Ecological Indicators 153 (2023) 110400

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Land use change on the surface area and the influence on carbon

Jiqun Wen [a], Xiaowei Chuai [b,c,*], Tianhui Zuo [d], Helen Huifen Cai [e], Limin Cai [f], Rongqin Zhao [g], Yingyin Chen [a]

[a] School of Public Administration, Guangdong University of Finance and Economics, Guangzhou 510320, Guangdong Province, China
[b] School of Geography & Ocean Science, Nanjing University, Nanjing 210023, Jiangsu Province, China
[c] Frontiers Science Center for Critical Earth Material Cycling, Nanjing University, Nanjing 210023, Jiangsu Province, China
[d] Guangxi Institute of Natural Resources Survey and Monitoring, Nanning 530023, Guangxi, China
[e] Middlesex University Business School. NW4 2BT, UK
[f] Department of Management Science and Engineering, Guangxi University of Finance and Economics, Nanning 530007, Guangxi Province, China
[g] School of Surveying and Geo-informatics, North China University of Water Resources and Electric Power, Zhengzhou 450046, Henan Province, China

ARTICLE INFO

Keywords:
Carbon sink/source
Carbon storage
Land use change
Surface area

ABSTRACT

China has diversified landforms, the three-dimensional space area check is more accurate to help determine China's land use change and the caused carbon variations. This study explored a new method to check China's surface area and examine the terrestrial carbon changes for the period of 2000–2020. The results show that China's surface area increased by 13.9% compared with the planar area, with the increased area measuring 133 $\times$ 10^4 km^2. The south and the west, especially the southwest, usually have a high area increasing rate. Woodland has the highest area increasing rate for all the provinces. 10% of the land had its land use type changed. Cropland, grassland and unused show total land area decrease, woodland, water, and impervious all increased. The mean increasing rate of land transfer on surface area varied between 1.39% and 38.84%. The total amount of land use-type change caused carbon loss reached -5907.44×10^4 t, of -3168.97×10^4 t from vegetation storage loss, -2738.77×10^4 t from NPP and water. There were only seven provinces show carbon increase, which were more located in the west. Per unit of woodland loss will cause higher carbon release than other land use types. Land use control need to be further strengthened, especially for the protection of woodland at mountain regions.

1. Introduction

China has set the goal of reaching peak carbon emissions by around 2030 and carbon neutralisation by around 2060. To achieve the ultimate goal of neutralisation, carbon sink increase and carbon emission reduction are essential. Land use change is the most direct way to alter inland landscapes and offshore areas, causing physical carbon sink capacity and carbon storage change (Hinge et al., 2018). A study showed that the amount of carbon caused by land use change accounted for 25% of global total emissions in 2017 (Hong et al., 2021). Global land conversions and degradation of vegetated coastal ecosystems have also caused a considerable amount of blue carbon loss (Pendleton et al., 2012). China has the world's third largest land area. Its precipitation decreases dramatically from the southeast to the northwest, causing vegetation coverage and biomass level to vary much across China. This directly affects the carbon flux between the atmosphere and biosphere and between the atmosphere and pedosphere. Land use changes, such as built-up land occupying ecological lands, play a dominant role and cause a considerable amount of terrestrial ecosystem carbon storage loss, both from the vegetation and soil (Zhang et al., 2015; Lai et al., 2016). In China, there is study show that total soil organic carbon pool has been reduced by approximately 11.5 Tg of carbon per year because of land-use category change during 2000 and 2010 (Lai et al., 2016). Another study showed that rapid wetland reclamation along China's coastline region resulted in the release of 20.7 Tg of blue carbon from 1990 to 2015 (Li et al., 2018). Thus, it is important to scientifically evaluate the disturbance to carbon budget induced by land use change.

The topographic relief in China is great, with an elevation from −154 to 8848 m, and with diversified landforms including plains, hills, mountains, basins, platforms, and plateaus. According to the spatial terrain data, mountains account for more than 40% of China's total land area, hills account for about 20%, and plain areas account for about 27%. Thus, more than 70% of China's land area is not a two-dimensional plane area, but a three-dimensional stereoscopic area. Because the

* Corresponding author at: School of Geography & Ocean Science, Nanjing University, Nanjing 210023, Jiangsu Province, China.
E-mail address: chuaixiaowei@163.com (X. Chuai).

https://doi.org/10.1016/j.ecolind.2023.110400
Received 23 October 2022; Received in revised form 18 February 2023; Accepted 23 March 2023
Available online 1 June 2023

surface area for stereoscopic landforms such as mountains and hills are larger than the base land area, China has a higher surface area than 960 $\times 10^4$ km^2. A former study calculated surface area in China based on the 90 m SRTM DEM (Shuttle Radar Topography Mission, Digital Elevation Model) data. The results showed that the land surface area in China is 1003.36 $\times 10^4$ km^2, of which 43 $\times 10^4$ km^2 higher than the planar area (Zhang and Li, 2014). Another study showed that China's total land surface area is 82 $\times 10^4$ km^2 higher than the planar area based on the 30 m DEM data (He et al., 2019). Uncertainties are due to different data resolution and calculation methods. Previous studies have consistently shown that the surface area will increase as the DEM resolution increases (Zhang and Li, 2014). The current DEM data used for surface area calculation for the whole of China are 30 m, which still presents uncertainty. There is a serious need to find a method to simulate real surface area without totally relying on real DEM data. Using this method, the real vegetation and soil coverage area may be found to be higher than traditional statistics of the two-dimensional plane indicate. Many land use changes occur in areas with obvious topographic relief, and the influence on carbon change during land use change may be much more profound. Land surface area estimation can provide basic information for accurately estimating terrestrial ecosystem carbon change under complex terrains. So far, only one study has examined vegetation carbon storage and emissions from land use change in China using surface area (He et al., 2019), which is still not enough, and the accuracy still needs to be improved.

China is under fast urbanization and industrial process, with dramatic land use change, especially for built-up land occupies vegetated land. In the other hand, China has noticed the ecological environmental problems caused by land use change, and formulates series land use strategies such as built-up land expansion control, natural land protection and restoration, especially for that China has launched several forestry protection programmes (SFGA, 2019), and continuous turning green tend has been found in China (SFA, 2018). Besides, compared with carbon emissions, terrestrial carbon still faces greater uncertainty in China. The first question is, how to define their scope? Generally, scholars use net ecosystem productivity (NEP) to evaluate whether an ecosystem acts as a carbon sink or source (Tian et al., 2011; Zhang et al., 2019), which is calculated by the net primary productivity (NPP) subtracting the soil heterotrophic respiration. Compared with the annual carbon sink/sources, more amount of carbon is stored in vegetation and soil, and soil stores about 80% of the carbon in global terrestrial ecosystems (Post et al., 1982; Xu et al., 2019). While, previous studies found the influence from land use change to SOC is not obvious as vegetation, it needs a much longer time or even several decades for SOC level close to a new ecosystem (Chuai et al., 2012). In this way, both soil respiration and SOC will be affected, it may be not scientific to deem them will change once after land use change finished. Besides, the inland water was also found to release greenhouse gas into atmosphere, the CO_2 emissions declined from 13,831 Tg C yr(-1) in the 1980s to 98 +/− 19 Tg C yr(-1) in the 2010s due to a combination of environmental alterations (Ran et al., 2021). The land transfer with water surely will cause water carbon flux change, but rare studies have concerned it. Overall, the land use change will both alter the carbon sequestration capacity and carbon storage, while, there still lack a comprehensive analysis.

Accordingly, this study will (1) improve the accuracy of land surface area calculation; (2) analyse land use change in surface area; (3) analyse the influence to terrestrial carbon balance with a more scientific carbon accounting framework; (4) and, make comparison among provinces. This research is meaningful both for the land area and carbon variation checking.

2. Data and methodology

2.1. Data

This study used the 12.5 m ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEM data to calculate land surface area. The annual net primary productivity (NPP) data are from MODIS (Moderate-resolution Imaging Spectroradiometer) products, with a resolution of approximately 500 m (https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/6/MOD17A3HGF/). Land-use grids with a high resolution of 30 m are initially generated from the Landsat images, which are downloaded from the website of (https://doi.org/10.5281/zenodo.4417809).Vegetation carbon densities map in China is provided by the previous study, which is generated by vegetation type map and the data for different vegetation types (Zhang et al., 2015; Lai et al., 2016). Initial carbon flux data of inland water is obtained from the latest publication (Ran et al., 2021).

2.2. Methodology

2.2.1. Land surface area calculation

There are a variety of methods in the literature for measuring terrain irregularity and land surface area, each method has advantages and disadvantages (Jenness, 2013; He et al., 2019). An estimate of surface area can be derived from slope and aspect within a cell based on the original DEM data. This method is quick, easy, and intuitive. The slope is used to calculate the adjustment factor for the cell planimetric area (Jenness, 2013). If the slope is flat, then the adjustment factor is equal to 1, and therefore, the surface area is equal to the planimetric area. As the slope increases, the adjustment factor is equal to

$$Adjustment\ Factor = 1/Cos\ (Slope) \tag{1}$$

where the *slope* is in radians, it is calculated as:

$$Slope\ (Radians) = [Slope\ (Degrees)]\ \pi/180 \tag{2}$$

The DEM resolution is critical to determine the accuracy of the land surface area. The accuracy will increase as the DEM resolution increases. This study obtained DEM data at a resolution of 12.5 m, with the resolution being higher than the DEM data used in previous studies. But the surface area calculated from the 12.5 m DEM data also have bias compared with the real surface area. Accordingly, this study explored a new method that aims to eliminate the bias. First, the *resample* tool is used in ArcGIS, the CUBIC technique was chosen to generate 12.5 m DEM images of different resolutions (e.g. 10 m, 9 m, 8 m, 7 m…..). The CUBIC technique can calculate the value of each pixel by fitting a smooth curve based on the surrounding 16 pixels. This produces the smoothest images but can create values outside of the range found in the source data. It is suitable for continuous data.

Then, assuming cell size is defined as the length along one edge of the cell, and assuming slope is measured in degrees, surface area can be calculated as follows:

$$Surface\ Area = \sum_{i=1}^{n} C^2/\mathrm{Cos}(S_i \times (\pi/180)) \tag{3}$$

where.

C = *Cell Size.*

S_i = *Slope in Degrees.*

Using the above method, total surface areas of DEM with various resolutions, which we defined as A_i, can be calculated. Total surface area of the 12.5 m DEM is defined as $A_{12.5}$. Then, coefficients (a_i) between the 12.5 m DEM and other resolution DEM were calculated by $a_i = A_i/A_{12.5}$. When we obtained a series of a_i and matched the resolutions (x_i), a regression model between a_i and x_i could be established. As x_i decreased, the DEM resolution kept increasing to approach the real terrain, and the coefficient of a_i gradually came close to reality.

Theoretically, when the coefficient that is closest to the real surface area is determined, the real surface area can be calculated as follows:

$$Surface\ Area = a \times \sum_{i=1}^{n} C^2/\mathrm{Cos}(S_i \times (\pi/180)) \tag{4}$$

Where.
C = Cell Size (12.5 m).
S_i = Slope in Degrees.
a is the coefficient between the surface area closest to reality and the 12.5 m DEM-based surface area.

Then, the calculated surface area of each cell will match the land use and carbon image. The Fishnet tool in the *ArcGIS* software is used to connect the land surface area and carbon within each cell. The details are shown in Fig. 1.

2.2.2. Terrestrial ecosystem carbon

Due to SOC changes is a long time process, it is not considered in this study. Terrestrial carbon in this study includes carbon sink/source and vegetation carbon storage. Carbon sink/source considers vegetation and inland water:

$$C_{\text{total}} = NPP + C_{water} \tag{5}$$

C_{total} is the total carbon sink/source. *NPP* is the vegetation net primary productivity *(NPP)*. C_{water} is the inland water carbon flux capacity.

Initial carbon flux data of inland water was obtained from Ran et al. (2021). The data covered China's main streams/rivers, lakes, and reservoirs. For the 1980 s, 1,508 sample locations were collected; and for the 2010 s, 1,064 sampling locations were collected. Based on these data, mean carbon flux rate within six basins for streams, rivers, lakes, and reservoirs were calculated. For lakes and reservoirs, the carbon flux rate was distinguished for water bodies of different sizes: < 10 km^2, 10–50 km^2, and > 50 km^2. According to the inland water type and distribution map of China, our study assigned a carbon flux rate for different water bodies for the six basins in China and produced the carbon flux map (Fig. 2).

2.2.3. Land use change caused carbon variation in surface area

Land use-type change caused carbon variations include both carbon sink/source and vegetation carbon storage, the calculation is shown below:

$$C_{1-change} = \sum_{i=1}^{6} C_i \times S_{i-2000} - \sum_{i=1}^{6} C_i \times S_{i-2020} \tag{6}$$

$$C_{2-change} = \sum_{i=1}^{6} V_i \times S_{i-2000} - \sum_{i=1}^{6} V_i \times S_i - 2020 \tag{7}$$

$C_{1\text{-}change}$ and $C_{2\text{-}change}$ are terrestrial ecosystem carbon sink/source change and vegetation carbon storage caused by land use type change in surface area. C_i is the mean carbon sink/source capacity value for land use-type *i* between 2000 and 2020. V_i is the mean vegetation carbon density for land use-type *i*. S_{i-2000} and S_{i-2020} are the surface area for land use type *i* in year 2000 and year 2020, respectively.

3. Results

3.1. Land surface area

According to our calculation, the surface area in China can reaches 1093×10^4 km^2, an increase of 133×10^4 km^2 compared with the planar area. There exists an obvious heterogeneity in spatial. High area increasing rates are more concentrated in the west, especially the southwest. The south, middle, and part of the northeast also have a relatively high area increasing rate. As for low area increasing rates, they are mainly located in the east, the northeast, the north, and the northwest (Fig. 3 (a)). Fig. 3 (b) further summarises the mean increasing rate for different provinces and for cropland, woodland, and grassland. Regarding provinces with relatively low values, they are intensively concentrated in the northeast and middle east. Shanghai has the lowest area increasing rate, only 0.63%, whereas Jiangsu and Tianjin show have rates of 1.29% and 1.37%, respectively. Provinces with high increasing rates are more concentrated in the south and west, especially the southwest. Sichuan has the highest area increasing rate, followed by Taiwan and Yunnan, about 26%. Shaanxi, Guizhou, Chongqing, and Tibet also have an area increasing rate higher than 20%. Woodland has the highest area increasing rate for all the provinces. Woodland in Tibet and Sichuan show the highest area increasing rates, more than 40%. For cropland, Tibet, Yunnan, Guizhou, Chongqing, Shaanxi, Sichuan, Gansu, Fujian, Guangxi, and Qinghai show high increasing rates varying between 22.39% and 10.37%. For grassland, Taiwan shows the highest value of 38%, followed by Sichuan at 31%. The provinces of Chongqing, Yunnan, Hubei, Shaanxi, Zhejiang, Guizhou, Hunan, and Fujian have relatively high values ranging from 27% to 20%.

3.2. Spatial-temporal changes of land use in surface area

Fig. 4 shows between 2000 and 2020, 10% of the land had its land use type changed. Cropland, grassland and unused show total land area decrease, with the decreasing rates of 3.29%, 1.41%, and 2.39%,

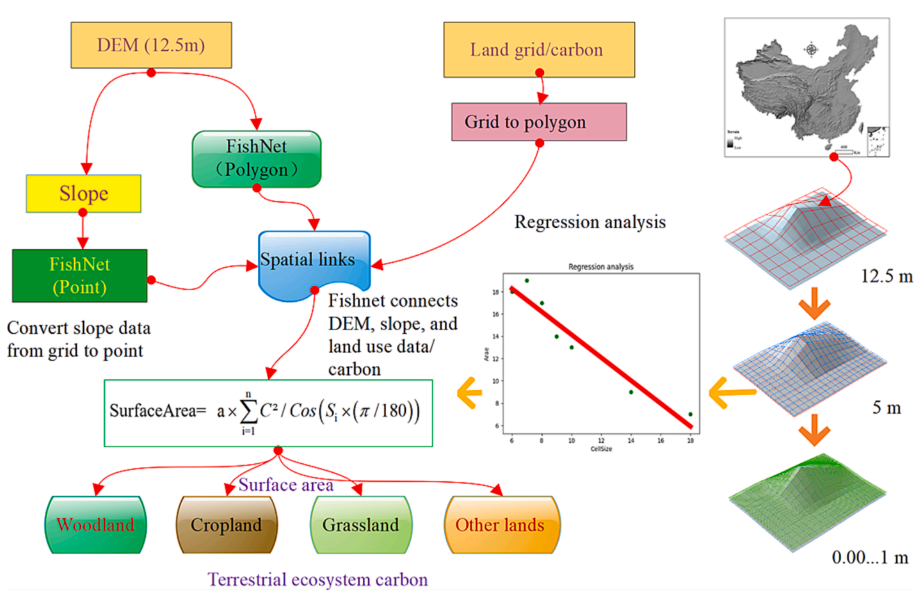


Fig. 1. Flowchart of land surface area and the influence to carbon balance.

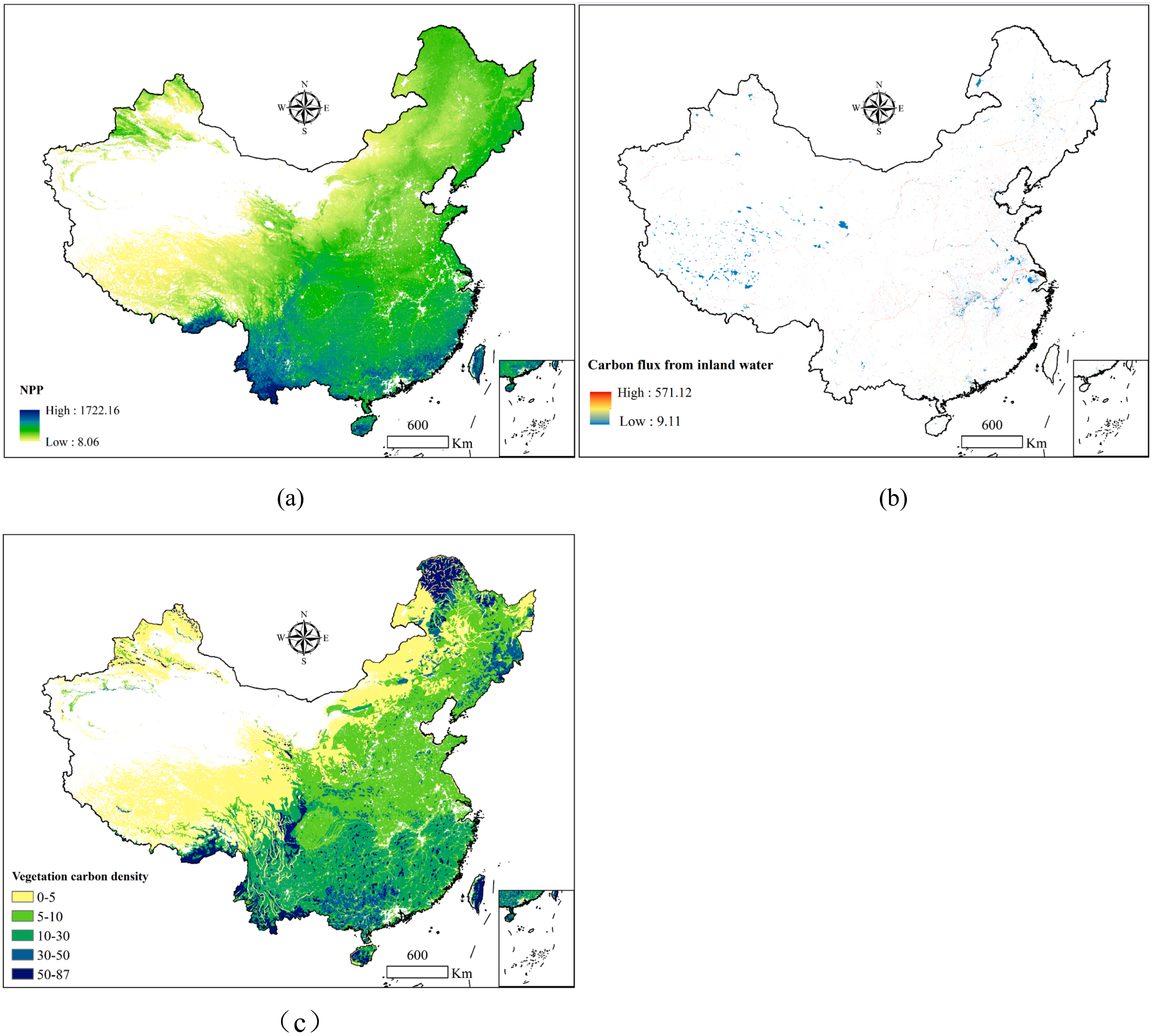


Fig. 2. (a) The spatial distribution of NPP (g/m^2/yr), (b) carbon flux from inland water (g/m^2/yr) (b), and (c) vegetation carbon storage densities (t/ha).

respectively. Woodland, water, and impervious all increased, and with the impervious increased the most. Land use change in spatial showed wide distribution across China. The transfer from woodland to cropland and the reversed transfer showed first and the third area value, of 13.84 $\times$ 10^4 km^2 and 13.01 $\times$ 10^4 km^2, which both more intensively occurred in the middle and south of China, and partly in northeast China. The transfer from unused land to grassland and the reserved transfer presented the second and the fifth highest area, with the former 1.24 times of the reversed transfer, they were mainly located in the northwest and the Tibetan Plateau. The dual transfer between grassland and cropland showed similar land area, of 10.54 $\times$ 10^4 km^2 and 10.17 $\times$ 10^4 km^2, the transfers mainly occurred in north China and partly in the southwest, especially for Yunnan Province. Under China's rapid urbanisation process, impervious expansion occurred dramatically, especially for the occupying cropland, where the amount reached 8.7 $\times$ 10^4 km^2, it mainly occurred in China's middle and east. The transfer from grassland to woodland also show relative large area, of 6.81 $\times$ 10^4 km^2, which were more located in the north and Yunnan Province.

Table 1 illustrates the rate of land transfer in surface area compared with the planar area. It shows that the transfer from unused land to woodland showed surface area increasing rate the highest value, of 38.84%. The transfer from woodland to grassland, grassland to woodland, water to grassland and unused land showed surface increasing rates higher than 20%. For impervious, both transfer-in and transfer-out showed relatively low increasing rates values, all below 10% except for the transfer from woodland to impervious.

3.3. Carbon variations caused by land use change on surface area

The total amount of land use-type change caused carbon loss of −5907.44 $\times$ 10^4 t, with −3168.97 $\times$ 10^4 t from vegetation storage loss, and −2738.77 $\times$ 10^4 t from NPP and water. For vegetation carbon storage loss, Heilongjiang shows the highest carbon loss with the amount of −1168.92 $\times$ 10^4 t. Jilin, Shandong and Zhejiang show vegetation carbon loss with the amount vary between −850.32 $\times$ 10^4 t and −780.98 $\times$ 10^4 t. Some provinces have vegetation carbon storage increased, with Inner Mongolia the highest, of 1585.76 $\times$ 10^4 t, which is a little higher than in Tibet. Xinjiang shows the third highest increase,

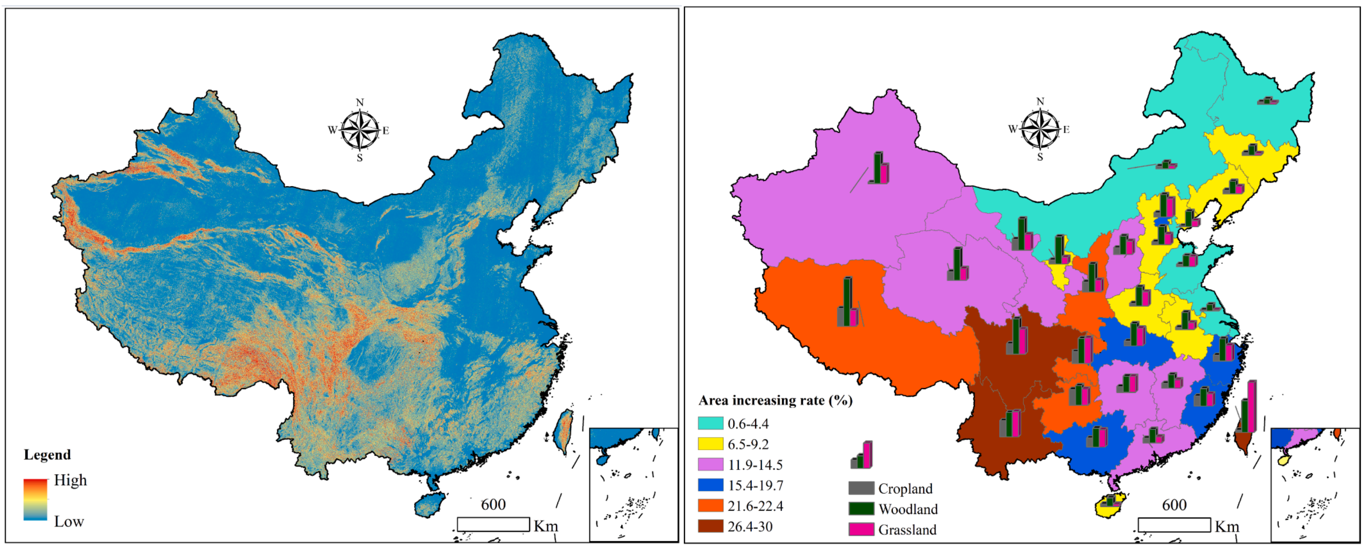


Fig. 3. (a) The increasing rate of land surface area compared with the planar area at grid scale (%), and (b) the surface area increasing rate at provincial scale and the increasing rate (%) for cropland, woodland, and grassland, respectively.

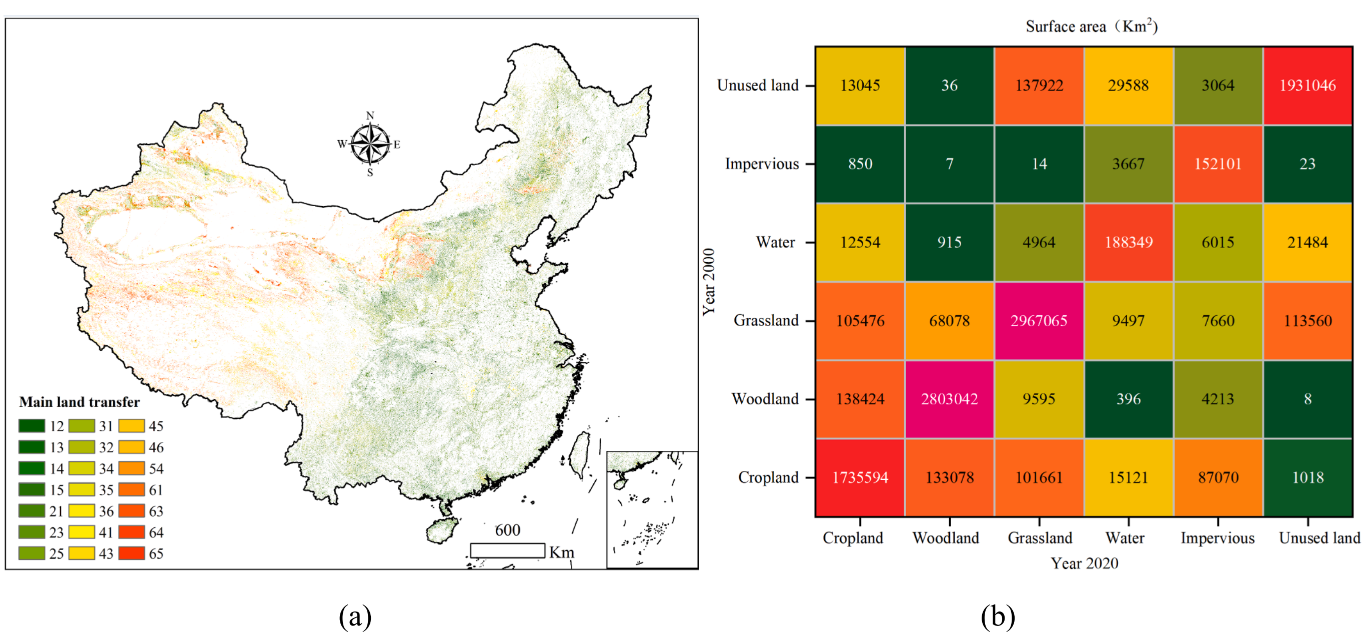


Fig. 4. (a) Spatial distribution of main land transfer between 2000 and 2020, and (b) the land transfer matrix between 2000 and 2020 on surface area. In Fig. 4(a), 1–6 represent cropland, woodland, grassland, water, impervious and unused land, respectively; 12 indicates land use change from cropland to woodland, land transfer type with area lower than 1000 km^2 are not shown.

Table 1
Increasing rate of land transfer on surface area compared with planar area (%).

2020 2000	Cropland	Woodland	Grassland	Water	Impervious	Unused land
Cropland	5.70	15.02	8.42	4.85	3.23	1.87
Woodland	14.78	23.70	26.59	13.69	10.16	19.97
Grassland	7.09	23.70	15.63	15.59	3.79	16.51
Water	2.55	16.40	25.38	4.93	2.19	20.10
Impervious	2.89	7.52	1.88	5.95	3.05	1.04
Unused land	1.39	38.84	13.61	8.14	2.07	7.94

with the amount of 1121.02 × 10^4 t. Gansu, Shaanxi, Sichuan and Ningxia also show increase trend, while the other provinces all lead to vegetation carbon storage loss induced by land use change. For total amount of NPP and carbon flux from water, Shandong and Jiangsu show the first and second highest decreasing amount, of −496.48 × 10^4 t and −415.13 × 10^4 t, respectively, and with Zhejiang and Henan follow behind, with the amount vary between −349.69 × 10^4 t and 324.33 × 10^4 t, respectively. Six provinces show increasing trend, with Tibet and Gansu the first and second highest, of 346.9 × 10^4 t and 322.18 × 10^4 t, Xinjiang, Inner Mongolia, Yunnan, and Shaanxi have the increase between 297 × 10^4 t and 63.85 × 10^4 t (Fig. 5).

Table 2 shows the contributions to total carbon changes from main land use-type change on the surface area. Generally, cropland and grassland change had caused −6997.36 × 10^4 t and −7998.35 × 10^4 t carbon loss, but luckily, woodland land increase brought 9241.95 × 10^4 t carbon increase. Provinces which had brought carbon increase usually locate in China's west, including Tibet, Inner Mongolia, Xinjiang, Gansu, Shanxi, Shaanxi, Sichuan and Ningxia. Woodland increase contributed the most for carbon increase in Tibet and Inner Mongolia; in Xinjiang, the cropland increase contributed more than twice of carbon increase than woodland, while, grassland showed obvious decrease and caused −1280.04 × 10^4 t carbon loss. For the other five provinces, the main carbon increases were also caused by woodland increase, especially for Sichuan, with the amount of 3510.66 × 10^4 t; while, it also showed high amount of carbon loss from both cropland and grassland decrease. Land use change in the left twenty-three provinces all caused carbon loss, high decreasing values were more found in the northeast, the east and the coastal region, such as Heilongjiang, Shandong, Zhejiang, Jilin. Jiangsu, and Guangdong Provinces, with the carbon loss amount vary from −1374.36 × 10^4 t to −809.09 × 10^4 t. In Shandong, Jiangsu and Guangdong, the cropland decrease contributed the most to carbon loss, woodland decrease in other of the above provinces show woodland increase contribute the most to carbon decrease. Due to land area differs much among provinces, per unit area carbon changes is also compared, Beijing, shanghai, Zhejiang and Guangxi show high carbon decrease intensity higher than 100 × 10^4 t/km^2, with Jiangsu, Tianjin, Shandong, Hainan and Jilin follows behind.

3.4. Carbon changes compared with the planar area

Fig. 6 (a) shows total carbon variations for each province on surface area compared with the amount on planar area. The surface area made provinces which loss carbon more and provinces which gained carbon stored more amount. On the surface area, Guangxi loss the highest amount of carbon than on the planar area, of −188 × 10^4 t, with Zhejiang, Jilin, Jiangxi, Hunan, Fujian and Guizhou followed behind, but the amount were much lower than Guangxi, changing between −66.74 × 10^4 t to −41.71 × 10^4 t. The surface area made Tibet to increase the most carbon, of 669.21 × 10^4 t. For the other seven provinces with carbon increase, the amounts were much lower than Tibet, with the second highest value in Shaanxi, of only 162.86 × 10^4 t. Gansu, Xinjiang, and Inner Mongolia all show carbon increase about 100 × 10^4 t. Considering provinces area difference, a further analysis was made to reveal the carbon change intensity on per unit area (Fig. 6(b)). It shows similar pattern with Fig. 6 (a), Guangxi and Zhejiang still showed the highest decrease values, of −7.98 t/km^2 and 6.47 t/km^2, respectively. For provinces with carbon increase, Shaanxi ranked the first, of 7.98 t/km^2, and with Tibet the second, of 5.56 t/km^2.

4. Discussion

China has set the goal of reaching carbon neutralisation by around 2060. Besides anthropogenic carbon emissions, land use change can also cause considerable amount of terrestrial ecosystem carbon loss (Lai et al., 2016; Arneth et al., 2017). Scientific evaluation of carbon loss from land use change is critical to achieve carbon emissions reduction. Our research makes several contributions. First, it establishes a carbon framework that incorporates NPP, vegetation carbon storage and inland water. Second, it considers a three-dimensional surface area, for both carbon examination and land use change analysis. Third, the difference among provinces is compared. This research can help for the understanding of land use change caused carbon loss, and can provide more accurate guidance for Chinese central and local governments to develop strategies to increase terrestrial ecosystem sequestration from aspect of land use control.

4.1. Surface area

Spatial area is the basic quantitative index for both carbon budget check and land use change analysis. Previous studies usually focused on planar area, which creates a great deal of bias in a country like China with diverse landforms and obvious elevation fluctuation (Yuan et al., 2018). This is especially the case in mountainous and hilly regions because of the greater elevation change. In calculation of surface area,

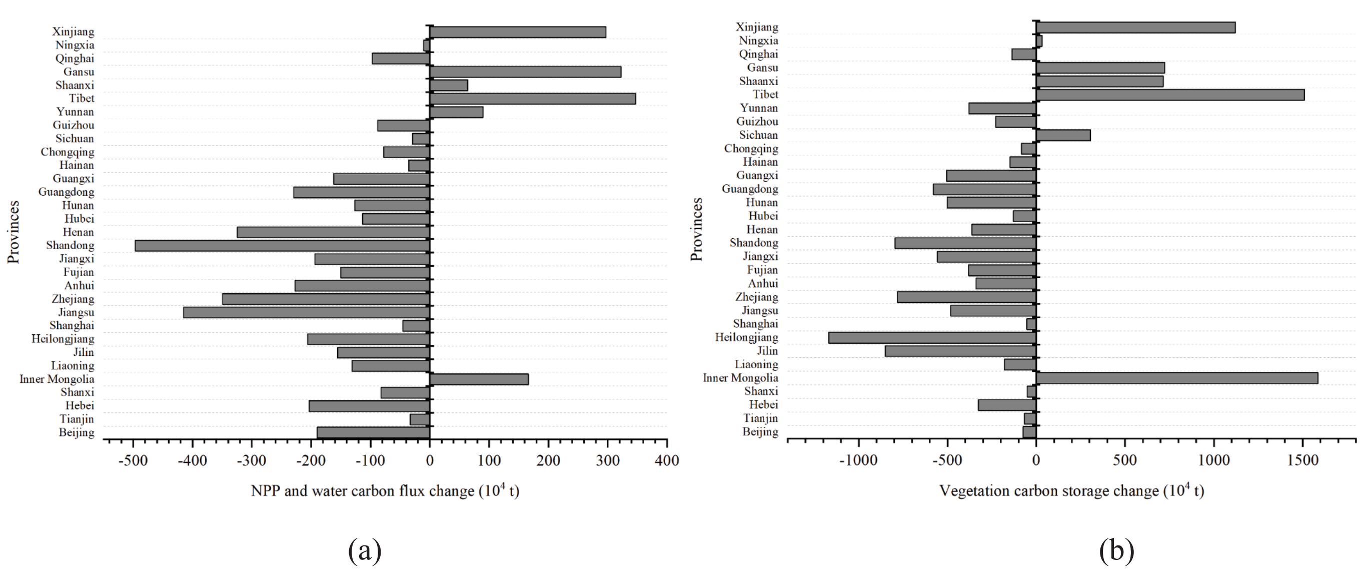
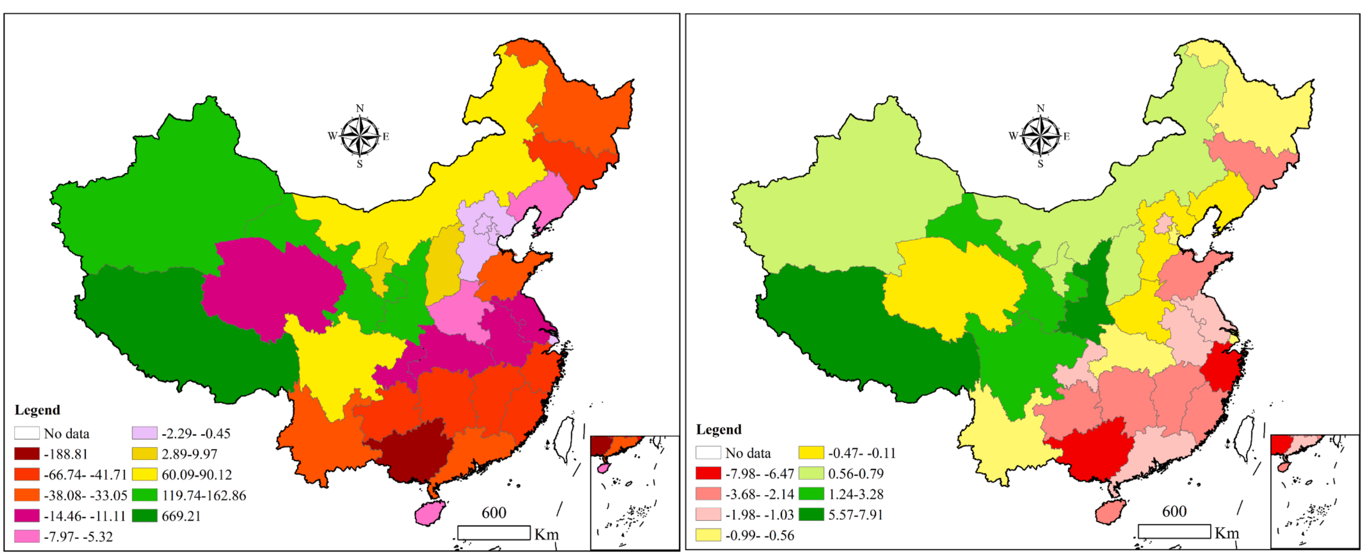


Fig. 5. (a) Land use-type change induced NPP and water carbon flux variations, and (b) vegetation carbon storage change. Both are calculated on surface area for 2000–2020.

Table 2
Total carbon changes caused by main land use-type changes in surface area (10^4 t).

Name	Cropland	Woodland	Grassland	Water	Total	Per unit (/km^2)
Beijing	−126.67	30.52	−20.00	−0.49	−116.64	−160.69
Tianjin	−99.96	−0.91	−2.30	2.48	−100.69	−86.74
Hebei	−811.16	816.34	−534.18	−1.09	−530.09	−28.21
Shanxi	−343.53	776.24	−561.78	−4.06	−133.13	−8.50
Inner Mongolia	−792.57	2215.45	315.45	13.83	1752.16	15.32
Liaoning	−284.02	215.37	−239.38	−1.38	−309.41	−21.15
Jilin	−10.39	−950.78	−43.02	−1.25	−1005.44	−52.61
Heilongjiang	57.23	−927.18	−487.69	−16.72	−1374.36	−30.37
Shanghai	−108.38	0.23	0.00	9.88	−98.27	−122.69
Jiangsu	−835.99	−63.94	−3.43	5.92	−897.44	−86.76
Zhejiang	−347.40	−783.71	0.87	−0.43	−1130.67	−109.54
Anhui	−623.49	79.15	−17.13	−5.22	−566.69	−40.42
Fujian	305.89	−827.96	−15.02	5.22	−531.87	−43.42
Jiangxi	406.87	−1130.22	−29.70	3.33	−749.72	−44.91
Shandong	−1231.58	186.29	−214.24	-32.35	−1291.88	−82.25
Henan	−888.76	394.16	−177.74	−13.71	−686.05	−41.43
Hubei	−629.83	594.24	−208.78	1.98	−242.39	−13.04
Hunan	711.09	−1348.75	−2.53	12.31	−627.88	−29.64
Guangdong	−1116.13	326.20	−30.39	11.23	−809.09	−45.10
Guangxi	220.12	−838.62	−48.63	−0.28	−667.41	−109.54
Hainan	221.19	−377.48	−27.85	0.55	−183.59	−53.74
Chongqing	−706.99	588.47	−30.53	−12.10	−161.15	−19.56
Sichuan	−1613.44	3510.66	−1603.06	−17.29	276.87	5.72
Guizhou	283.38	−111.67	−485.54	−3.56	−317.39	−18.02
Yunnan	1422.55	1057.30	−2761.63	−6.73	−288.51	−7.53
Tibet	54.98	1867.78	−35.25	−31.09	1856.42	15.45
Shaanxi	−1390.93	2130.72	43.89	−5.94	777.74	37.80
Gansu	−408.53	965.98	495.39	−7.97	1044.87	25.82
Qinghai	−153.05	40.44	−99.43	−22.99	−235.03	−3.28
Ningxia	−120.44	38.68	105.32	−2.54	21.02	4.06
Xinjiang	1962.58	768.95	−1280.04	-33.47	1418.02	8.65
China	−6997.36	9241.95	−7998.35	−153.93	−5907.69	−8.43



(a) (b)

Fig. 6. (a) The surface area caused total carbon changes compare with the planar area (10^4t) and (b) the carbon changes per unit area for each province (t/km^2).

both DEM resolution data and the used methods can affect the results. Previous studies found the regularity that the surface area will increase with the DEM resolution increase (Zeng et al., 2014). They usually used the DEM data with spatial resolution of 90 m and 30 m. The results showed that China's total land area can increase by 43×10^4 km^2 based on the 90 m DEM (Zhang and Li, 2014) and 82×10^4 km^2 based on the 30 m DEM (He et al., 2019). In our study, 12.5 m DEM data is used as basic data for surface area calculation. We explored a model to establish the relationships for different DEM resolutions and surface areas, through which we can make infinite attempts to approach the vector real surface. This approach provides guidance for surface area calculation without totally relying on real DEM data. With resolution improvements, we can update the basic DEM data used to make predictions for other DEM data and improve the accuracy of the predictions. Our results showed that China's total surface area increased by 133×10^4 km^2 compared with the planar area, which is consistent with previous studies' finding that the regularity of area increases with data resolution improvement. In this way, per unit land use change will cause more terrestrial ecosystem carbon change.

4.2. Terrestrial ecosystem carbon

For terrestrial ecosystem carbon sink/source, previous studies usually use NEP as an indicator. which is calculated by NPP subtract soil heterotrophic respiration (Rh). While, during the process of land use change, SOC variations need much longer time than vegetation carbon change (Chuai et al., 2012), that is the reason why we do not consider soil in this study, including both carbon stored in soil, and soil respirations. If SOC is considered, terrestrial ecosystem carbon change induced by land use change may be much higher, since the level of carbon stored to soil is much higher than vegetation (IPCC, 2000; Li et al., 2021). Precipitation in China shows an obvious decrease from the southeast to the northwest, which well determines the vegetation distribution. The southeast regions usually have high biomass level, leading to high NPP and vegetation carbon storage capacity. Per unit vegetated land use change will cause higher carbon loss, so, land use control, especially for built-up land expansion restriction should be strengthened. Inland China, especially for the west and northwest, vegetation biomass level is relatively low, grass and meadow are widely distributed, especially for Inner Mongolia and Tibet. Although per unit land use change may led to low carbon changes, since the ecological environment is very fragile, green land protection, such as desertification control, afforestation, ecological restoration is the most important task to the local government. If the ecological degradation continues to deteriorate, an ecosystem may be change from carbon sink to carbon source (Gatti et al., 2021). Luckily, China is turning green and obvious carbon sequestration increase have been found (Lu et al., 2018), with China's national ecological restoration projects made great contributions (Wang et al, 2021a). It has been reported that the forest stocking volume increased from 8.7 billion m^3 to 17.6 billion m^3, and the total forest area increased from 121.9 million ha to 220.5 million ha (SFA, 2018; SFGA, 2019). The carbon flux from inland water is driven by a combination of environmental alterations, climate conditions, physical and chemical properties of water body (Raymond et al., 2013; Paranaiba et al., 2018). It is reported that river and stream have high carbon flux capacity than lake and reservoirs, there was a substantial decrease in CO_2 emissions from Chinese inland water from the 1980s to 2010s, but the increasing was found the Tibetan Plateau inland waters due to increased terrestrial deliveries of organic carbon and expanded surface area (Ran et al., 2021). Although inland water can release carbon into the atmosphere, this does not mean water areas should be eliminated; they have various ecological functions such as supplying aquatic products, supplying aquatic plants, carrying out climate regulation, and carrying out biodiversity maintenance (Zhu et al., 2020).

4.3. Land use change and the influence to carbon

China is facing is the rapid urbanisation process, which has inevitably driven urban land expansion, this is the reason why the impervious land increased the most compared with other land use types. In this process, large areas of ecological land have been occupied, especially for China's east, with more built-up land expansion occurred in the plain area, the surface area increase has been relatively low, with unit area changes showing relatively lower influence than in mountainous and hilly areas. While, since vegetation biomass level is usually high in these regions, it will cause considerable amount of carbon loss. Besides, these regions usually have high population densities, intensive industries distribution, which makes lands carries high anthropogenic carbon emissions (Gao et al.,2016), the built-up land expansion can also induce much larger amount of carbon emissions than terrestrial ecosystem carbon loss (Chuai et al., 2015; Luo et al., 2021). Generally, resolving the contradiction between the high population and environment and controlling built-up land expansion are the most important tasks in these regions. Cropland decreased the most, it is an ecosystem highly disturbed by human activities. Different from other ecosystem, agricultural plants will be eliminated after crop harvesting, and finally will be burned, return to soil or be made as animal feed. In this way, the influence from land use may be called as theoretical carbon change. The biggest problem from cropland loss is the threats to food security, the Chinese government has noticed this problem and has delimited protective zone of basic farmland (Chen et al., 2021), which will also promote agricultural carbon sequestration. While, only land area protection is not enough, new land management strategies and technology development is a new research direction. For example, residue retention seems more critical for SOC sequestration (Xiao et al., 2021), and, appropriate agricultural management measures should be designed according to the local situation. Grassland degradation showed the largest area, similar results were also found in previous studies. For example, studies found grassland degradation to be widespread, especially in the semiarid and arid grasslands of the Tibetan Plateau (Dong et al., 2020; Liu et al., 2020; Peng et al., 2020). The reason for this is that the Tibetan Plateau has a high average elevation of about 4 km, harsh climatic conditions, and a fragile natural environment (Sun et al., 2018; Sun et al., 2020), and human activities have also had an obvious negative influence (Zhou et al., 2021). The degradation may also cause other ecological problems, such as problems with ecological services and functions (Huang et al., 2021), biodiversity (Hu et al., 2016), and the nutrient balance in soil and plants (Liu et al., 2018). Fortunately, China launched six key national ecological restoration projects, leading to an obvious increase in carbon sequestration (Liu et al., 2014; Lu et al., 2018; Wang et al., 2021b). This is one of the most important reasons for the significant carbon increase in our result. The above-mentioned areas are mostly mountainous and hilly, with a high increasing surface area, indicating that unit land use type change will have a much greater influence on carbon and that ecological protection has profound importance. Land transfer causes carbon changes, and the transfer-in and transfer-out of woodland contributes the most to these changes. Accordingly, hilly and mountain area is the core area where have high carbon sequestration increase potentiality.

4.4. Limitations and Uncertainties

The carbon framework did not consider soil due to the SOC changes need much longer time than vegetation. For carbon flux from inland water, the original data were compiled over several years to compose the 2010 s database, and we assumed that each year between 2000 and 2020 witnessed carbon flux intensity. Surface area is totally considered, while, there may some naked rock on high mountain areas without soil and vegetation, which may bring some bias to the analysed result. And, the accuracy of the real surface area still need enhancing with the topography data resolution improving.

CRediT authorship contribution statement

Jiqun Wen: Writing - Original draft preparation, Validation. **Xiaowei Chuai:** Writing-Original draft preparation, Supervision, Conceptualization, Writing - Reviewing and Editing. **Tianhui Zuo:** Data curation and Methodology. **Helen Huifen Cai:** Revision and Editing. **Limin Cai:** Editing. **Rongqin Zhao:** Methodology. **Yingyin Chen:** Figures revision

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research is supported by the Natural Science Foundation of Guangdong Province (2020A1515010730; 2023A1515010560), and the National Science Foundation of China (71921003).

References

Arneth, A., Sitch, S., Pongratz, J., Stocker, B.D., Ciais, P., Poulter, B., Bayer, A.D., Bondeau, A., Calle, L., Chini, L.P., Gasser, T., Fader, M., Friedlingstein, P., Kato, E., Li, W., Lindeskog, M., Nabel, J.E.M.S., Pugh, T.A.M., Robertson, E., Viovy, N., Yue, C., Zaehle, S., 2017. Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed. Nat. Geosci. 10 (2), 79–84.

Chen, Y., Yao, M., Zhao, Q., Chen, Z., Jiang, P., Li, M., Chen, D., 2021. Delineation of a basic farmland protection zone based on spatial connectivity and comprehensive quality evaluation: A case study of Changsha City, China. Land Use Policy 101, 105145.

Chuai, X.W., Huang, X.J., Wang, W.J., Zhang, M., Lai, L., Liao, Q.L., 2012. Spatial variability of soil organic carbon and related factors in Jiangsu province, China. Pedosphere 22, 404–414.

Chuai, X.W., Huang, X.J., Zhang, M., Zhao, R.Q., Lu, J.Y., 2015. Spatiotemporal changes of built-up land expansion and carbon emissions caused by the Chinese construction industry. Environ. Sci. Tech. 49 (21), 13021–13030.

Dong, S., Shang, Z., Gao, J., Boone, R.B., 2020. Enhancing sustainability of grassland ecosystems through ecological restoration and grazing management in an era of climate change on Qinghai-Tibetan Plateau. Agric. Ecosyst. Environ. 287, 106684.

Gao, C.C., Liu, Y.H., Jin, J., Wei, T.Y., Zhang, J.Y., Zhu, L.Z., 2016. Driving forces in energy-related carbon dioxide emissions in east and south coastal China: Commonality and variations. J. Clean. Prod. 135, 240–250.

Gatti, L.V., Basso, L.S., Miller, J.B., Gloor, M., Domingues, L.G., Cassol, H.L.G., Tejada, G., Aragao, L.E.O.C., Nobre, C., Peters, W., Marani, L., Arai, E., Sanches, A. H., Correa, S.M., Anderson, L., Von Randow, C., Correia, C.S.C., Crispim, S.P., Neves, R.A.L., 2021. Amazonia as a carbon source linked to deforestation and climate change. Nature 595 (7867), 388–393.

He, Q.S., Tan, S.K., Xie, P., Liu, Y.L., Li, J., 2019. Re-assessing vegetation carbon storage and emissions from land use change in China using surface area. Chin. Geogr. Sci. 29 (4), 601–613.

Hinge, G., Surampalli, R.Y., Goyal, M.K., 2018. Regional carbon fluxes from land-use conversion and land-use management in Northeast India. J. Hazard. Toxic Radioact. Waste 22 (4), 04018016.

Hong, C.P., Burney, J.A., Pongratz, J., Nabel, J.E.M.S., Mueller, N.D., Jackson, R.B., Davis, S.J., 2021. Global and regional drivers of land-use emissions in 1961–2017. Nature 589 (7843), 554–561.

Hu, G.Z., Liu, H.Y., Yin, Y., Song, Z.L., 2016. The role of legumes in plant community succession of degraded grasslands in Northern China. Land Degrad. Dev. 27, 366–372.

Huang, L., He, C.L., Wang, B., 2021. Study on the spatial changes concerning ecosystem services value in Lhasa River Basin, China. Environ. Sci. Pollut. Res. 29 (5), 7827–7843.

Intergovernmental Panel on Climate Change (IPCC), 2000. Land Use, Land-Use Change and Forestry, Cambridge, p. 375.

Jenness, J. 2013. DEM Surface Tools. Jenness Enterprises. Available at: http://www.jennessent.com/arcgis/surface_area.htm.

Lai, L., Huang, X.J., Yang, H., Chuai, X.W., Zhang, M., Zhong, T.Y., Chen, Z.G., Chen, Y., Wang, X., Thompson, J.R., 2016. Carbon emissions from land-use change and management in China between 1990 and 2010. Sci. Adv. 2 (11), e1601063.

Li, J.S., Guo, X.M., Chuai, X.W., Xie, F.J., Yang, F., Gao, R.Y., Ji, X.P., 2021. Reexamine China's terrestrial ecosystem carbon balance under land use-type and climate change. Land Use Policy 102, 105275.

Li, Y., Qiu, J.H., Li, Z., Li, Y.F., 2018. Assessment of blue carbon storage loss in coastal wetlands under rapid reclamation. Sustainability 10, 2818.

Liu, S., Zamanian, K., Schleuss, P., Zarebanadkouki, M., Kuzyakov, Y., 2018. Degradation of Tibetan grasslands: Consequences for carbon and nutrient cycles. Agric. Ecosyst. Environ. 252, 93–104.

Liu, M., Zhang, Z., Sun, J., Li, Y., Liu, Y.u., Liyew Berihun, M., Xu, M., Tsunekawa, A., Chen, Y., 2020. Restoration efficiency of short-term grazing exclusion is the highest at the stage shifting from light to moderate degradation at Zoige, Tibetan Plateau. Ecol. Indicat. 114, 106323.

Liu, W.H., Zhu, J.J., Jia, Q.Q., Zheng, X., Li, J.S., Lou, X.D., Hu, L.L., 2014. Carbon sequestration effects of shrublands in Three-North Shelterbelt Forest region, China. Chin. Geograph. Sci. 24 (4), 444–453.

Lu, F., Hu, H.F., Sun, W.J., Zhu, J.J., Liu, G.B., Zhou, W.M., Zhang, Q.F., Shi, P.L., Liu, X. P., Wu, X., 2018. Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. PNAS 115 (16), 4039–4044.

Luo, Y.L., Shen, J., Chen, A.F., Tao, Q., Li, Q.Q., White, P.J., Li, T.Q., Li, B., Chen, L., Li, H.X., Gao, X.S., Xu, Q., Wang, C.Q., 2021. Loss of organic carbon in suburban soil upon urbanization of Chengdu megacity, China. Sci. Total Environ. 785, 147209.

Paranaiba, J.R., Barros, N., Mendonça, R., Linkhorst, A., Isidorova, A., Roland, F., Almeida, R.M., Sobek, S., 2018. Spatially resolved measurements of CO_2 and CH_4 concentration and gas-exchange velocity highly influence carbon-emission estimates of reservoirs. Environ. Sci. Tech. 52 (2), 607–615.

Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S., Craft, C., Fourqurean, J.W., Kauffman, J.B., Marba, N., Megonigal, P., Pidgeon, E., Herr, D., Gordon, D., Baldera, A., 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLoS One 7 (9), e43542.

Peng, F., Xue, X., Li, C.Y., Lai, C.M., Sun, J., Tsubo, M., Tsunekawa, A., Wang, T., 2020. Plant community of alpine steppe shows stronger association with soil properties than alpine meadow alongside degradation. Sci. Total Environ. 733, 139048.

Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and world life zones. Nature 298 (5870), 156–159.

Ran, L.S., Butman, D.E., Battin, T.J., Yang, X.K., Tian, M.Y., Duvert, C., Hartmann, J., Geeraert, N., Liu, S.D., 2021. Substantial decrease in CO_2 emissions from Chinese inland waters due to global change. Nat. Commun. 12 (1), 1730.

Raymond, P.A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Durr, H., Meybeck, M., Ciais, P., Guth, P., 2013. Global carbon dioxide emissions from inland waters. Nature 503, 355–359, 7476.

SFA (State Forestry Administration). 2018. Evaluation project of forest ecosystem service in China. In China Forest Resources and Ecosystem Function—40 Years of Monitoring and Evaluation; China Forestry Publishing House: Beijing, China.

SFGA (State Forestry and Grassland Administration). 2019. China Forestry and Grassland Yearbook; China Forestry Publishing House: Beijing, China.

Sun, J., Zhou, T.C., Liu, M., Chen, Y.C., Shang, H., Zhu, L.P., Shedayi, A.A., Yu, H., Cheng, G.W., Liu, G.H., Xu, M., Deng, W., Fan, J.H., Lu, X.Y., Sha, Y.K., 2018. Linkages of the dynamics of glaciers and lakes with the climate elements over the Tibetan Plateau. Earth Sci. Rev. 185, 308–324.

Sun, J., Zhou, T.C., Liu, M., Chen, Y.C., Liu, G.H., Xu, M., Shi, P.L., Peng, F., Tsunekawa, A., Liu, Y., Wang, X.D., Dong, S.K., Zhang, Y.J., Li, Y.N., 2020. Water and heat availability are drivers of the aboveground plant carbon accumulation rate in alpine grasslands on the Tibetan Plateau. Glob. Ecol. Biogeogr. 29 (1), 50–64.

Tian, H., Melillo, J., Lu, C., 2011. China's terrestrial carbon balance: Contributions from multiple global change factors. Global Biogeochem. Cycles 25, GB1007.

Wang, H., He, M.Y., Ran, N., Xie, D., Wang, Q., Teng, M.J., Wang, P.C., 2021a. China's key forestry ecological development programs: Implementation, environmental impact and challenges. Forests 12 (1), 101.

Wang, J., Liu, Y., Yang, D.X., 2021b. To explore the distribution of carbon sink in China: From atmospheric CO_2 measurements. Chin. Sci. Bull. Chin. 66 (7), 709–710.

Xiao, L.G., Kuhn, N.J., Zhao, R.Q., Cao, L.H., 2021. Net effects of conservation agriculture principles on sustainable land use: A synthesis. Glob. Chang. Biol. 27 (24), 6321–6330.

Xu, L., Yu, G.R., He, N.P., 2019. Increased soil organic carbon storage in Chinese terrestrial ecosystems from the 1980s to the 2010s. J. Geog. Sci. 29, 49–66.

Yuan, Y., Shi, X.Y., Zhao, Z.Q., 2018. Land use types and geomorphic settings reflected in soil organic carbon distribution at the scale of watershed. Sustainability 10 (10), 3490.

Zeng, Z., Yang, B.Y., Fan, J.R., Liu, F., Jing, Y.Q., 2014. Calculating landscape surface area based on the geology significance of the surface roughness. Remote Sens. Technol. Appl. 29 (5), 846–852 in Chinese.

Zhang, M., Huang, X.J., Chuai, X.W., Yang, H., Lai, L., Tan, J.Z., 2015. Impact of land use type conversion on carbon storage in terrestrial ecosystems of China: A spatial-temporal perspective. Sci. Rep. 5, 10233.

Zhang, W., Li, A.N., 2014. Study on calculating surface area in China based on SRTM DEM data. Geogr. Geo-inform. Sci. 30, 51–55 (in Chinese).

Zhang, L., Ren, X.L., Wang, J.B., He, H.L., Wang, S.Q., Wang, M.M., Piao, S.L., Yan, H., Ju, W.M., Gu, F.X., Zhou, L., Niu, Z.G., Ge, R., Li, Y.Y., Lv, Y., Yan, H.M., Huang, M., Yu, G.R., 2019. Interannual variability of terrestrial net ecosystem productivity over China: Regional contributions and climate attribution. Environ. Res. Lett. 14, 014003.

Zhou, T.C., Zong, N., Sun, J., Hou, G., Shi, P.L., 2021. Plant nitrogen concentration is more sensitive in response to degradation than phosphorus concentration in alpine meadow. Ecol. Eng. 169, 106323.

Zhu, J.F., Zhou, Y., Wang, S.X., Wang, L.T., Liu, W.L., Li, H.T., Mei, J.J., 2020. Ecological function evaluation and zoning of Baiyangdian wetlands. Acta Ecol. Sin. 40 (02), 459–472 (in Chinese).