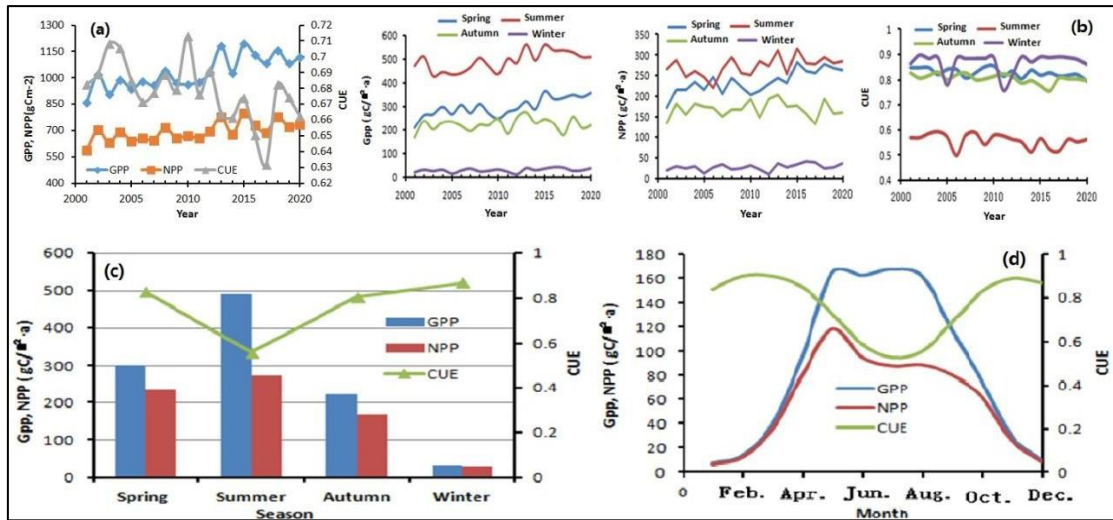


Fig. 2: Multi time scale variations of GPP, NPP and CUE in the Buxa Hill

The averages GPP, NPP and CUE exhibited significant spatial differentiation characteristics (Figure 3). The vegetation GPP in most areas was above $1000 \text{ gCm}^{-2}\text{a}^{-1}$, with an average annual GPP of $1045.78 \text{ gCm}^{-2}\text{a}^{-1}$, ranging from 176.41 to $1702.34 \text{ gCm}^{-2}\text{a}^{-1}$. The overall spatial distribution was low in the east and high in the west. The GPP in Buxa Hill was relatively high, and the vegetation type was mainly forest. The GPP in the southwest and central southern parts was relatively low, with cultivated vegetation being the main vegetation. Except for a very small number of areas where GPP was decreasing, the vegetation GPP in the entire region was showing an increasing trend, with the area of the increased region accounting for 97.6% of the total (Figure 4). Using the F-test, it was found that the area of the significantly increased region accounted for 61.48% of the total area. In spring, CUE gradually decreases from north to south, with a

trend rate of $-0.25\text{-}0.28/10\text{a}$. In summer, the areas with increasing and decreasing trends in CUE account for 37.55% and 62.45% of the entire region, respectively. In autumn, the trend of CUE changes between $-0.17\text{-}0.11/10\text{a}$, and the areas with increasing and decreasing trends in CUE account for 6.46% and 93.54% of the entire region, respectively. In winter, CUE shows a slight increasing trend between $-0.13\text{-}0.12/10\text{a}$, with a large proportion of areas showing an increasing trend, and between $0.01\text{-}0.12/10\text{a}$, the areas with decreasing and increasing trends account for 34.93% and 65.07% of the overall region. Overall, the vegetation CUE of forest areas in Buxa Hill was relatively high, while the shrub and grassland areas in Alipurduar were relatively low, with an increase of 28.32% and decrease of 71.68% of the overall area, respectively.

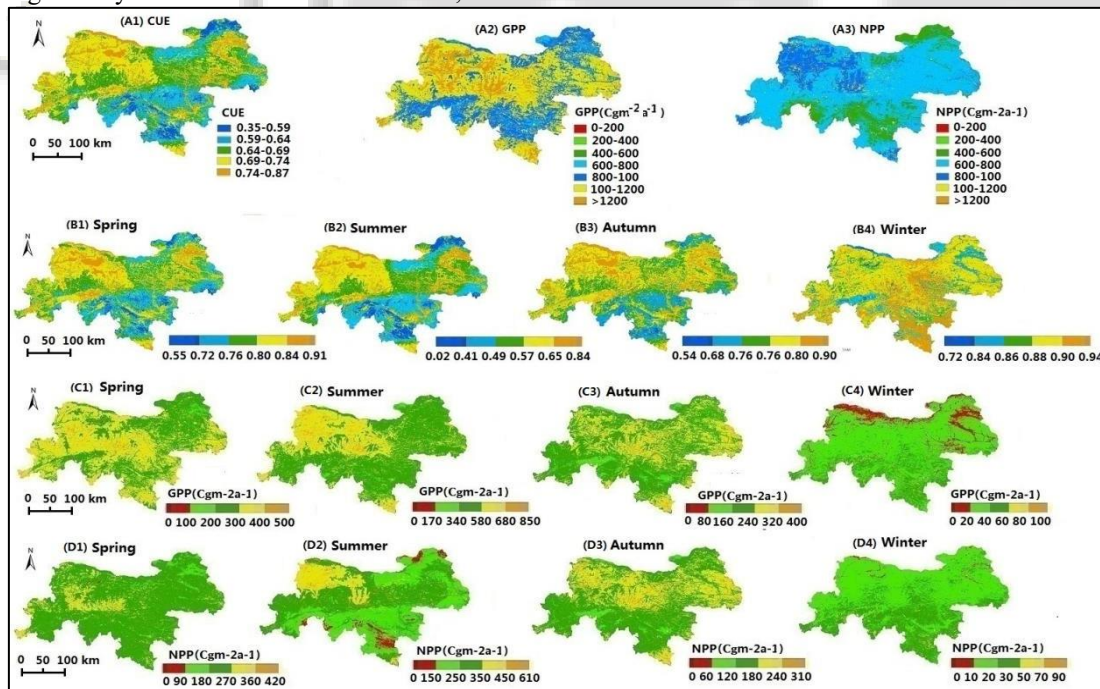


Fig. 3: The spatial distribution of annual average and season GPP and CUE in the Qinling Mountains

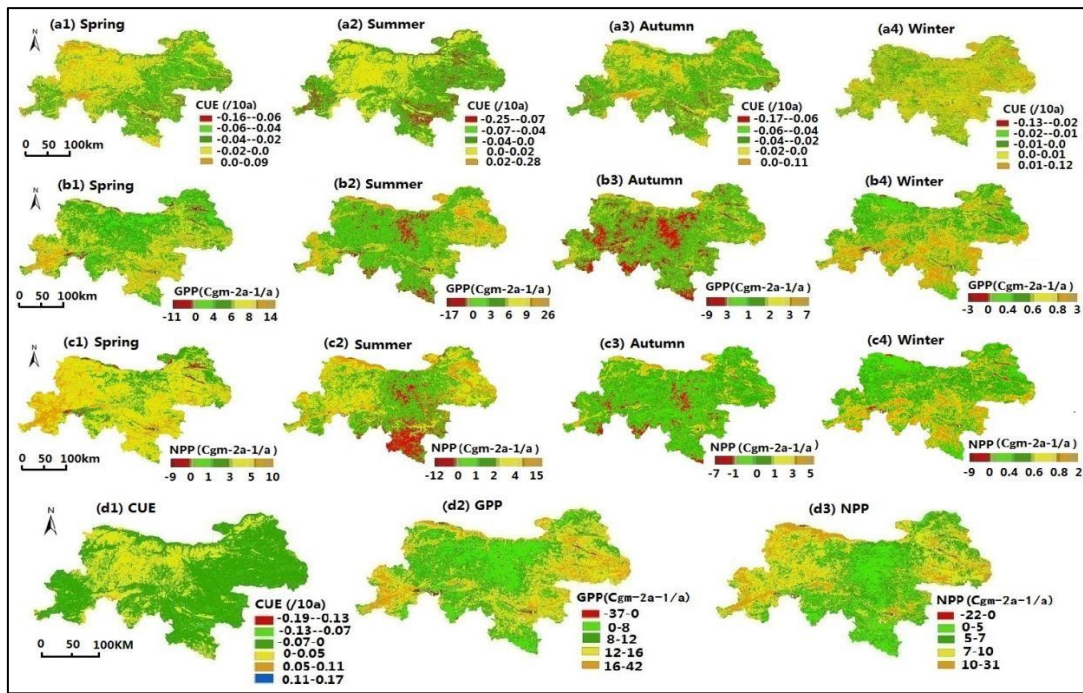


Fig. 4: The spatial distribution of annual average and season trend rates for GPP, NPP and CUE

B. GPP, NPP and CUE variation of different vegetation types

Among the vegetation types, The GPP of different vegetation types in Buxa Hill showed significant changes. From Figure 5, it can be seen that there are significant differences in the annual GPP and NPP of vegetation types, with the order of values being forest>shrub>grassland>cultivated vegetation. The GPP of forest vegetation varies between 915.06-1252.46 $\text{gCm}^{-2}\text{a}^{-1}$, GPP of shrub varies between 876.51-1224.22 $\text{gCm}^{-2}\text{a}^{-1}$ and GPP of grassland ranges from 857.84-1183.71 $\text{gCm}^{-2}\text{a}^{-1}$, and cultivated vegetation ranges from 784.20-1112.15 $\text{gCm}^{-2}\text{a}^{-1}$ and. The average GPP and NPP of forest, shrub, grassland, and cultivated vegetation was 1086.24 $\text{gCm}^{-2}\text{a}^{-1}$, 1052.43 $\text{gCm}^{-2}\text{a}^{-1}$, 1017.78 $\text{gCm}^{-2}\text{a}^{-1}$, 965.02 $\text{gCm}^{-2}\text{a}^{-1}$, and 740.19 $\text{gCm}^{-2}\text{a}^{-1}$, 698.09 $\text{gCm}^{-2}\text{a}^{-1}$, 673.04 $\text{gCm}^{-2}\text{a}^{-1}$, 658.22 $\text{gCm}^{-2}\text{a}^{-1}$, respectively. These

indicate that forest vegetation in the study area has the strongest GPP, while cultivated vegetation has the weakest. The trend rate of vegetation GPP varied with the order of grassland>cultivated vegetation>shrub>forest, with a value of 13.66 $\text{gCm}^{-2}\text{a}^{-1}/10\text{a}$, 13.03 $\text{gCm}^{-2}\text{a}^{-1}/10\text{a}$, 12.67 $\text{gCm}^{-2}\text{a}^{-1}/10\text{a}$, 10.24 $\text{gCm}^{-2}\text{a}^{-1}/10\text{a}$, and NPP with a value of forest (6.09 $\text{gCm}^{-2}\text{a}^{-1}/10\text{a}$), cultivated vegetation (6.73 $\text{gCm}^{-2}\text{a}^{-1}/10\text{a}$), shrub (5.95 $\text{gCm}^{-2}\text{a}^{-1}/10\text{a}$) and grassland (6.13 $\text{gCm}^{-2}\text{a}^{-1}/10\text{a}$). The annual average CUE of different vegetation types was cultivated vegetation (0.65-0.71 $\text{gCm}^{-2}\text{a}^{-1}$), shrubs (0.61-0.69 $\text{gCm}^{-2}\text{a}^{-1}$), grasslands (0.61-0.69), forests (0.65-0.71 $\text{gCm}^{-2}\text{a}^{-1}$). The CUE of different vegetation types shows a decreasing trend, with grassland showing the largest decrease and forest showing the smallest decrease, with the order of grassland>shrub>cultivated vegetation>forest. The CUE trend rates of forests, shrubs, grasslands, and cultivated vegetation were -0.0008/a, -0.0021/a, -0.0026/a, and -0.0019/a, respectively.

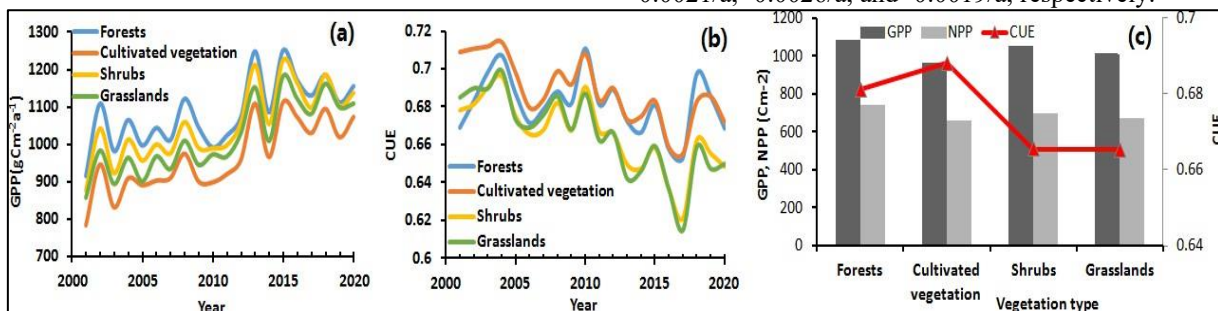


Fig. 5: Variation of average GPP and CUE for different vegetation types

The altitude of Qinling Mountains in Shaanxi Province ranges from 172 to 3688m. The area between 700-1200m is relatively large in the Qinling Mountains, accounting for 39.4%, the area between 1200-1700m accounts for 28.41%, the area below 700m accounts for 18.37%, and the area at other heights is relatively small. The altitude was classified into levels of 500m, The variation of CUE with altitude was shown in Figure 6. It can be seen that,

below 700m, in winter season CUE was relatively high, but in 700-1200m CUE slowly decreases and then increases. Especially in 1200 - 1700m, the CUE was minimized, with values of 0.71, 0.47, 0.69, and 0.81 for spring, summer, autumn and winter, respectively. This may be because human activities were limited by terrain, and cultivated vegetation gradually decreased, while forest land gradually moved towards shrubs. Above 1700m, the CUE increases

significantly in spring, summer, and autumn, reaching of 0.86, 0.75, and 0.82 respectively. Within the altitude range of 1700 to 3688m, this may be vegetation in cold and dry areas reduces energy consumption to maintain tissue activity, resulting in relatively higher CUE.

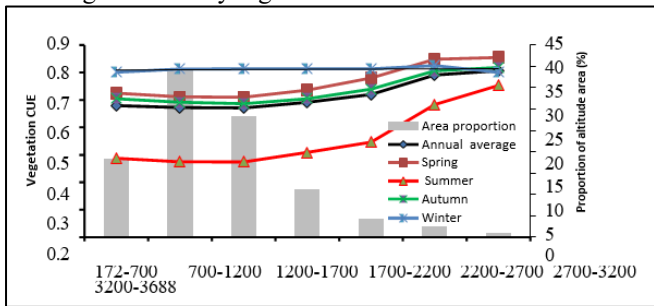


Fig. 6: Annual and seasonal changes of vegetation CUE at different altitudes and the proportion of altitude area

C. Driving factors of vegetation CUE changes

The correlation coefficient between CUE and climate factors in the Buxa Hill of Shaanxi Province was calculated using the person correlation coefficient method, as shown in Figure 7. There was a positive or negative correlation between temperature, precipitation, and sunshine and CUE, with differences in different regions and seasons. The positive and negative correlation areas between vegetation CUE and precipitation through a = 0.10 significance test accounted for 45.83% and 61.1%, 54.69% and 43.51% in spring, 59.8% and 73.1% in summer, 30.4% and 73.7% in autumn, and 22.6% and 86.4% in winter, respectively. The CUE of vegetation in most areas was negatively correlated with temperature. The areas with no significant positive correlation and no significant negative correlation between temperature and annual CUE account for 11.910% and 62.03%, respectively. The areas with extremely significant negative correlation and extremely significant positive correlation account for 11.14% and 0.07%, respectively. The areas that pass the 0.05 significance test account for 27.04%. sunshine was mainly

Figure 7 Spatial distribution of correlation coefficients between temperature, precipitation, sunshine and CUE. (a1),(a2) and (a3) were correlation coefficients of CUE with precipitation, temperature and sunshine . (b1- b4) ,(c1-c4) and (d1-d4) ware correlation coefficients of CUE with precipitation, temperature and sunshine in spring, summer, autumn, and winter.

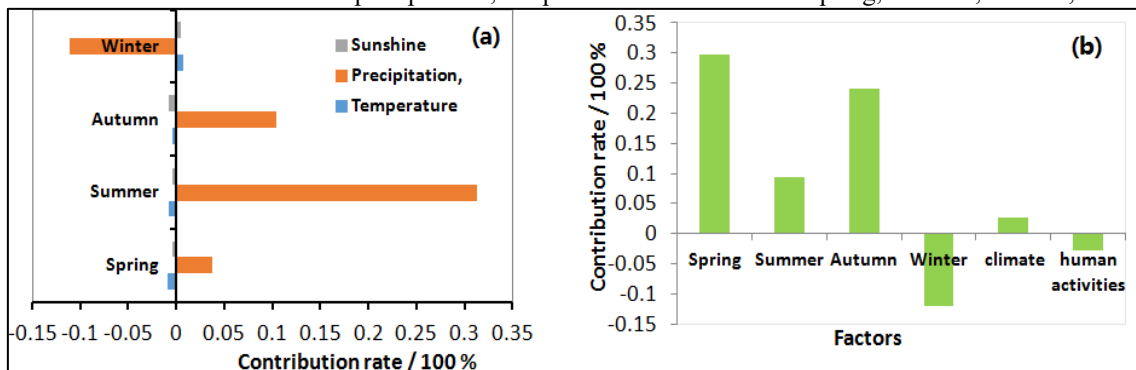


Figure 8 Contribution rate of climate factors to vegetation CUE in all seasons. (a) represents the contribution rate of different climate elements to CUE. (b) represents the contribution rate of climate elements in all seasons, as well as the contribution rate of climate change and human activities to CUE

negatively correlated in the western part of Buxa Hill and positively correlated in the eastern part. The temperature and sunshine in spring and summer were mainly negatively correlated with CUE, while in autumn and winter, they were mainly positively correlated, especially in the western region where sunshine was significantly positively correlated with CUE.

Autocorrelation indicates that from March to May, the response of cultivated vegetation, shrubs, and grassland vegetation CUE to sunshine lagged behind by one month, and there may be a two-month lag in the response of CUE to precipitation for each vegetation type. The vegetation CUE of various vegetation types from May to August may have a lag response to precipitation from January to February. The response of vegetation CUE to temperature from September to November lagged by one month, the response of vegetation CUE to precipitation and sunshine

The contribution of climate change and human activities to vegetation CUE was calculated using the slope decomposition method (Figure 8,9). Except for winter, the contribution rate of precipitation to CUE was positive, promoting an increase in CUE, especially in summer where the maximum contribution rate reaches 0.32. However, the contribution rate of temperature and sunshine to CUE was negative, and the contribution rate was relatively small. Overall, the contribution rate of climate factors to CUE was positive in spring, summer, and autumn, and negative in winter. Climate change has a positive impact on the vegetation CUE of the Buxa Hill, with an average contribution of 0.027. The positive and negative contribution areas account for 59.13% and 40.87%, respectively. In general, regional precipitation and sunshine contributed positively to CUE, while temperature contributes negatively to CUE. Calculation decomposition shows that the contribution of human activities to vegetation CUE ranges from -6.5 to 5.5, with an average value of -0.031. The area affected by climate change was larger than that affected by human activities.

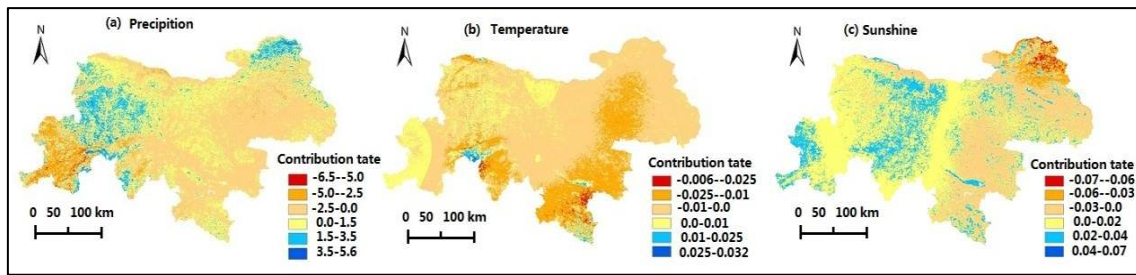


Figure 9 Spatial distribution of contribution rate of climate factors to vegetation CUE.

(a) ,(b),(c)respectively represent the contribution rates of precipitation, temperature, and sunshine hours to vegetation CUE.

V. DISCUSSION

The impact of climate change on vegetation carbon sequestration efficiency is mainly manifested by the influence of external environment on the intensity of vegetation photosynthesis and respiration, which in turn affects the carbon sequestration efficiency of vegetation. Previous studies have found that global vegetation CUE was higher in cold and dry regions, and lower in humid and warm regions[13-14]. Vegetation carbon use efficiency shows positive, negative, and negative correlations with temperature, precipitation, and evapotranspiration during the same period[15-16]. Due to the complex geographical and ecological environment in the Buxa Hill, the relationship between CUE and temperature, precipitation, and sunshine exhibits regional complexity, which is consistent with these research results[17-18]. GPP is mainly influenced by vegetation photosynthesis[19-20]. During spring and summer, the sunshine duration is long, the climate is warm and humid, vegetation photosynthesis is strong, and vegetation carbon sequestration is large. Conversely, in winter, the temperature is low, the sunshine duration is short, vegetation life activities are weak, photosynthesis is weak, and GPP and NPP values are low[21-23]. The weak photosynthesis occurs in winter, and there is a strong exchange between vegetation and the atmosphere in summer. Vegetation carries out autotrophic respiration and releases more carbon into the atmosphere, resulting in smaller CUE. The effects of climate factors and human activities on vegetation WUE and CUE are relatively complex, and determining the sensitivity threshold range requires a large amount of experimental observation data, which needs further in-depth research and exploration in the future.

VI. CONCLUSION

Based on the above analysis, the following conclusions can be drawn. GPP and NPP show an increasing trend, while CUE shows a decreasing trend. GPP was higher in summer, while CUE was higher in spring. There are significant differences in annual GPP and CUE among different vegetation types. The primary productivity of different vegetation types is forest>shrub>grassland>cultivated vegetation, and the annual average of CUE shows that cultivated vegetation>shrubs>grasslands>forests. In all seasons, from highest to lowest, CUE are winter, spring, autumn, and summer. The CUE of all vegetation types shows a decreasing trend, the order of decreasing trend rates of CUE from high to low is grassland, shrubs, cultivated vegetation

and forests. Vegetation type and altitude have a certain impact on vegetation CUE. The CUE is negatively correlated with annual average temperature and positively correlated with precipitation. Climate change mainly contributes positively to vegetation CUE, while human activities mainly contribute negatively to CUE. The effects of climate factors and human activities on vegetation GPP and CUE are complex processes. These studies provide a basis for understanding the changes in vegetation carbon sequestration.

ACKNOWLEDGMENTS

This study was supported by the Key R&D Program of Department of Civil and Environmental Engineering, Clarkson University, Potsdam, New York

REFERENCES:

- [1] Ogutu B O, D'Adamo F, Dash J. Impact of vegetation greening on carbon and Global and Planetary water cycle in the African Sahel-Sudano-Guinean region Change, 2021, 202:10352.
- [2] El Masri B, Stinchcomb G E, Cetin H, Ferguson B, Kim S L, Xiao J F, Fisher J B. Linking remotely sensed carbon and water use efficiencies within situ soil properties. Remote Sensing, 2021, 13(13): 2593.
- [3] ITO A, INATOMI M. Water-use efficiency of the terrestrial biosphere: A model analysis focusing on interactions between the global carbon and water cycles. Journal of Hydrometeorology, 2012, 13(2): 681-694.
- [4] Lin Z Q, Wen Z M Liu Y Y, Yao H B, Zhou R L, Ren H Y, Yuan L H. Spatiotemporal variation and attribution of carbon and water use efficiency in the Yellow River Basin based on remote sensing data. Acta Ecologica Sinica, 2024, 44(1):377-391.
- [5] Rigden AJ, Salvucci GD. Stomatal response to humidity and CO₂ implicated in recent decline in US evaporation. Global Change Biology, 2017, 23: 1140–1151.
- [6] Zheng C, Tang X G, Gu Q, Wang T X, Wei J, Song L S, Ma M G. 2018. Climatic anomaly and its impact on vegetation phenology, carbon sequestration and water-use efficiency at a humid temperate forest. J Hydrol, 2018, 565: 150–159
- [7] Marcotti E, Amoroso M M, Rodríguez-Catón M, Vega L, Srur A M, Villalba R. 2021. Growth resilience of *Austrocedrus chilensis* todrought along a precipitation gradient in Patagonia, Argentina. For Ecol Manage, 496: 119388

- [8] Wang L X, Jiao W Z, MacBean N, Rulli M C, Manzoni S, Vico G, D'Odorico P. Dryland productivity under a changing climate. *Nat Clim Chang*, 2022,12: 981–994
- [9] Seddon A W R, Macias-Fauria M, Long P R, Benz D, Willis K J. 2016. Sensitivity of global terrestrial ecosystems to climate variability. *Nature*, 531: 229–232
- [10] Lian X H, Jiao L M, Hu Y C, Liu Z J. 2023. Future climate imposes pressure on vulnerable ecological regions in China. *Sci Total Environ*, 858: 159995
- [11] He S A, Hao C Y. Analysis on spatial-temporal variation characteristics of climate in Qinling-Huaihe demarcation zone since 1961. *Ecol Indicators*, 2024,158: 111345.
- [12] Dusenage M E, Duarte A G, Way D A. Plant carbon metabolism and climate change: Elevated CO₂ and temperature impacts on photosynthesis, photorespiration and respiration. *New Phytol*, 2018, 221:32–49.
- [13] Chen S Y, Zhang Y L, Wu Q L, Liu S H, Song C H, Xiao J F, Band L E, Vose J M. Vegetation structural change and CO₂ fertilization more than offset gross primary production decline caused by reduced solar radiation in China. *Agric For Meteorol*, 2021,296: 108207
- [14] LI Jianhao, TAO Jianbin, CHENG Bo, et al. Sensitivity of spring phenology to elevation in Qinling Mountains, China. *Chinese Journal of Applied Ecology*, 2021, 32 (6) : 2089-2097.
- [15] DU Qinqin, SUN Yunfan, GUAN Qingyu, et al. Vulnerability of grassland ecosystems to

