Journal of Animal & Plant Sciences, 31(6): 2021, Page: 1598-1609
ISSN (print): 1018-7081; ISSN (online): 2309-8694
https://doi.org/10.36899/JAPS.2021.6.0364

THE CONTRIBUTION OF LAND USE AND LAND COVER ON CARBON STORAGE IN THE NORTH TIBET PLATEAU, CHINA

Z. Xu[1*], Z. Zhao[1] and C. Lu[1]

[1]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A Datun Road, Chaoyang District, Beijing 100101, PR China
[*]Corresponding author's email: xuzr@igsnrr.ac.cn

ABSTRACT

It's important for understanding the impact of land use/ land cover (LULC) on carbon storage to optimize land use and ecosystem service payment scheme. Integrated the InVEST model with statistical analysis, carbon storage change in the Northern Tibetan Plateau (NTP), China from 2001 to 2010 was estimated, and the contribution of LULC to carbon storage change was assessed from both aspects of land cover conversion and carbon density change. Our conclusions showed that: carbon storage increased by 78.4 million tons, it's stable in the southeast and middle, and an increase in the northwest of NTP. Land conversion was characterized by the decrease with the low carbon density land type, and increase with the high carbon density land type, dominated by net conversion of sparse vegetation into grassland. The carbon density of the NTP increased overall, especially that of grassland. The contribution of LULC to carbon storage increase reached about 80%, with the land conversion to carbon storage increase being 43.6%, while that of land carbon density to carbon storage increase being 37.1%. As a dominated land cover, policy-makers should focus on maintaining area of grassland and reducing grazing intensity, and a subsidized scheme to grassland conservation should be built based on the carbon sequestration capacity of NTP.

Key words: carbon storage and sequestration; land use/ land cover (LULC); carbon density; land conversion; InVEST model; Northern Tibetan Plateau

Published first online March 31, 2021 Published final Nov. 20, 2021.

INTRODUCTION

Carbon storage is a measure of an ecosystem's capacity to retain carbon while carbon sequestration relates to mitigation of anthropogenic carbon emissions (Triviño *et al*., 2015). Carbon is stored in soil, vegetation and atmosphere, with soil organic carbon (SOC) containing about 1400–1500 gigaton (Gt), terrestrial vegetation 500–600 Gt, and the atmosphere 750 Gt, globally (Eswaran *et al*., 1993; Jin *et al*., 2000; Chen *et al*., 2019). Generally, ecosystem carbon pools include aboveground biomass (AGB), belowground biomass (BGB), dead biomass (dead standing, fallen biomass and litter, DB) and SOC (Law *et al*., 2015). Carbon storage varied among different ecosystem in different regions. For examples, carbon storage in boreal forest varied 200-310 t C.ha^{-1} in Canada (Laganière, *et al*., 2015). The SOC in China reached 92.4 Gt, with an average carbon density of 105.3 t.ha^{-1} (Wang *et al*., 2000; Balasubramanian *et al*., 2020). In the arid environment in western rangelands of Iran, SOC had an increasing trend with increasing vegetation cover (Yazdanshenas *et al*., 2018), but a decreasing trend with increasing elevation (Nie *et al*., 2019). The impacts of temperature on SOC are complicated. SOC density will increase in the global warming scenario across the Three Rivers Source Region (TRSR) shrubland (Nie *et al*., 2019). However, in grasslands of Yunnan province in southwestern China, SOC (0-100 cm) increased as mean annual temperature decreased and as mean annual precipitation increased. The mean SOC varied from 76 t ha^{-1} for temperate desert to 173 t ha^{-1} for alpine meadow. Brown earth soils (Luvisols) had the highest carbon density with 195 t ha^{-1}, while chernozem soils had the lowest with 68 t ha^{-1}. Grazing/cutting regimes significantly affected SOC with lowest value (79 t ha^{-1}) of cutting grass, seasonal grazing (114 t ha^{-1}), year-long grazing (122 t ha^{-1}), while the highest value in the ungrazed areas (167 t ha^{-1}) (Balasubramanian *et al*., 2020).

Knowledges of the effects of LULC on carbon storage are critical to adaptation global climate change (Lawler *et al*., 2014). Land use can affect biogeochemical cycles in relation to primary production, material recycling, as well as carbon storage and carbon sequestration (Haberl *et al*., 2007). LULC influence on the accumulation and decomposition of litter and the distribution of soil organic matter in terrestrial ecosystems (Fu *et al*., 2012). High-intensity land use such as overgrazing can lead to grassland degradation and soil erosion (Valentin *et al*., 2008; Tang *et al*., 2020) as well as a decline in carbon storage. The impacts of LULC on SOC have been assessed using the Intergovernmental Panel on Climate Change (IPCC) carbon budget approach and land conversion matrix (Liu *et al*., 2004). The impacts of deforestation, afforestation and forest land conversion on carbon storage in central Asia were analyzed between 1975 and 2005 (Chen *et al*., 2015). Contributions of land use history to carbon accumulation in U.S. forests (Caspersen, 2000), "Grain for Green" driven LULC and carbon sequestration on the Loess Plateau, China (Deng *et al*., 2014), and impacts of grazing on SOC of grasslands in Inner Mongolia, China (Wang and Chen, 1998) have also been explored. Remote sensing and Geographic Information Systems (GIS) provide effective tools to monitor carbon storage change, especially vegetation biomass (Gonzalez *et al*., 2010; Xu *et al*., 2012). Dong *et al*. (2003) analyzed the relationship between the Normalized Difference Vegetation Index (NDVI) and biomass. Recently, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model was applied to modelling carbon storage. InVEST model revealed that conversion of natural vegetation covers (forest) into human-induced land cover (crop) resulted in a decrease of the carbon storage in the western coast of central Mexico (Hernández-Guzmán *et al*., 2019). The decline of carbon storage from 2015 to 2030 will range from 16.40 Tg to 24.22 Tg under different scenarios in urban area of Hubei Province, central China, and the scenario featuring steady climate conditions, low population growth, moderate economic growth and high-quality urbanization will better maintain carbon storage (Yang *et al*., 2020).

Estimating carbon storage is not just a question of multiplying a static carbon density by the land area because of factors introduced by vegetation and soil C cycling processes and shifting land uses (Dixon *et al*., 1994). LULC can be classified into land cover conversion and land quality modification (GLP, 2005). More studies were focused on the impact of land cover conversion on carbon storage than that of land quality modification on carbon storage (Zhang *et al*., 2015a). Currently, InVEST model just assumes that carbon density of land cover are not gaining or losing over time, and only change in carbon storage due to land cover conversion (Hernández-Guzmán *et al*., 2019) was considered. In order to improve the methodology to assess the contribution of LULC on carbon storage more scientifically, we presented a method to explore the contribution of LULC to carbon storage change in both aspects, i.e., land conversion and land modification (namely carbon density change) in the Northern Tibetan Plateau (NTP) during 2001-2010, based on the InVEST model (Sharp *et al*., 2018) in this study.

MATERIALS AND METHODS

Study area: The Northern Tibetan Plateau (NTP) of China located in the hinterland of the Tibetan plateau (Figure 1). The NTP covers 371,000 km^2 with an average altitude of 4000 meters above the sea level. It is an important ecological barrier region. It protects south Asia from the Siberian cold fronts in winter. It provides freshwater to eastern China and Southeast Asia as it is the river header of the Salween river and Yarlung Zangbo river. It is also an important habitat for species of wildlife, including some endemic to the Tibetan plateau. However, the NTP is a typically fragile alpine grassland characterized by a scarcity of oxygen, very cold, and low primary productivity. It is sensitive to global warming, which lead to more melting of permafrost and permanent glaciers in warmer conditions (Zhang *et al*., 2015b). Furthermore, increasing pressure from human activities, like over-grazing, has resulted in grassland degradation (Shao and Cai, 2008). To restore degraded ecosystems, governments have implemented some ecosystem restoration programmers, such as the establishment of Chang tang and Siling Co nature reserves since 2000, and ecological protected areas since 2008 (Xu and Zou, 2020), which leading to LULC in terms of both land conversion and land modification, and driving carbon storage change.

The carbon storages were modelled with carbon densities and areas of the 17 land cover types by the InVEST. For mapping conveniently and clearly, the 17 land covers were integrated into five land groups: forest (evergreen needle leaf forest, evergreen broadleaf forest, deciduous needle leaf forest, deciduous broadleaf forest, and mixed forest); Grasslands (woody savannas, savannas, and grasslands); Croplands (croplands, cropland/natural vegetation mosaic, urban and built-up[1]); Wetlands (water, permanent wetlands, snow and ice); and sparse vegetation (barren or Sparse vegetation, and shrublands). Carbon density of the five land groups were calculated as the weighted-sum of carbon densities of the 17 land covers, with the area of the land covers being the weights.

Figure 1. location of the Northern Tibetan Plateau (NTP) in China

[1] Urban and built-up was integrated into the cropland group for: 1) the urban and built-up always distributed near to the cropland and land conversion between the two kind of land cover was frequently. 2) the size of urban and built-up area is small, being less than 5% of the cropland.

Data sources

1) Land cover: the land cover data for the NTP in 2001 and 2010 were derived from the Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1), at a spatial resolution of 500 meters. **2) NDVI**: MODND1M is the monthly NDVI product within China's boundary captured by the Terra satellite, with a spatial resolution of 1 km. Annual NDVI values in 2000, 2010 were acquired by averaging monthly NDVI during the growing season (from June to October). It was accessed from the Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). **3) Carbon density in 2001**: a grid of biomass carbon density was derived from the Carbon Dioxide Information Analysis Center (CDIAC) (Ruesch and Gibbs, 2008), with a spatial resolution of 1 km. The carbon density of SOC at a depth of 0–30 cm was derived from the Joint Research Centre (JRC) (Carré *et al*., 2010), also in a 1 km grid. The DB and the ratio of root to stem were referenced from the 2006 IPCC guidelines for national greenhouse gas inventories (IPCC, 2006). All the 1 km data was resampled into 500m in the ArcGIS 10.2 (Esri Inc, New York, USA).

Methods

Extrapolation carbon density with regression function: The average carbon density of biomass (aggregation of AGB and BGB), SOC and NDVI at land cover scale in 2001 was retrieved by spatial analysis in ArcGIS10.2. With statistical analysis in SPSS 16.0 (IBM, USA), the annual NDVI, biomass and SOC of various land covers were distributed normally. The linear correlations between NDVI and biomass, NDVI and SOC were significant at the 95% level according to significance tests on correlation coefficients (α = 0.05), respectively. A linear regression function of BIOMASS-NDVI and a logarithmic regression function of SOC-NDVI in NTP in 2001 were built (Figure 2). Both the regression functions were tested through the analysis of variance (ANOVA) and T-tests on regression coefficients ($p < 0.01$). The carbon density of biomass and SOC of various land covers in 2010 was modeled by extending the regression functions built with data of 2001, assumed that the relationship between the NDVI-biomass and NDVI-SOC was stable during the period of 2001-2010. The DB pool was assumed to be unchanged because of its relative stability over time (Zhang, 2013).

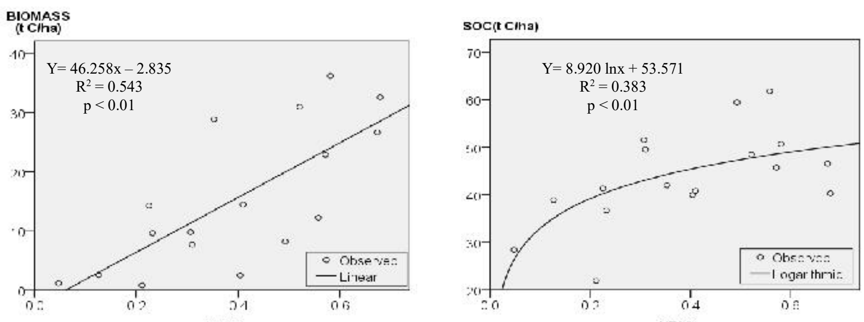


Figure 2. Regression functions of BIOMASS-NDVI and SOC-NDVI in NTP in 2001

Calculation of carbon storage: The carbon density of AGB, BGB, SOC and DB as well as the land cover data were entered into the InVEST carbon model to calculate ecosystem carbon storage in 2000, 2010. The formula of the carbon storage calculation in InVEST is shown as follows:

$$C = \sum_{i=1}^{n} Ai * Di \quad (1)$$

$$Di = Di_{AGB} + Di_{BGB} + Di_{DB} + Di_{SOC} \quad (2)$$

Where C is carbon storage, Ai is the area of land cover i (ha), Di is the carbon density of land cover i (t C.ha^{-1}), Di_{AGB} is the carbon density of AGB of land cover i, Di_{BGB} is the carbon density of BGB, Di_{DB} is the carbon density of DB, and Di_{soc} is the carbon density of SOC.

Contribution of LULC to carbon storage change: The procedure to assess the contribution of land conversion and carbon density change to carbon storage is shown as follows:

a) The carbon storage change (△*C*): can be denoted by the difference between the carbon storage at the beginning year (2001) and end year (2010) of the period, considering both LULC aspects, i.e., the land conversion and carbon density change.

$$\Delta C = \sum_{i=1}^{n} (A_{i2}D_{i2} - A_{i1}D_{i1}) \quad (3)$$

Where A_{i1}, A_{i2} is the area of land cover i in 2001 and 2010, and D_{i1}, D_{i2} is the carbon density of land cover i in 2001 and 2010.

b) Land conversion contribution to carbon storage: It is assumed that the carbon density of land covers keep invariant, only the land conversion contributes to the carbon storage change. In this situation, carbon storage change originating from the land conversion is denoted by ΔC_l:

$$\Delta C_l = \sum_{i=1}^{n}(A_{i2} - A_{i1}) D_{i1} \quad (4)$$

c) Land carbon density change contribution to carbon storage: It is assumed that there is no land conversion among land covers, only the carbon density change of land covers contribute to the carbon storage change. In this situation, carbon storage change originating from carbon density change is denoted by ΔC_d:

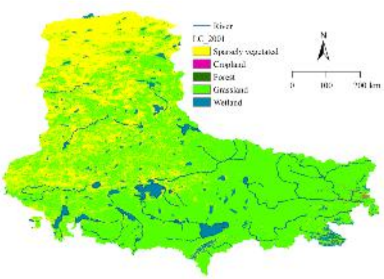
$$\Delta C_d = \sum_{i=1}^{n} A_{i1} (D_{i2} - D_{i1}) \quad (5)$$

d) The contribution ratio of LULC to carbon storage change: is estimated by the contribution ratio of land conversion (R_l) and that of carbon density change of land covers (R_d):

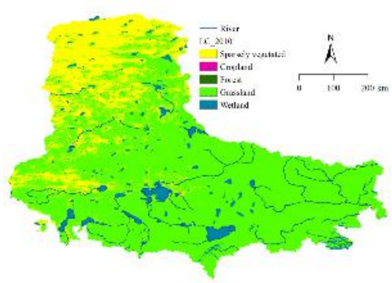
$$R_l = \Delta C_l / \Delta C \, ^* \, 100\%$$
$$R_d = \Delta C_d / \Delta C \, ^* \, 100\% \quad (6)$$

RESULTS

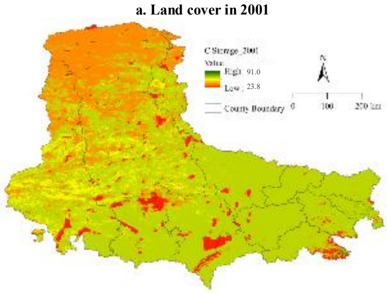
Carbon storage change: The carbon storage in the NTP was 2164.19 million tons (Mt) in 2001 and 2242.59 Mt in 2010. An additional 78.4 Mt of carbon was stored, with an annually growth rate of 0.36%. There was a distribution gradient of land covers, with forest, grassland, and sparse vegetation distributing from southeast to northwest along the decline trend of precipitation and temperature in NTP (Figure 3a, b). Coinciding with the land cover pattern, carbon storage declined along the gradient from southeast to northwest (Figure 3c, d). The change during 2001–2010 showed that carbon storage stabilized in the southeast and the center, and increased in the northwest and southeast of the NTP. Carbon storage increase in the northwestern NTP was mainly due to the establishment of Chang tang Nature Reserve, and carbon storage increases in the Nyainqêntanglha Range in the southeastern NTP was mainly because of water and soil conservation areas (Figure 3e).



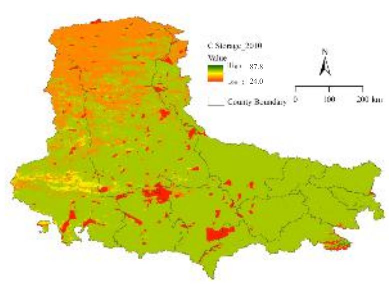
a. Land cover in 2001



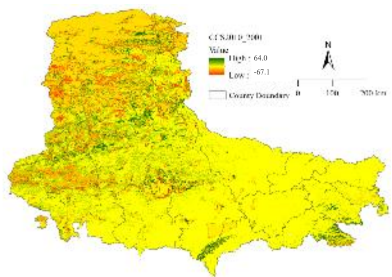
b. Land cover in 2010



c. Carbon storage in 2001



d. Carbon storage in 2010



e. Carbon storage change in the period of 2001-2010

Figure 3. Spatial pattern of carbon storage in NTP in 2001, 2010, respectively (t C.ha^{-1})

Commented [XU1]: Please pay attention to the note of legend in the picture, the right value is 64.0- -67.1.

Contribution of land conversion to carbon storage

Carbon storage variations with land groups: As an arid alpine area, the NTP was dominated by grassland in terms of both land cover area and carbon storage. Grassland is the biggest carbon pool and the major contributor to carbon storage change in NTP. Both area and carbon density of grassland group was increased from 2001 to 2010. The proportion of grassland group accounted for 66.3% and 74.5% of the total area of NTP in 2001 and 2010, respectively. The carbon density of grassland group increased from 65.3 t C.ha^{-1} in 2001 to 67.4 t C.ha^{-1} in 2010. Carbon storage in grassland group increased from 1607.85 Mt in 2001 to 1864.74 Mt in 2010, and the proportion of carbon storage of grassland group in total NTP increased from 74.3% in 2001 to 83.2% in 2010. The area proportion of sparse vegetation group in total NTP decreased from 28.9% in 2001 to 20.9% in 2010, and the carbon density of sparse vegetation group also decreased from 47.1 to 42.8 t C.ha^{-1}. As a result, the proportion of carbon storage of sparse vegetation group in total NTP decreased distinctly from 23.3% to 14.8%. Carbon storage in wetlands group declined slightly from 42.05 Mt in 2001 to 39.84 Mt in 2010. The area proportion of wetlands group was about 4.4%, contributing only 1.9% to total carbon storage. The proportion both of area and carbon storage of forest group in total NTP was stable by 0.2% during the period. Carbon storage of croplands group was almost negligible, with the proportion of carbon storage of cropland group in total NTP decreased from 0.21% to 0.04% during 2001-2010 (Table 1).

Table 1. Carbon storage by land groups in NTP in 2001, 2010, respectively (Unit: area, km^2; C density, t C.ha^{-1}; carbon storage, Mt C).

Land group	2001			2010		
	Area/ percent	C density	C Storage/ percent	Area/ percent	C density	C Storage/ percent
Forest	581/0.2	79.6	4.62/0.2	595/0.2	80.9	4.81/0.2
Grasslands	246167/66.3	65.3	1607.85/74.3	276587/74.5	67.4	1864.74/83.2
Croplands	620/0.2	73.3	4.54/0.2	120/0.0	77.9	0.93/0.0
Wetlands	16548/4.5	25.4	42.05/1.9	16127/4.3	24.7	39.84/1.8
Sparse vegetation	107137/28.9	47.1	505.13/23.3	77624/20.9	42.8	332.27/14.8
Total	**371053/100**	**58.3**	**2164.19/100**	**371053/100**	**60.4**	**2242.59/100**

Contribution of land conversion to carbon storage change: Assuming that the carbon density of various land covers was unchanged during 2001–2010, carbon storage was increased by 34.14 Mt in NTP (Figure 4), with carbon storage of 2164.19 Mt and 2198.34 Mt in 2001 and 2010, respectively. In this situation, only land conversion contributed to the carbon storage increase. Considering carbon storage increase of 78.4 Mt based on both land conversion and carbon density change, only the contribution of land conversion to the carbon storage change was 43.6% (Table 4). This was because land conversions were dominated by the land cover with low carbon density conversion into that of a relatively high carbon density, which resulted in improving carbon storage capacity. Specifically, the land conversions were dominated by the sparse vegetation conversion into grassland in the NTP. According to the land conversion matrix, the area of grassland increased 12.4%, with the

28,860 km^2 of net conversion from sparse vegetation into grassland, and the 1089 km^2 of net conversion from wetland into grassland (Table 2). For example, if the carbon density of grassland and sparse vegetation remained invariant during the period (i.e., carbon density of grassland and sparse vegetation in 2010 was calculated as 65.3 and 47.1 t C.ha^{-1}, respectively, as same as in 2001), only the net conversion from sparse vegetation into grassland could result in an increase of 52.52 Mt of carbon storage.

Table 2. Land conversion matrix in NTP in 2001–2010 (area/km^2).

2010 / 2001	Wetlands	Forest	Sparse vegetation	Grasslands	Croplands	Total area in 2001
Wetlands	14267	102	179	2001	0	16548
Forest	57	304	30	189	0	581
Sparse vegetation	864	44	61068	45156	5	107137
Grasslands	912	143	16296	228716	100	246167
Croplands	27	2	50	525	15	620
Total area in 2010	16127	595	77624	276587	120	371053

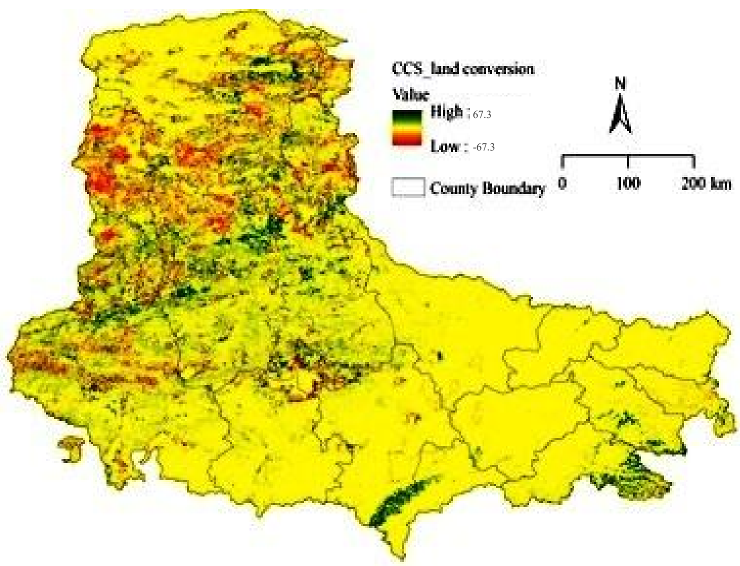


Figure 4. Change in carbon storage derived from land conversion in NTP during 2001–2010 (t C.ha^{-1})

Commented [XU2]: Please pay attention to the note of legend in the picture, the right value is 67.3- -67.3.

Contribution of carbon density change to carbon storage

Carbon density of various land covers: In terms of land groups, the carbon density of grassland, forest and cropland increased, while that of sparse vegetation and wetlands decreased during the period. Carbon density of AGB, BGB, and SOC across various land groups changed markedly. Carbon density of grasslands group was increased by 2.1 t C.ha^{-1}, with that of AGB increased by 0.5 t C.ha^{-1}, and BGB increased by 1.6 t C.ha^{-1}. Carbon density of forest group increased by 1.3 t C.ha^{-1}, with that of SOC increased by 7.0 t C.ha^{-1}, while that of AGB declined by 2.5 t C.ha^{-1} and BGB declined by 3.2 t C.ha^{-1}. Carbon density of croplands group increased by 4.6 t C.ha^{-1}, with an increase in AGB and BGB of 10.6 t C.ha^{-1}, although that of SOC declined by 6 t C.ha^{-1}. Carbon density of sparse vegetation group declined by 4.3 t C.ha^{-1}, with a decrease of 1.3 t C.ha^{-1} in biomass and 3.0 t C.ha^{-1} in SOC. Carbon density of wetlands group was decreased slightly by 0.7 t C.ha^{-1}. In the land cover scale, besides the mixed forest, carbon density of other forest cover decreased. Carbon density of grassland cover was increased distinctly. Carbon density of croplands and croplands mosaic increased, while that of urban and built-up decrease slightly (Table 3).

Table 3 Carbon density of different carbon pools by land cover and land group in NTP in 2001, 2010, respectively (Unit: area, km2; carbon density, t C.ha^{-1}).

	2001						2010					
Land cover/land group	Area	D_{AGB}	D_{BGB}	D_{SOC}	D_{DB}	Aggregation	Area	D_{AGB}	D_{BGB}	D_{SOC}	D_{DB}	Aggregation
Evergreen Needleleaf forest	71	24.0	7.0	48.5	5.2	84.6	106	22.0	6.4	48.5	5.2	82.1
Evergreen Broadleaf forest	38	29.5	6.8	50.7	4.1	91.0	4	26.8	6.2	50.7	4.1	87.7
Deciduous Needleleaf forest	12	22.4	6.5	42.0	2.8	73.7	18	19.3	5.6	42.1	2.8	69.8
Deciduous Broadleaf forest	6	21.7	5.0	46.6	2.1	75.3	8	19.9	4.6	47.1	2.1	73.7
Mixed forest	454	12.5	20.1	40.3	5.2	78.1	459	10.2	16.3	49.5	5.2	81.1
Forest group	**581**	**15.3**	**17.2**	**42.1**	**5.0**	**79.6**	**595**	**12.8**	**14.0**	**49.1**	**5.1**	**80.9**
Woody savannas	106	3.8	10.7	40.8	3.0	58.3	37	4.2	11.7	45.5	3.0	64.4
Savannas	25	2.5	7.1	36.8	4.0	50.4	7	3.8	10.8	43.1	4.0	61.7
Grasslands	246036	2.6	7.2	51.5	4.0	65.3	276543	3.1	8.8	51.5	4.0	67.4
Grasslands group	**246167**	**2.6**	**7.2**	**51.5**	**4.0**	**65.3**	**276587**	**3.1**	**8.8**	**51.5**	**4.0**	**67.4**
Croplands	471	3.2	9.0	61.8	1.0	75.1	111	6.1	17.2	55.7	1.0	80.0
Cropland/Natural vegetation mosaic	143	5.6	2.6	59.4	1.0	68.6	2	8.6	4.1	59.4	1.0	73.1
Urban and built-up	6	1.7	0.8	40.0	1.0	43.5	6	1.5	0.7	40.0	1.0	43.2
Croplands group	**620**	**3.8**	**7.5**	**61.0**	**1.0**	**73.3**	**120**	**5.9**	**16.0**	**55.0**	**1.0**	**77.9**
Water	11926	0.6	0.3	22.0	1.0	23.8	13050	0.7	0.3	22.0	1.0	24.0
Permanent wetlands	12	2.0	5.7	49.5	3.0	60.3	46	1.7	4.8	49.5	3.0	59.1
Snow and ice	4610	0.8	0.4	28.4	0.0	29.6	3032	0.8	0.4	26.1	0.0	27.3
Wetlands group	**16548**	**0.6**	**0.3**	**23.8**	**0.7**	**25.4**	**16127**	**0.7**	**0.4**	**22.8**	**0.8**	**24.7**
Closed shrublands	7	8.8	14.1	45.7	4.0	72.7	2	8.6	13.8	48.2	4.0	74.7
Open shrublands	31020	5.5	8.8	41.3	3.0	58.6	9969	4.9	7.8	39.4	3.0	55.0
Barren or sparsely vegetated	76109	1.7	0.8	38.9	1.0	42.5	67653	2.6	1.2	36.2	1.0	41.0
Sparse vegetation group	**107137**	**2.8**	**3.1**	**39.6**	**1.6**	**47.1**	**77624**	**2.9**	**2.1**	**36.6**	**1.3**	**42.8**
Total	**371053**	**2.6**	**5.7**	**46.8**	**3.2**	**58.3**	**371053**	**3.0**	**7.0**	**47.2**	**3.3**	**60.4**

Note: Di_{AGB} (t C.ha^{-1}) is the carbon density of AGB of land cover i, Di_{BGB} is the carbon density of BGB, Di_{DB} is the carbon density of DB, and Di_{soc} is the carbon density of SOC.

Contribution of carbon density change to carbon storage: If we assumed that there was no land conversion among land covers, carbon storage increased by 29.10 Mt in NTP during 2001–2010 (Figure 5). In this situation, only the land covers' carbon density change contributes to the carbon storage change. Considering carbon storage increase of 78.4 Mt based on both land conversion and carbon density change, the contribution of carbon density change to the carbon storage increase was 37.1% (Table 4).

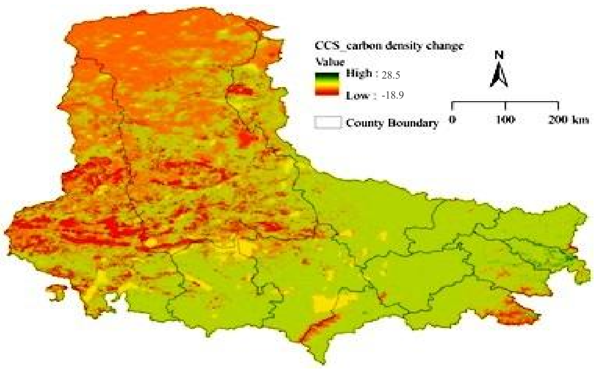


Figure 5. Change in carbon storage derived from carbon density change in NTP during 2001–2010 (t C.ha^{-1})

Table 4. change of carbon storage (CCS) and its contributor in NTP during 2001–2010 (Unit: Mt C)

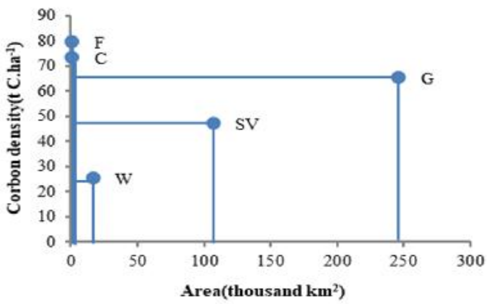
Contributor	CCS		CCS_L		CCS_D		CCS_ELSE
	C storage	ΔC	C storage	ΔC_l	C storage	ΔC_d	ΔC_e
2001	2164.19	-	2164.19	-	2164.19	-	-
2010	2242.59	78.40	2198.34	34.14	2193.29	29.10	15.16
Proportion	100.0%		43.6%		37.1%		19.3%

Note: $\triangle C$, carbon storage change during study period considering both land conversion and carbon density change; $\triangle C_l$, carbon storage change due to land conversion only; $\triangle C_d$, carbon storage change due to carbon density change only.

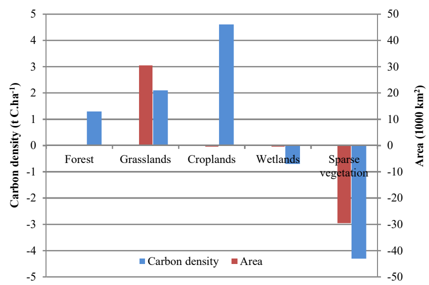
DISCUSSION

Carbon storage and the area and carbon density in land group scale: The grassland group was the major contributor to the increase of carbon storage in NTP in 2001-2010. The carbon storage of grassland group increased remarkably for both the increase in land area and carbon density. The situation was opposite for the sparse vegetation group, which carbon storage decreased remarkably for both decreasing in land area and carbon density. The carbon storage of forest group increased slightly mainly for the increase in carbon density. The carbon storage of wetlands group was decreased for both the area and carbon density decrease. The carbon storge of croplands group was decreased mainly for the remarkable decrease in the area (Figure 6).

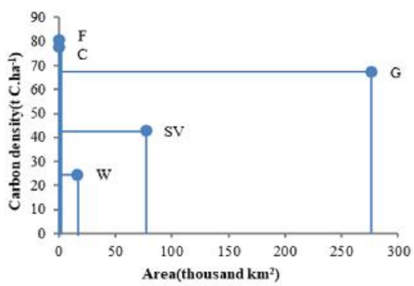
Contribution of land conversion and land use intensity on carbon storage: Thanks to establishment of the Nature Reserves and ecological protected areas, which contributed to land use system optimizing and carbon storage in China (Xu *et al*., 2017). Forest land has the highest bulk soil organic carbon (WBC), total carbon (TC) values while barren land having least amount of WBC, TC in mid-Himalaya, Indian. TC were increase in the grass and forest land as compared to barren and cultivated land (Meena *et al*., 2018). Main cause of carbon storage loss due to cropland expansion is that cropland replaces large areas of forest and wetland. So the land cover types with high carbon density (e.g., forest, and grassland) should be protected from being encroached by bare land or cropland (Tang *et al*., 2020). Furthermore, restoration of degraded barren and cultivated land to grass and forest land and decrease in intensity of land use could increase carbon storage (Meena *et al*., 2018). In the upper reaches of the Heihe River Basin in the northeastern Tibetan plateau, carbon storage increased 0.27% annually from 2001 to 2015 due to increasing the proportion of land cover types with higher carbon storage capacity (Zhao *et al*., 2019). Carbon storage increased 0.36% annually, with the carbon density increased slightly from 58.3 to 60.4 t C.ha^{-1} in NTP during 2001-2010 in our study. The primary reason of carbon storage increase is that the land conversion was characterized with the low carbon density land group (sparse vegetation) converted into the high carbon density land group (grassland). The second reason is the land use intensity decline, especially, grazing reduction. Numbers of livestocks increased to the peak historically in 2005, and dropped distinctly since then in the NTP (Figure 7). Grassland conservation and grazing reduction is effective to conserve ecosystem and maintain carbon storage (Bryan *et al*., 2018). Currently, finance transfer from the Chinese central government to the NTP reached about 1.2 billion RMB annually (1US \$ = 6.67 RMB on 1st July 2017)[2], which could just cover the cost of grassland conservation and grazing reduction, while other ecosystem services such as carbon sequestration has not been subsidized. In the future, it is needed to build a carbon sequestration payment mechanism that integrated forces of governments and market to incentivize actions of carbon sequestration.



a. carbon storge, land area and carbon density in 2001



c. change of land area and carbon density during 2001-2010



b. carbon storage, land area and carbon density in 2010

Figure 6. Change of area and carbon density of land groups in NTP during 2001–2010

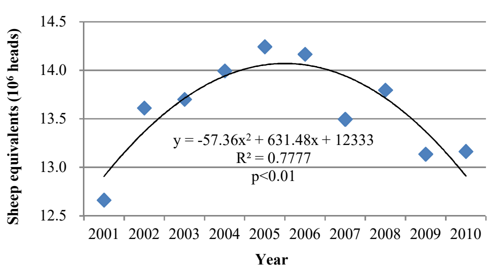


Figure 7. livestocks in NTP during 2001-2010

[2] "Scheme of subsidizing and rewarding for grassland conservation in Tibet Autonomous Region (TAR)" was annually issued by the government of TAR since 2011.

Data source: we collected livestocks numbers from agro-husbandry bureau of local governments and calculation by ourselves.

Uncertainty in the assessment of carbon storage: Semi-arid ecosystems are responsible for most of the variability in carbon sequestration and storage (Ahlström *et al*., 2015). LULC such as the advance of forest into tundra can increase aboveground carbon storage, but enhance belowground decomposition, resulting in a net loss of ecosystem carbon (Kane, 2012). Forest carbon density in mid-latitude regions was 57 and 96 t $C.ha^{-1}$ in the vegetation and at soil depths of 100 cm, respectively (Dixon *et al*., 1994). In Tibetan plateau, mean density of SOC in the top 100cm soil of the alpine steppe, alpine meadow and alpine shrubland was 43.8, 92.5, and 262.1 t $C.ha^{-1}$ (Nie *et al*., 2019). Carbon storage increased during 1982–2011 on the Tibetan plateau overall, although it decreased in degraded ecosystems (Li *et al*., 2013). The average density of SOC in grassland was 51.5 g C/ha in the study, which was bigger than the SOC density of alpine steppe while less than that of alpine meadow in Tibetan plateau as Nie *et al*. (2019) found. Besides, the SOC density of grassland in NTP was just from a soil depth of 30cm, rather than a depth of 1 meter as Nie *et al*. (2019). The precision in estimating carbon storage is depended on the precision of data including land cover and carbon storage density. The land cover data applied in the study originated from the MODIS MCD 12Q 500m, which is enough to identify the forest, grassland and wetland, while there was some uncertainty to identifying the small landscape such as urban and built-up.

Conclusions: We have presented a method to assess contribution of LULC to carbon storage change at a regional scale based on the InVEST model. Using data of land covers and carbon density, we modeled the carbon storage change in NTP during 2001–2010, and ascertained the contribution of land cover conversion and carbon density change to carbon storage change. A carbon storage increase of 78.4 Mt was found in NTP. Carbon storage change in NTP was dependent on the tradeoff between grassland and sparse vegetation. Carbon storage of grassland increased because both the proportion of land area and carbon density increased during the period, while that of sparse vegetation decreased because both proportion of the area and carbon density declined. Carbon density of NTP increased overall, with average carbon density was 58.3 and 60.4 t $C.ha^{-1}$ in NTP in 2001 and 2010, respectively. The contribution of land conversion to carbon storage increases was 43.6%, while that of carbon density changes was 37.1%, and the total contribution of LULC to carbon storage increase was approximately 80%. The contribution of the LULC to carbon storage change can be measured clearly in both aspects, i.e., land conversion and land modification. To improve carbon sequestration capacity, policy-makers should inhibit land conversions such as land cover with high carbon density (e.g. grassland) changed into land cover with low carbon density (e.g. sparse vegetation), control livestock numbers and reduce grazing intensity, build a subsidized scheme to land use system based on the carbon sequestration capacity.

Acknowledgments: The authors are grateful for the constructive and valuable comments from the anonymous reviewers. Financial support provided by the second Tibetan Plateau Scientific Expedition and Research Program (STEP), China *(Grant No. 2019QZKK0603, 2019QZKK0406)*, the National Natural Science Foundation of China (NSFC) (*Grant No. 41971263, 41571496)*, the national key Research and Development Programme, China (*Grant No. 2016YFC0503403*), were greatly appreciated. Special thanks go to the editor of this journal.

REFERENCES

Ahlström, A., Raupach, M.R., Schurgers, G., *et al*., 2015. The dominant role of semi-arid ecosystems in the trend and variability of the land CO2 sink. Science 348, 895-899.

Balasubramanian, D., Zhou, W.J., Ji, H.L., *et al*., 2020. Environmental and management controls of soil carbon storage in grasslands of southwestern China. J. Environmental Management, 254: 109810.

Bryan, B.A., Gao, L., Ye, Y., *et al*., 2018. China's response to a national land-system sustainability emergency. Nature, 559(7713): 193-204.

Carré, F., Hiederer, R., Blujdea, V., *et al*., 2010. Background guide for the calculation of land carbon stocks in the Biofuels Sustainability Scheme drawing on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Luxembourg: Joint Research Center, European Commission, EUR 24573, 109.

Caspersen, J.P., 2000. Contributions of Land-Use History to Carbon Accumulation in U.S. Forests. Science 290, 1148-1151.

Chen, Y., Luo G., Ye H., *et al*.,2015. Sources and Sinks of Carbon Caused by Forest Land Use Change from 1975 to 2005 in Central Asia. J. Natural Resources, 30(03): 397-408 (in Chinese).

Chen, S., Arrouays, D., Angers, D.A., *et al*., 2019. National estimation of soil organic carbon storage potential for arable soils: A data-driven approach coupled with carbon-landscape zones. Science of The Total Environment, 666: 355-367.

Deng, L., Shangguan, Z.P., Sweeney, S., 2014. "Grain for Green" driven land use change and carbon sequestration on the Loess Plateau, China. Scientific Reports 4.

Dixon, R.K., Solomon, A.M., Brown, S., *et al*., 1994. Carbon Pools and Flux of Global Forest Ecosystems. Science 263, 185-190.

Dong, J.R., Kaufmann, R.K., Myneni, R.B., *et al*., 2003. Remote sensing estimates of boreal and temperate forest woody biomass: carbon pools, sources, and sinks. Remote Sensing of Environment 84, 393-410.

Eswaran, H., Vandenberg, E., Reich, P., 1993. Organic-Carbon in Soils of the World. Soil Science Society of America J. 57, 192-194.

Fu, C., Yu, G., Fang, H. *et al*.,2012. Effects of Land Use and Cover Change on Terrestrial Carbon Balance of China. Progress in Geography Science, 31(01): 88-96 (in Chinese).

GLP, 2005. Science Plan and Implementation Strategy. IGBP Secretariat, Sweden: Stockholm, p. 64.

Gonzalez, P., Asner, G.P., Battles, J.J., *et al*., 2010. Forest carbon densities and uncertainties from Lidar, QuickBird, and field measurements in California. Remote Sensing of Environment 114, 1561-1575.

Haberl, H., Erb, K.H., Krausmann, F., *et al*., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. P Natl Acad Sci USA 104(31), 12942-12947.

Hernández-Guzmán, R., Ruiz-Luna, A. and González, C., 2019. Assessing and modeling the impact of land use and changes in land cover related to carbon storage in a western basin in Mexico. Remote Sensing Applications: Society and Environment, 13: 318-327.

IPCC, 2006. IPCC guidelines for national greenhouse gas inventories, in: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Agriculture, Forestry and Other Land Use. Institute for Global Environmental Strategies, Hayama, Japan.

Jin, F., Yang, H., Zhao, Q.,2000. Research progress on soil organic carbon storage and its influencing factors. Soil, 01:12-18 (in Chinese).

Kane, E.S., 2012. Ecosystem carbon storage: Squeezing the Arctic carbon balloon. Nature Clim. Change 2, 841-842.

Laganière, J., Cavard, X., Brassard, B.W.,*et al*., 2015. The influence of boreal tree species mixtures on ecosystem carbon storage and fluxes. Forest Ecology and Management, 354: 119-129.

Law, E.A., Bryan, B.A., Torabi, N., *et al*., 2015. Measurement matters in managing landscape carbon. Ecosystem Services 13, 6-15.

Lawler, J.J., Lewis, D.J., Nelson, E., *et al*., 2014. Projected land-use change impacts on ecosystem services in the United States. Proceedings of the National Academy of Sciences 111, 7492-7497.

Li, W., Zhao, X., Zhang, X., *et al*.,2013. Change mechanism in main ecosystems and its effect of carbon source/sink function on the Qinghai-Tibetan Plateau. Nature Journal, 35(03): 172-8(in Chinese).

Liu, J., Wang, S., Chen, J., *et al*.,2004. Storage of Soil Organic Carbon and Nitrogen and Land Use Changes in China:1990-2000. J. Geography, 59(04): 483-96(in Chinese).

Meena, V.S., Mondal, T., Pandey, B.M., *et al*., 2018. Land use changes: Strategies to improve soil carbon and nitrogen storage pattern in the mid-Himalaya ecosystem, India. Geoderma, 321: 69-78.

Nie, X., Yang, L., Li, F., *et al*., 2019. Storage, patterns and controls of soil organic carbon in the alpine shrubland in the Three Rivers Source Region on the Qinghai-Tibetan Plateau. CATENA, 178: 154-162.

Ruesch, A., Gibbs, H.K., 2008. New IPCC Tier-1 global biomass carbon map for the year 2000. The Carbon Dioxide Information Analysis Center [http://cdiac.ornl.gov], Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Shao, Wei , Cai, Xiaobu, 2008. Grassland degradation and its formation causes analysis in Tibetan plateau. Science of Soil and Water Conservation,6(1):112-116 (in Chinese).

Sharp, R., Tallis, H.T., Ricketts, T., *et al*., 2018. InVEST 3.7.0. User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Tang, L., Ke, X., Zhou, T.,*et al*., 2020. Impacts of cropland expansion on carbon storage: A case study in Hubei, China. J. Environmental Management, 265: 110515.

Triviño, M., Juutinen, A., Mazziotta, A., *et al*., 2015. Managing a boreal forest landscape for providing timber, storing and sequestering carbon. Ecosystem Services 14, 179-189.

Valentin, C., Agus, F., Alamban, R., *et al*., 2008. Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. Agriculture, Ecosystems & Environment 128, 225-238.

Wang, S., Zhou, C., Li, K., *et al*.,2000. Analysis on Spatial Distribution Characteristics of Soil Organic Carbon Reservoir in China. J. Geography 67(05): 533-44 (in Chinese).

Wang, Y., Chen, Z. ,1998. Distribution of Soil Organic Carbon in the Major Grasslands of Xilinguole, Inner Mongolia, China. Acta Phytoecologica Sinica, 22(06): 545-551 (in Chinese).

Xu, S., Ceng, B., Su, X., *et al*.,2012. Spatial distribution of vegetation and carbon density in Jinyun Mountain Nature Reserve based on RS /GIS. Acta Ecologica Sinica, 32(07): 2174-84 (in Chinese).

Xu, W.H., Xiao, Y., Zhang, J.J., *et al*., 2017. Strengthening protected areas for biodiversity and ecosystem services in China. Proceedings of the National Academy of Sciences of the United States of America, 114(7): 1601-1606.

Xu, Z. and Zou, X., 2020. Evaluation of social-ecological effectiveness of protected areas on the Chang tang plateau, Acta Ecologica Sinica, 40(23):8743-8752 (in Chinese).

Yang, H., Huang, J. and Liu, D., 2020. Linking climate change and socioeconomic development to urban land use simulation: Analysis of their concurrent effects on carbon storage. Applied Geography, 115: 102135.

Yazdanshenas, H., Tavili, A., Jafari, M. *et al*., 2018. Evidence for relationship between carbon storage and surface cover characteristics of soil in rangelands. CATENA, 167: 139-146.

Zhang, H.,2013. Distribution Characteristics of Soil Organic Carbon and Its Composition under Erosion Environment in Different Vegetable Regions of Loess Plateau. Xi'an: Northwest Agriculture and Forestry University (in Chinese).

Zhang, X., Yang, Y., Piao S., *et al*., 2015b. Ecological change on the Tibetan Plateau. Chinese Science Bulletin, 2015, 60(32): 3048-3056(in Chinese).

Zhang, M., Huang, X.J., Chuai, X.W., *et al*., 2015a. Impact of land use type conversion on carbon storage in terrestrial ecosystems of China: A spatial-temporal perspective. Sci Rep-Uk 5.

Zhao, M., He, Z., Du, J., *et al*., 2019. Assessing the effects of ecological engineering on carbon storage by linking the CA-Markov and InVEST models. Ecological Indicators, 98: 29-38.