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Impacts of Land Cover Changes on Ecosystem Carbon Stocks Over the Transboundary Tumen River Basin in Northeast Asia

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Abstract: Understanding the effects of land cover changes on ecosystem carbon stocks is essential for ecosystem management and environmental protection, particularly in the transboundary region that has undergone marked changes. This study aimed to examine the impacts of land cover changes on ecosystem carbon stocks in the transboundary Tumen River Basin (TTRB). We extracted the spatial information from Landsat Thematic Imager (TM) and Operational Land Imager (OLI) images for the years 1990 and 2015 and obtained convincing estimates of terrestrial biomass and soil carbon stocks with the InVEST model. The results showed that forestland, cropland and built-up land increased by 57.5, 429.7 and 128.9 km^2, respectively, while grassland, wetland and barren land declined by 24.9, 548.0 and 43.0 km^2, respectively in the TTRB from 1990 to 2015. The total carbon stocks encompassing aboveground, belowground, soil and litter layer carbon storage pools have declined from 831.48 Tg C in 1990 to 831.42 Tg C in 2015 due to land cover changes. In detail, the carbon stocks decreased by 3.13 Tg C and 0.44 Tg C in Democratic People's Republic of Korea (North Korea) and Russia, respectively, while increased by 3.51 Tg C in China. Furthermore, economic development, and national policy accounted for most land cover changes in the TTRB. Our results imply that effective wetland and forestland protection policies among China, North Korea, and Russia are much needed for protecting the natural resources, promoting local ecosystem services and regional sustainable development in the transnational area.

Keywords: land cover change; carbon stock; InVEST model; Transboundary Tumen River Basin; Northeast Asia

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1 Introduction

Carbon storage represent one of the world's most important types of ecosystem services (Deng et al., 2016). Terrestrial ecosystems are the most significant carbon pool in the global carbon cycle, containing a large amount of carbon (Davies et al., 2011; Guo et al., 2014). At present, the maintenance of ecosystem carbon stocks is one of the hotspots of common concern worldwide (Song and Deng, 2015). The quantitative research helps to enhance the understanding that it is important to protect natural ecosystems, use natural resources sustainably and develop the economy (Deng et al., 2015). Moreover, it can provide comprehensive management of theoretical foundation on land cover and carbon conservation (Poeplau and Don, 2013).

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Land cover is an important parameter for calculating carbon storage. How land cover changes affect ecosystem carbon stocks is often determined by the issue of a particular interest and importance. This is because land is not only the locus that terrestrial natural ecosystem functions occur, it also can be used by humans in multiple ways (Kreuter et al., 2001; Hao et al., 2012). For a long time, irrational use of land has resulted in severe land degradation, for example, deforestation, mining, steep slope reclamation and overgrazing are the main causes of soil erosion and desertification, so that actual carbon stocks of all ecosystems were lower than the potential carbon stocks (Lal, 2008). Thus, land cover changes affect ecosystem carbon stocks, for example, expansion of cropland has promoted the economic benefits of ecosystem services，but it may have destroyed wetland, forestland and other ecosystems, thereby reducing the ecosystem services value in terms of carbon sequestration. Previous studies about the effects of land cover changes on ecosystem carbon stocks have provided crucial insights into and direction to land and environmental policy makers (Hao et al., 2012b).

The transboundary Tumen River basin (TTRB) is the area bordering China, North Korea, and Russia, which plays an important role in Northeast Asian economic development and cooperation (Guo, 2012). In the TTRB, cross-border environmental degradation seems to have the potential of exacerbating land cover change and carbon stocks change issues among the China, North Korea, and Russia. Most current studies in the basin have been focused on the landscape dynamics and land use/cover changes (Nan et al., 2012; Zheng et al., 2017a), whereas the response of ecosystem services to land cover change has not been sufficiently considered, especially in a comparative study among the three countries. Pursuing cross-border research and the creation of bilateral and/or multilateral cooperative mechanisms in internationally adjacent areas is an important contribution to the management of natural resources (Guo, 2018). Border areas have attained a status of special interest, not only with respect to national administration but also with regard to the cooperation between environments (Castanho et al., 2017). However, there are few studies on cross-border ecosystem carbon stocks and it is urgent to carry out relevant research. The goal of this paper is to systematically analyze the impacts of land cover change on regional ecosystem carbon stocks in the TTRB.

Specifically, the objectives of this study are to: 1) characterize land cover changes across different countries from 1990 to 2015 in the TTRB; 2) identify the carbon stocks in different land cover types, such as forestland, cropland, grassland, and wetland; 3) quantify carbon stocks that are influenced by land cover change at the aboveground biomass, belowground biomass, litter layer organic and soil organic carbon pools. This study could help understand the relationship between land cover change and carbon stocks and help managers improve environmental protection in the TTRB.

2 Data and Methods

2.1 Study area

The transboundary Tumen River Basin (TTRB) is located at the borders of China, Democratic People's Republic of Korea (D. P. R. Korea, North Korea) and Russia, ranging in latitude from 41°09′N to 44°01′N and in longitude from 128°07′E to 131°51′E (Fig. 1). The Tumen River is an important international river trespassing across China, North Korea and Russia. It flows from south to north through China, North Korea, Hassan District of Russia, and ends up into the Japan Sea bordering upon North Korea and Russia. The TTRB includes seven counties, i.e., Hunchun, Tumen, Helong, Longjing, Antu, Yanji and Wangqing, in China; Ryanggang and Hamgyeongbuk-do in North Korea and the Hassan District in Russia. The TTRB has a total area of about 37 568.3 km^2, dominated by mountains with a temperate continental monsoon climate, that is featured with prevalent northwestward winds in winter and southeastward winds in summer. The average annual rainfall is 400–650 mm, the average annual temperature is 2℃–6℃ (Zheng et al., 2017b). About 70% of the rainfall is concentrated between June and September (Kang et al., 2017; Qin et al., 2017). The natural vegetation of this region is characterized by a mosaic of forestland, cropland, grassland and wetland. The forest coverage in the area is as high as 80%, mainly distributed in the Changbai Mountains.

2.2 Data and processing

In this study, we used multi-source datasets, including remote sensing dataset, ground survey dataset, and statistical dataset. The remote sensing dataset included Landsat Thematic Mapper (TM) images obtained in

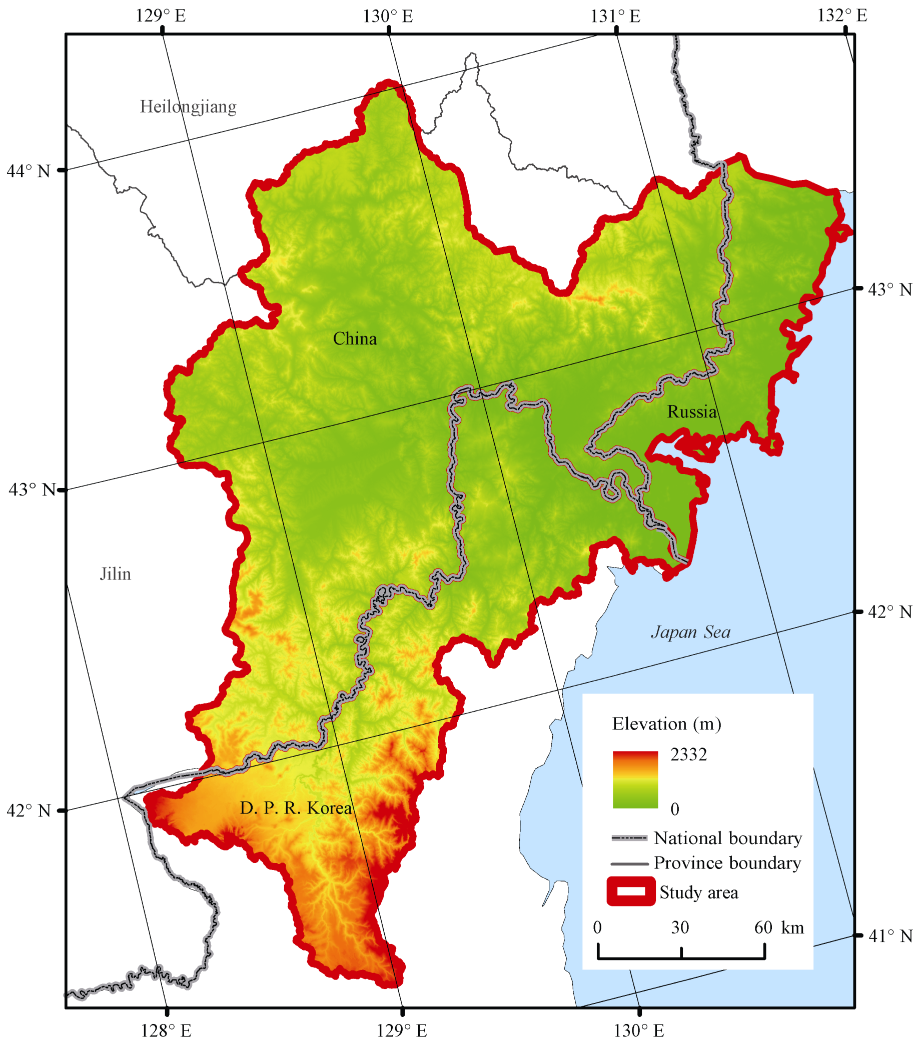

Fig. 1 The geographical location of the transboundary Tumen River Basin

1990, and Landsat Operational Land Imager (OLI) images obtained in 2015. The data were downloaded from the United States Geological Survey (http://glovis.usgs.gov/), with a total of 12 images at a spatial resolution of 30 m. The remote sensing images in July and August were selected with cloud cover less than 8%, with high radiation resolution. Ground surveys were conducted in June 2015 to collect ground truth data, which were also collected from high-resolution images available on Google Earth. These surveys resulted in 226 points covering all land cover types within the study area. Historical Google Earth images, as well as information obtained from interviews with local experts and residents, were used as reference data in the assessment of the classification results from 1990 (Li et al., 2017). Statistical data used for the analysis of factors affecting land cover changes were collected from statistical yearbooks of Jilin Province, China. These statistical data include the status of agriculture, population, and environmental protection. The similar statistical data for Russia and North Korea were not used because these data are inaccessible.

Data processing tools included ENVI5.1, ArcGIS10.2 and eCognition8.64. We used ENVI to pre-process the images. We also applied ArcGIS to project all the images to the Universal Transverse Mercator (UTM) coordinate system, Zone 52 North, ensuring the consistency between datasets during analysis. The eCognition software was used to establish interpretation marks and obtain the preliminary interpretation results. Six land cover categories were identified considering the local specific conditions and following the approaches of Wu (2017): forestland, grassland, cropland, wetland, built-up land and barren land.

2.3 Land cover classification and accuracy assessment

In this study, the object-oriented classification method was conducted by the eCognition Developer 8.64 software. An object-based classification approach, which has been proven to be more accurate and effective than the pixel-based approaches, was used for land cover interpretation (Aguirre-Gutiérrez et al., 2012). The advantages of the object-based method are widely described, such as the faster processing is suitable for large scale image classification, overcoming 'salt-and-pepper effects', and providing geo-information that can be directly stored into geographical databases (Jensen, 1986; Johnsson, 1994; Yu et al., 2006). This process includes two steps as follows:

1) First, image segmentation. On the basis of a large number of experimental analyses and comparisons, vegetation and non-vegetation on a large scale are divided using scale 100; then wetland, cropland and grassland are divided using scale 50; finally, a scale of 30 is used to segment built-up land and barren land(Jia et al., 2013; Liu et al., 2017). Meanwhile, the shape factor was set to 0.2 and the compactness parameter was set at 0.5 to balance compactness with smoothness.

2) Second, calculating spectral indices and creating spectral parameters for each object. In this study, the spectral indices were NDVI, NDWI, LSWI, EVI, and RRI (Chen et al., 2018). The selected spectral parameters are the color combination of R: G: B = TM 5: TM 4: TM 3 and the color combination of R: G: B = OLI 4: OLI 3: OLI 2. A trial-and-error process was practiced to establish the following land cover classification decision tree (Fig. 2).

After obtaining the land cover types, accuracy of the classification results were evaluated using field measurements and the high-resolution remotely sensed data from Google Earth in 2015. First, the land cover classification results for the 226 sample points representing forestland (56), grassland (26), cropland (64), wetland (41), built-up land (24) and barren land (15) were extracted and examined in reference to the field data and the high-resolution remote sensing data. Then, the confusion matrix was computed and analyzed for the evaluation of classification accuracy of land cover data. The results showed that the overall accuracy was 93%, and overall Kappa coefficient was 0.92, indicating that the classification was highly accurate.

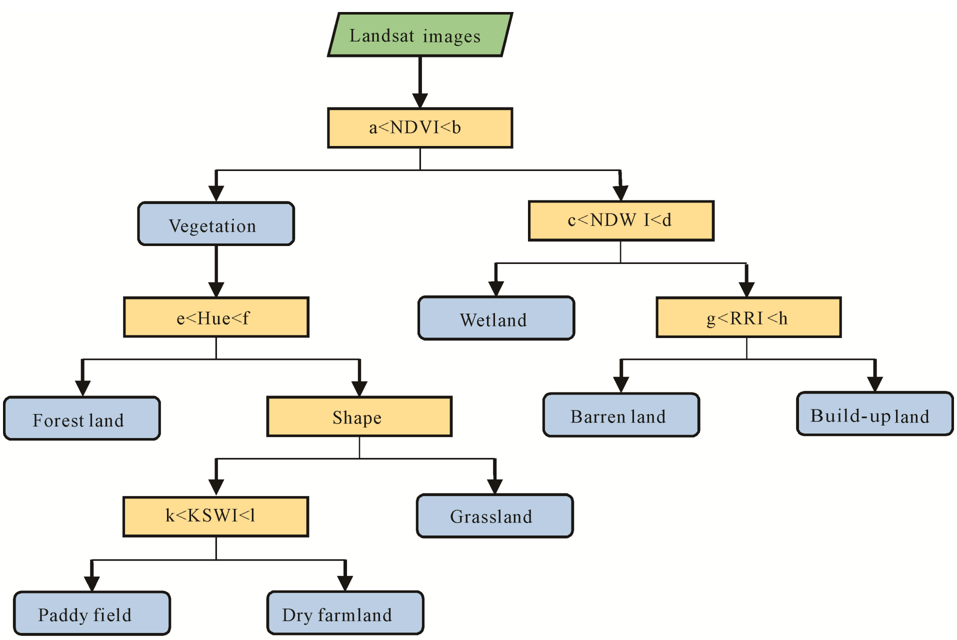

Fig. 2 Rules set of land cover classifications. (NDVI is the normalized difference vegetation index. NDWI is the normalized difference water index. RRI is the ratio resident-area index. EVI is enhanced vegetation index varied in time. LSWI is the land surface water index. The lowercase letters (a, b, c, d, e, f, g, h, i, j) in the figure represent the parameter thresholds and the different image thresholds are different.)

2.4 Estimation of carbon stocks for different land cover types

We used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to estimate carbon stocks with regard to specific land cover types. InVEST is a geospatial modeling framework tool to assess the impact of land cover changes on ecosystem services (Hamel et al., 2015). The InVEST Carbon Storage model summarizes the amount of carbon stored in these pools based on user-generated land cover maps and classifications. Carbon storage largely depends on the sizes of four carbon 'pools': aboveground biomass, belowground biomass, soil, and litter layer organic matter (Tallis et al., 2013; Sharp et al., 2015a; Zhang D et al., 2017). Aboveground biomass includes all living plant materials (e.g., bark, trunks, branches, leaves) above the soil surface; belowground biomass encompasses the living root systems of aboveground biomass. Soil organic matter is the organic part of soils, which represents the largest terrestrial carbon pool; Litter layer organic matter includes rubbish and litter layer wood lying and standing (Sharp et al., 2015b). Following Jiang et al. (2014), we used the InVEST Carbon Storage and Sequestration module to calculate carbon stocks in the TTRB. The carbon density for land cover type *i* can be expressed as:

$$C_i = C_{i(\text{above})} + C_{i(\text{below})} + C_{i(\text{litter layer})} + C_{i(\text{soil})} \quad (1)$$

where $C_{i\,(\text{above})}$, $C_{i\,(\text{below})}$, $C_{i\,(\text{litter layer})}$, and $C_{i\,(\text{soil})}$ represent aboveground carbon density, belowground carbon density, litter layer organic carbon density and soil carbon density for land cover type *i*, respectively (Table 1). The regional carbon stocks *C* is calculated as:

$$C = \sum_{i}^{n} C_i \times S_i \quad (2)$$

where S_i denotes the area for land cover type and *n* denotes the number of land cover types.

Table 1 Land cover types and carbon density (t/ha)

Land cover type	Land cover type	$C_{(\text{above})}$	$C_{(\text{below})}$	$C_{(\text{soil})}$	$C_{(\text{litter layer})}$	Source
Forestland	Broadleaf forest	53.50	26.75	170.51	2.51	CFSDC (http://hljsdc.nefu.edu.cn/)
	Evergreen forest	147.37	73.68	189.91	2.16	(Yuan et al., 2014)
	Conifer forest	68.10	34.05	166.20	2.16	(Wang, 2016)
	Mixed forest	60.03	30.01	160.92	2.16	(Wang, 2016)
	Broadleaf shrubland	9.37	4.69	118.61	2.23	(Wang, 2016)
Grassland	Alpine steppe	1.66	3.41	10.93	2.00	(Wang, 2016)
	Temperate steppe	2.33	7.30	43.72	3.80	(Wang, 2016)
	Lawn	90.00	60.00	110.00	30.00	(Wang, 2016)
	Tussock	1.52	3.11	34.80	1.99	(Wang, 2016)
Cropland	Paddy field	4.70	0	33.46	0	(Wang, 2016)
	Dry farmland	4.70	0	33.46	0	(Wang, 2016)
Wetland	Herbaceous wetland	4.80	2.40	382.80	1.50	(Wang, 2016)
	Shrub wetland	15.90	7.95	330.60	1.80	(Mou et al., 2013)
	Lakes	2.75	0	144.13	0	(Mi et al., 2013)
	Reservoir/Pond	2.30	0	146.26	0	(Wang, 2016)
	River	3.25	0	0	0	(Wang, 2016)
Built-up land	Settlement	0	0	0	0	(Wang, 2016)
	Transportation land	0	0	0	0	(Wang., 2016)
Barren land	Bare rock	0	0	0	0	(Wang, 2016)
	Bare soil	0	0	0	0	(Wang, 2016)

3 Results

3.1 Analysis of land cover changes

Table 2 indicate the areal extent of each type of land covers and their distributions. In 1990, the dominant land cover was forestland (78.2%, 29 364.7 km^2), followed by cropland (12.8%, 4811.2 km^2), wetland (5.7%, 2156.3 km^2), and grassland (1.9%, 697.8 km^2). Built-up land and barren land accounted for the smallest portion in area of the TTRB. In 2015, forestland and cropland were dominant in area, accounting for 78.3% (29 422.2 km^2) and 14.0% (5240.9 km^2) of the area, respectively. The remaining area was taken up by other land cover types, including grassland, wetland, built-up land and barren land. By comparing land covers among the three countries in 1990 and 2015 each, we concluded that China was mainly covered by forestland (81.9%, 82.8%) and cropland (12.9%, 13.2%), North Korea also was mainly covered by forestland (72.8%, 71.0%) and cropland (17.6%, 21.0%), and Russia was mainly covered by forestland (72.0%, 73.0%) and wetland (24.7%, 23.5%).

From 1990 to 2015, forestland, cropland and built-up land in China increased by 203.3 km^2, 67.2 km^2, and 102.3 km^2, respectively. By contrast, grassland, wetland, and barren land decreased by 23.9 km^2, 344.9 km^2, and 3.9 km^2, respectively. Meanwhile, cropland and built-up land in North Korea increased by 359.6 km^2 and 20.3 km^2, respectively. Conversely, forestland, grassland, wetland and barren land decreased by in area of 187.4 km^2, 1.6 km^2, 151.7 km^2 and 39.2 km^2, respectively. Forestland, grassland, cropland and built-up land in Russia expanded by 41.6 km^2, 0.6 km^2, 2.9 km^2 and 6.2 km^2, respectively. Only wetland reduced by 51.3 km^2.

3.2 Carbon stocks estimation for different land cover types

The total carbon stocks of the TTRB and their spatial distributions in 1990 and 2015 are described in Fig. 3, Table 3 and Table 4. The changes of land covers resulted in a slight decrease in carbon storage in the whole TTRB area, roughly 0.06 Tg C. In 1990, the carbon stocks was 755.82 Tg C for forest, 39.79 Tg C for wetland, 18.36 Tg C for cropland and 17.52 Tg C for grassland in the TTRB. Such a same sequence of carbon stocks for the land cover types of the region was observed again in 2015.

In 1990 and 2015, comparing carbon stocks per unit area of the three countries in the TTRB, the largest was Russia (26 487.76 and 26 384.92 t/km^2 in above two years), followed by China (21 823.48 t/km^2 and 21 978.55 t/km^2) and North Korea (21 030.61 t/km^2 and 20 737.92 t/km^2). Considering the three countries respectively in the TTRB, we concluded that forestland was the largest carbon stock, followed by cropland, wetland and grassland in China. And in North Korea, forestland was also the largest carbon stock, followed by grassland, while cropland and wetland stored relatively little carbon. In Russia, carbon storage in grassland was relatively smaller than in the wetland, but compared to carbon stored in forestland, wetland carbon storage were relatively small.

In 1990 and 2015, in China, the highest carbon storages of the four basic carbon pools was soil organic (328.53 and 330.70 Tg C), followed by aboveground biomass (107.45 and 108.37 Tg C) and belowground biomass (53.03 and 53.49 Tg C). Carbon stored in litter layer organic was the smallest component, only 4.96 and 4.93 Tg C. In North Korea, a similar carbon stocks

Table 2 Areas and ratio to total areas of different land covers of the transboundary Tumen River Basin in 1990 and 2015

Land cover type	1990								2015							
	TTRB		China		North Korea		Russia		TTRB		China		North Korea		Russia	
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Forestland	29364.7	78.2	18537.2	81.9	7753.8	72.8	3073.7	72.0	29422.2	78.3	18740.5	82.8	7566.4	71.0	3115.2	73.0
Grassland	697.8	1.9	92.4	0.4	517.3	4.9	88.2	2.1	672.9	1.8	68.4	0.3	515.6	4.8	88.8	2.1
Cropland	4811.2	12.8	2914.1	12.9	1877.7	17.6	19.3	0.5	5240.9	14.0	2981.3	13.2	2237.3	21.0	22.3	0.5
Wetland	2156.3	5.7	728.1	3.2	373.0	3.5	1055.2	24.7	1608.3	4.3	383.2	1.7	221.3	2.1	1003.9	23.5
Built-up land	422.2	1.1	349.8	1.5	39.7	0.4	32.7	0.8	551.1	1.5	452.1	2.0	60.0	0.6	38.9	0.9
Barren land	108.2	0.3	12.1	0.1	96.1	0.9	0	0	65.2	0.2	8.2	0.0	56.9	0.5	0.0	0.0

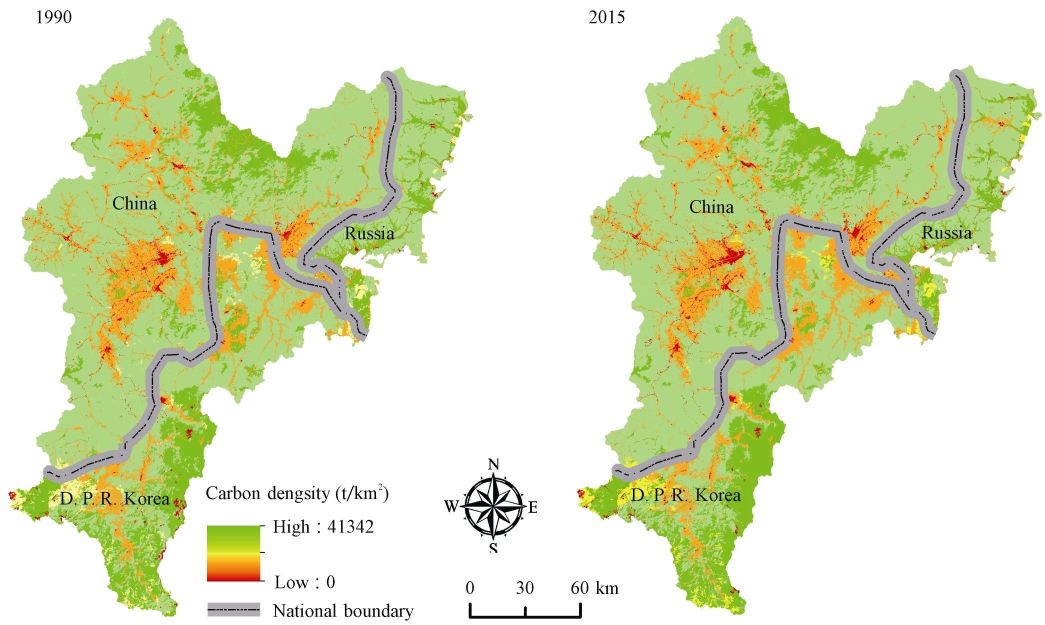

Fig. 3 Carbon density map of the transboundary Tumen River Basin in 1990 and 2015

sequence was observed: soil organic carbon (139.13 and 137.37 Tg C), aboveground biomass (54.36 and 53.52 Tg C), belowground biomass (27.45 and 26.97 Tg C), and litter layer organic carbon (3.23 and 3.19 Tg C). In Russia, the highest carbon stock was soil organic, where the carbon stocks changed from 86.64 Tg C and 85.89 Tg C, followed by aboveground biomass (17.15 Tg C and 17.35 Tg C), belowground biomass (8.58 and 8.68 Tg C). Carbon stored in litter layer organic was the smallest component ranging from only 0.956 Tg C and 0.961 Tg C (Table 3 and Table 4).

3.3 Carbon stock alteration caused by land cover changes

As shown in Table 3 and Table 4, when carbon stocks of individual land cover types is considered in China, wetland and grassland carbon stocks decreased by 1.37 Tg C and 0.66 Tg C, respectively, as opposed to

Table 3 Biomass and soil carbon stocks in terrestrial land covers of the transboundary Tumen River Basin in 1990 (Tg C)

Land cover type	Aboveground carbon stocks			Belowground carbon stocks			Soil carbon stocks			Litter layer carbon stocks			Total carbon stocks		
	China	North Korea	Russia	China	North Korea	Russia	China	North Korea	Russia	China	North Korea	Russia	China	North Korea	Russia
Forestland	105.40	48.70	16.53	52.70	24.35	8.26	314.15	126.43	52.31	4.54	1.68	0.77	476.79	201.16	77.86
Grassland	0.40	4.66	0.15	0.29	3.10	0.11	0.69	5.69	0.42	0.40	1.55	0.06	1.78	15.00	0.74
Cropland	1.37	0.88	0.01	0	0	0	9.75	6.28	0.06	0	0	0	11.12	7.17	0.07
Wetland	0.28	0.12	0.47	0.04	0	0.21	3.95	0.73	33.85	0.01	0	0.13	4.27	0.85	34.66
Total	107.45	54.36	17.15	53.03	27.45	8.58	328.53	139.13	86.64	4.96	3.23	0.96	493.97	224.18	113.33

Table 4 Biomass and soil carbon stocks in terrestrial land covers of the transboundary Tumen River Basin in 2015 (Tg C)

Land cover type	Aboveground carbon stocks			Belowground carbon stocks			Soil carbon stocks			Litter layer carbon stocks			Total carbon stocks		
	China	North Korea	Russia	China	North Korea	Russia	China	North Korea	Russia	China	North Korea	Russia	China	North Korea	Russia
Forestland	106.60	47.76	16.75	53.30	23.88	8.37	317.58	123.44	53.02	4.59	1.64	0.78	482.07	196.71	78.92
Grassland	0.20	4.64	0.15	0.16	3.09	0.11	0.44	5.67	0.42	0.33	1.55	0.06	1.12	14.96	0.74
Cropland	1.40	1.05	0.01	0	0	0	9.98	7.49	0.07	0	0	0	11.38	8.54	0.08
Wetland	0.16	0.07	0.45	0.03	0	0.20	2.71	0.78	32.38	0.01	0	0.12	2.91	0.85	33.15
Total	108.37	53.52	17.35	53.49	26.97	8.68	330.70	137.37	85.89	4.93	3.19	0.96	497.48	221.06	112.89

forestland and cropland in which carbon stocks increased by 5.28 Tg C and 0.26 Tg C, respectively. In North Korea, carbon stocks dramatically decreased by 4.44 Tg C in forestland as opposed to a small decrease in grassland and wetland by 0.04 Tg C and 0.01 Tg C, respectively, but a significant increase of 1.37 Tg C in cropland. The dramatic shift in land covers in Russia has caused a decrease of carbon stocks in wetland by 1.51 Tg C, but an increase in cropland and forestland by 0.01 Tg C and 1.05 Tg C, respectively.

Meanwhile, from 1990 to 2015, in the China part, carbon stocks increased by 0.92 Tg C for aboveground biomass, 0.46 Tg C for belowground biomass , and 2.16 Tg C for soil carbon, but decreased by 0.03 Tg C for litter layer carbon. In the North Korea part, carbon stocks in the four carbon pools decreased by 0.84 Tg C, 0.48 Tg C, 1.76 Tg C, and about 0.04 Tg C, respectively, for aboveground biomass, belowground biomass, soil carbon and litter layer carbon during the same time interval. In the Russia part, aboveground carbon stocks increased by 0.20 Tg C, belowground biomass by 0.10 Tg C, and litter layer organic carbon by about 0.01 Tg C, while soil organic carbon stocks decreased by 0.75 Tg C.

4 Discussion

4.1 Effects of land cover changes on carbon stocks

To our knowledge, this is the first attempt to characterize the variation of carbon stocks in the three countries as a result of land cover change in terrestrial ecosystems of the TTRB. Land cover change is of global importance (Foley et al., 2005) because of its major implications for changes in carbon stocks (Houghton, 2012). In this study, a wide range of land cover types such as forestland, grassland, cropland and wetland were taken into account in the quantification of carbon stocks changes in the TTRB. It is well known that declining forest and wetland are major drivers for reducing terrestrial carbon stocks (Tao et al., 2015; Zhang et al., 2015a; Lai et al., 2016a). First, forests play a key role in storing abundant carbon, and provide ecosystem services to regulate global climate change, implying the importance of promoting the protection of forestry areas (Chen et al., 2017; Tolessa et al., 2017). Wei et al. (2014) observed that the conversion of forestland to cropland caused a rapid initial decrease in carbon stocks. Some afforestation projects formulated by the Chinese government led to an increase of 0.7% in the area of forestland from 1990 to 2010 (Lai et al., 2016b), which is comparable to the 1.1% increase in forest area from 1990 to 2015 in this study area. The reduction of forest carbon stocks by 4.4 Tg C in the North Korea part of Tumen River investigated in this paper is comparable to the reduction of 8.32 Tg C in forest carbon stocks in North Korea, indicating that our research was reliable and consistent with the published results (Cui et al., 2014). It is also found that any land cover conversion involving with wetlands resulted in a large carbon stocks change, and the conversion of wetland to built-up land or cropland greatly resulted in a significant loss of carbon stocks (Xiong et al., 2014).

From 1990 to 2015, the causes for changes of carbon stocks were quite different among these three countries. As described in section 3.1, and shown in Fig. 4, the obvious conversions of forestland, cropland, and wetland resulted in changes in land cover types of carbon stocks (Table 5). In China, an area of 211.4 km^2 forestland arose from the conversion of other land cover types. Among them, the conversion from wetland, cropland, grassland and barren land accounted for 82.2%, 8.2%, 7.8% and 1.8%, respectively. The conversion of land cover types led to an increase of forest carbon stocks of 5.51 Tg C. A total of 136.4 km^2 wetland was converted into cropland accounting for 95% of the total conversion, resulting in a decrease of 1.09 Tg C in wetland carbon stocks. In North Korea, the area of forestland transitioned into cropland and built-up land was 256.6 km^2, with cropland accounting for 97.9% and built-up land for 2.0%, resulting in a decrease of 4.42 Tg C in forestland carbon stocks. Wetlands with area of 110.6 km^2 have been transformed into cropland, making up 30.1% of the total conversion, resulting in an increase of 0.42 Tg C in cropland carbon stocks. In Russia, the area of wetland converted into non-wetland was 51.4 km^2, of which the area converted into forestland was 44.5 km^2, approximately 86.6% of the total loss of wetland, resulting in an increase of 1.13 Tg C in forestland carbon stocks and a decrease of 1.52 Tg C in wetland carbon stocks.

Land cover type conversion has important impacts on carbon stocks in terrestrial ecosystems (Zhang et al., 2015b). According to the results from this study, each region should be treated according to its unique situation

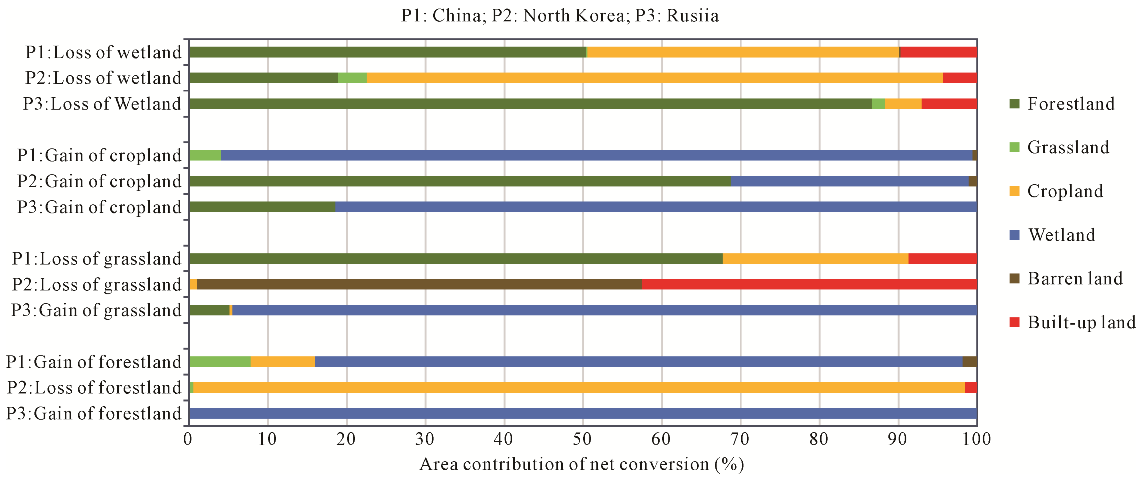

Fig. 4 The net area changes of land cover types in the transboundary Tumen River Basin from 1990 to 2015

Table 5 Carbon stocks variations caused by land cover changes in the transboundary Tumen River Basin from 1990 to 2015 (Tg C)

Country	Land cover type	Forestland	Grassland	Cropland	Wetland	Barren land	Built-up land
China	Forestland	0	0.43	0.45	4.53	0.10	–0.23
	Grassland	–1.48	0	–0.52	0.05	0	–0.19
	Cropland	–0.05	0.02	0	0.42	0	–0.18
	Wetland	–1.39	0	–1.09	0	–0.01	–0.27
North Korea	Forestland	0	–0.03	–4.35	0.68	0.89	–0.07
	Grassland	–0.05	0	0	0.16	–0.09	–0.07
	Cropland	0.96	0	0	0.42	0.01	–0.03
	Wetland	0	0	–0.01	0	0	0
Russia	Forestland	0	0	–0.01	1.13	0	–0.06
	Grassland	0	0	0	0	0	0
	Cropland	0	0	0	0.01	0	0
	Wetland	–1.31	–0.03	–0.07	0	0	–0.11

Notes: Positive values represent carbon stocks increased. Negative values represent carbon stocks reduced

revealed in this paper. In China, the growth of forestland should be encouraged, but the loss of wetland should be addressed adequately. In North Korea, forestland should be strictly protected or recovered, and the expansion of cropland should be controlled. In Russia, effective policies should be continuously practiced to protect forestland, and more efforts are needed to protect wetland.

4.2 Anthropogenic factors influencing land cover changes

The three countries in the TTRB have different policies and socio-economic development status. In China, urbanization, water pollution, tourism and farming contributed to the reduction of wetland, grassland and barren land. In the late 1980s, more than 2000 ha of wetland were recovered in Jingxin Town, Hunchun (Yang et al., 2002a). By the beginning of 1998, however, about one quarter of the area was reclaimed as paddy fields (Yang et al., 2002b). In 1991, the United Nations Development Program decided to make the development of the Tumen River Region a priority support project. Therefore, the resulting socio-economic development had some direct impacts on land cover changes in this area (Hou, 2015; Yirsaw et al., 2017). Moreover, afforestation and closed forests also caused an area increase of forest. In North Korea, the aim at improving the output value of agriculture, forestry and aquaculture resulted in the reduction of forestland, wetland and grassland, and the increase of cropland. The significantly increased demand for grain in the 1990s forced a large number of government-led masses to reclaim cropland from wetland and forestland, resulting in a significant increase in cropland and decrease in wetland and forestland. In Russia, the development of new forest laws resulted in the increase of forestland area. Furthermore, in the Hassan region of Russia, population decreased by 35,610 people during the past decade. The decline of population brought about the saturation of social and economic development, and the impact of human disturbances on wetland was limited. Therefore wetland experienced only a small loss to urban expansion (Dong, 2011a).

In order to protect the landscape more effectively in the TTRB, China, North Korea and Russia should better strengthen their cooperation to jointly protect forestland and wetland in the area. The three countries should better mitigate the contradictions between socio-economic development and environmental protection by formulating reasonable and effective regional development policies. Moreover, national governments should better work together to establish land monitoring and protection management agencies, formulate land planning systems, improve the status of environment in the region, and maintain and promote regional sustainable development (Mondal et al., 2017; Yigezu et al., 2017).

4.3 Implications and future perspectives

In this study, the InVEST model was used to evaluate the effects of land cover changes on terrestrial carbon stocks in the TTRB based on reliable estimates of aboveground biomass, belowground biomass, soil, and litter layer organic matter. Land cover change has been found to be responsible for the presence of hotspots for variations in carbon stocks. The total carbon stocks in the TTRB decreased by about 0.06 Tg C in the past 25 years. As recent human activities continued, the shrinkage of wetland and the fragmentation of forestland was highly significant mainly due to cropland reclamation, making land cover change an increasingly important driver of regional carbon changes. The results from this study suggest a need for potential policy enforcement to mitigate losses in carbon stocks due to land cover change in the TTRB and the expansion of some fast-growing cities in Northeast Asia. Impervious surfaces in the existing territory areas such as forestland, lakes and marsh wetland can be established as natural reserves and wetland parks to greatly increase biomass. Additionally, legislation should be implemented to protect wetland and forestland that serve the key leading role of storing large amounts of biomass carbon over time. In 1998, the Chinese government completed the 'The Land Administration Law of the People's Republic of China' and formulated a systematic land protection policy at a national scale (Wang et al., 2003; Liu et al., 2016). At the provincial level, Huangnong River Provincial Nature Reserve of Jilin Province was formally established in 2000, and Jilin Hunchun Northeast Tiger Nature Reserve was formally established in 2001. In North Korea, the central government released the 'Land and Environmental Conservation Management Act' in 1998, the 'Environmental Protection Law' in 1999, and the 'River Law' in 2003. The introduction of various laws and regulations has strengthened the link between land management and environmental protection, as well as the protection of forestland and wetland (Dong, 2011b). In Russia, the State Duma of Russia enacted the 'Russian Federation Law on the Protection of Nature Reserves' in 1995. With the support of that regulation, the country set up a number of state-level protected areas, such as nature reserves, national parks, natural parks, and national banned logging zones, which play a positive role in the protection of forestland and wetland (Zhu, 2002; Umberto et al., 2017).

There are still some limitations in this study. First, carbon density values used in this study were not field survey data, which may influence the accuracy of carbon stocks calculation (Zhang F et al., 2017). Second, some other important ecosystem services, such as water retention, crop production and soil retention were not considered in this study (McInnes and Everard, 2017). Finally, the evaluation of the impacts of land cover changes on carbon stocks is only a rough assessment, and did not consider the impacts from the perspective of ecological mechanism. However, these limitations did not fundamentally affect the results of this study. This paper depicted the changes of land cover in the TTRB from multiple scales and evaluated its impact on land cover carbon stocks, which had certain theoretical and practical significances.

In summary, this paper explored the responses of carbon stocks to land cover changes in the TTRB, and discussed the results from different type of carbon pools. The new Chinese Environmental Protection Law also emphasizes the conservation of forestland, wetland, and other natural ecosystems (Yang, 2014a). The effective implementation of new environmental law will greatly promote the increase of carbon stocks (Yang, 2014b). Therefore, this study can be very helpful for planners, policy makers and scholars concerned with carbon storage in China, North Korea and Russia. In future studies, we plan to verify the accuracy of carbon density estimates through field measurements, and some other important ecosystem services will be considered, including carbon sequestration (Collard and Zammit, 2006; Ouyang et al., 2016), water purification (Fiquepron et al., 2013; Arantes et al., 2016), climate regulation (Li et al., 2007), and recreation and aesthetic value (Nahuelhual et al., 2013). Furthermore, we will explore the impacts of land cover changes on ecosystem services from the perspective of ecological mechanisms and processes.

5 Conclusions

This study analyzed the spatial pattern of land cover change in the TTRB from 1990 to 2015. Land cover changes occurred in China, North Korea and Russia were highly different, especially on wetland and forestland. The wetland area decreased by 47.4%, 40.7%, and 4.9% in China, North Korea, and Russia, respectively. On the other hands, while the forestland area in China and Russia increased by 203.3 km^2 and 41.6 km^2, respectively, the forestland area of North Korea decreased by 187.4 km^2.

As a result of land cover changes, the carbon stocks was observed to change from 1990 to 2015, and decreased by 0.06 Tg C in the TTRB. Furthermore, the net balance of carbon stocks differed among China, North Korea, and Russia. The carbon stocks increased by 3.51 Tg C mainly due to the reforestation in China; meanwhile, deforestation in North Korea caused carbon stocks decreased by 3.13 Tg C; in Russia, the carbon stocks decreased by 0.44 Tg C mainly because of wetland shrink. The results of this study could assist China, North Korea and Russia to protect the land resources and promoting sustainable development in this region.

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