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Diverse policies leading to contrasting impacts on land cover and ecosystem services in Northeast China

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ABSTRACT

Understanding where important ecosystem services originate in space and how they change in time is essential for sustainable ecosystem management. Spatially explicit information of integrated changes in land cover and ecosystem services impacted by diverse policies has been unavailable in Northeast China, limiting the improvement of human well-being. Therefore, this study integrated remote sensing, meteorological records, and statistical data to evaluate the impacts of policies on land cover and ecosystem services from 2000 to 2015. The results reveal that diverse policies induced both notable changes in land cover, as well as geospatially varied changes in ecosystem services. Specifically, agricultural cultivation was still the dominant factor driving the losses of woodland, grassland, and wetland, while large areas of croplands have been returned to natural land cover, including a net area increase in woodland (2256 km^2). Cropland expansion occurred at the expense of wetland (7121 km^2), while the expansion of built-up land was converted primarily from cropland (62.8%). Marked decrease in water yield was observed, while sandstorm prevention, habitat suitability, and grain production have been enhanced on the scale of Northeast China. Moreover, soil retention and ecosystem carbon stock decreased slightly. In terms of present policies and changes in ecosystem services, it is important to rethink the emphasis on food production, reduce policy-driven natural ecosystem losses, and enhance the effectiveness of ecological projects. The findings are expected to help achieve win-win outcomes between ecological conservation and social-economic development in Northeast China.

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1. Introduction

Ecosystem services are the benefits humans derived from ecosystems, which play important roles in the sustainable development of human society and economy (Nelson et al., 2009). Continuous population growth, urbanization, and industrialization worldwide have imposed considerable pressures on ecosystems, altering the ecosystem services (Cumming et al., 2014). Over the past several decades, 60% of worldwide ecosystem services have degraded, which has led to remarkable negative influences on human well-being (Costanza et al., 2014). Therefore, understanding the spatiotemporal patterns of ecosystem services and their drivers has been a central issue for achieving natural resource management and sustainability on multiple scales.

A large number of studies have revealed that change in land cover is a primary driver of changes in ecosystems and their services (Lawler et al., 2014), while policy plays critical role in driving land cover change (Hansen et al., 2013; Mao et al., 2018a). Despite enhanced food production, agricultural land expansion has caused obvious declines in other ecosystem services such as water yield and carbon sequestration (Wang et al., 2015). A series of policies have promoted rapid economic development and urbanization, which induced a significant loss in natural habitats, leading to a remarkable loss of ecosystem services (He et al., 2014). Under the policies of economic development, mining destroyed the ecosystems and resulted in degraded ecosystem services (Allred et al., 2015). However, additional policies were created to mitigate these consequences, and policy-driven ecological restoration has

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enhanced diverse ecosystem services (Barral et al., 2015; Benayas et al., 2009). For example, a recent study revealed that the national conservation policies of China contributed significantly to the increase in ecosystem services including carbon sequestration, soil and water retention, sandstorm prevention, and flood mitigation (Ouyang et al., 2016). For sustainable ecosystems and social-economic development, we need to understand the responses of ecosystems to these polices. With the rapid development in remote sensing technology, the quantification of land cover changes and ecosystem services has become more accessible (de Araujo Barbosa et al., 2015). Therefore, a comprehensive and spatially explicit assessment in the impacts of diverse policies on land cover and multiple ecosystem services is essential.

Ecosystems simultaneously produce multiple ecosystem services that interrelate in complex and dynamic ways (Bennett et al., 2009). When humans pursue grain, timber, aquatic products, and other economic benefits, other services that are also important for human well-being may be underestimated (Lu et al., 2015). Scientific ecosystem management should therefore understand the relationships between these ecosystem services and balance them to maximize human well-being. Synergies and trade-offs between ecosystem services have thus been mostly focused worldwide (Howe et al., 2014). Previous studies documented that relationships between ecosystem services frequently change on both spatial and temporal scales (Bennett et al., 2009; Zheng et al., 2016). Therefore, additional studies in different regions are necessary to evaluate changes in multiple ecosystem services.

Northeast China is world-famous for its natural resources, grain production, and industrial base. Since the 1950s, large demands for food and economic development have destroyed significant natural land resources (Mao et al., 2018b), which has caused serious ecological consequences such as loss of biodiversity and water shortage (Jiang et al., 2017). Most recently, many policies, such as the “achieving an additional 50 million tons of grain production” and “Revitalizing the Old Industrial Base of Northeast China”, were developed to increase grain yield and revitalize the regional economy (Mao et al., 2018b). Although several ecological conservation policies and management measures were formulated to protect and restore natural ecosystems in this region (Cao et al., 2011; Mao et al., 2018a), their effectiveness was rarely evaluated. Further, information that integrates changes in land cover and ecosystem services is also hampered by a lack of quantitative and spatially explicit data. This information deficiency has limited decision-making for promoting regional economic development and improving human well-being. A comprehensive study focusing on how multiple ecosystem services have changed with land cover changes, impacted by diverse policies, is thus urgently needed for sustainable development in Northeast China.

This study aimed primarily to investigate the impacts of diverse policies on land cover and ecosystem services in Northeast China from 2000 to 2015. Specifically, we aimed to (1) examine land cover changes after 2000 in this eco-sensitive region, (2) document the spatially explicit information of multiple ecosystem services, and (3) identify the spatially varied changes in ecosystem services by dividing Northeast China into six geographic regions. The findings of this study are expected to improve sustainable management decisions in Northeast China.

2. Materials and methods

2.1. Study area

Northeast China extends from 115°32′E to 135°09′E, and 38°42′N to 53°35′N (Fig. 1), covering the Heilongjiang, Jilin, and Liaoning Provinces, as well as eastern portions of the Inner Mongolia Autonomous Region. The land area of Northeast China is approximately 1.24×10^6 km^2, accounting for 13% of the land area of China. Based on the pattern of the terrain, Northeast China can be divided into six geographic regions as shown in Fig. 1. Most of the study area is characterized by a temperate monsoon continental climate, except for areas located above 50°N latitude, which are dominated by the cold monsoon. Winter is long and cold, but the summer is short. Mean annual air temperature varies spatially from south to north, from 12 to -5 °C. Precipitation varies significantly within the year and decreases from 1100 mm in the southeast to 300 mm in the northwest. Northeast China plays a critical role both in ecological conservation and food security in China (Mao et al., 2014).

2.2. Datasets

From the database of the U.S. Geological Survey (USGS), we collected 256 scenes of Landsat Thematic Mapping/Enhanced Thematic Mapping Plus (TM/ETM+) images in 2000 and 289 scenes of Landsat OLI images in 2015 with lower cloud cover (<10%) to obtain land cover datasets in Northeast China. Images were limited to the months from May to October when plants are actively growing and no influence of snow cover. The digital elevation model (DEM) data with a resolution of 30 m and covering the study area were also obtained from the USGS. Additionally, this study also acquired the MODIS products, including surface reflectance (MOD09A1), land surface temperature (MOD11A1), and broadband white sky albedo (MOD43B3), from the USGS to support the estimation of evapotranspiration.

Meteorological records on the monthly scale were collected from the China Meteorological Data Sharing Service System. To control data quality, the missing climatic data in specific station and month were interpolated using the meaning value of adjacent two months. Vector boundaries of different ecological projects, and locations of nature reserves in Northeast China were obtained from the Chinese Academy of Sciences.

Information on the grain yield in 2000 and 2015 for each county in Northeast China was collected from the statistical yearbooks for each province. Gross domestic product (GDP) from the 1950s for Heilongjiang, Jilin, and Liaoning Provinces, as well as for all of China, were also collected from the Chinese statistical yearbooks to discuss changes in economic contribution of Northeast China to the whole country.

2.3. Land cover classification

Prior to image classification, all images were geo-rectified to 1:100,000 topographic maps using ground control points (GCPs). Each image had more than 30 evenly distributed GCPs to ensure that the root mean squared error of geometric rectification was less than 1 pixel (30 m). The land cover types were categorized into woodland, grassland, wetland, farmland, built-up land, and barren land. An object-oriented classification approach on the platform of eCognition Developer 8.64 software was used for the image classification. The classification process included four key steps: multiresolution segmentation, decision rule-based classification, preliminary result revision, and product accuracy assessment (Mao et al., 2018b). Satellite images were segmented into heterogeneous objects based on three parameters including scale, shape, and compactness. We compared these segmentation results on five scales: 5, 10, 20, 30, and 50, to match the landscape boundaries. By visual comparison, the optimal scale matching for the landscape features of specific region was determined. For most areas, the scale of 10 was the most acceptable for object boundary. Multiple decision rules referring to spectral features, landscape features, and

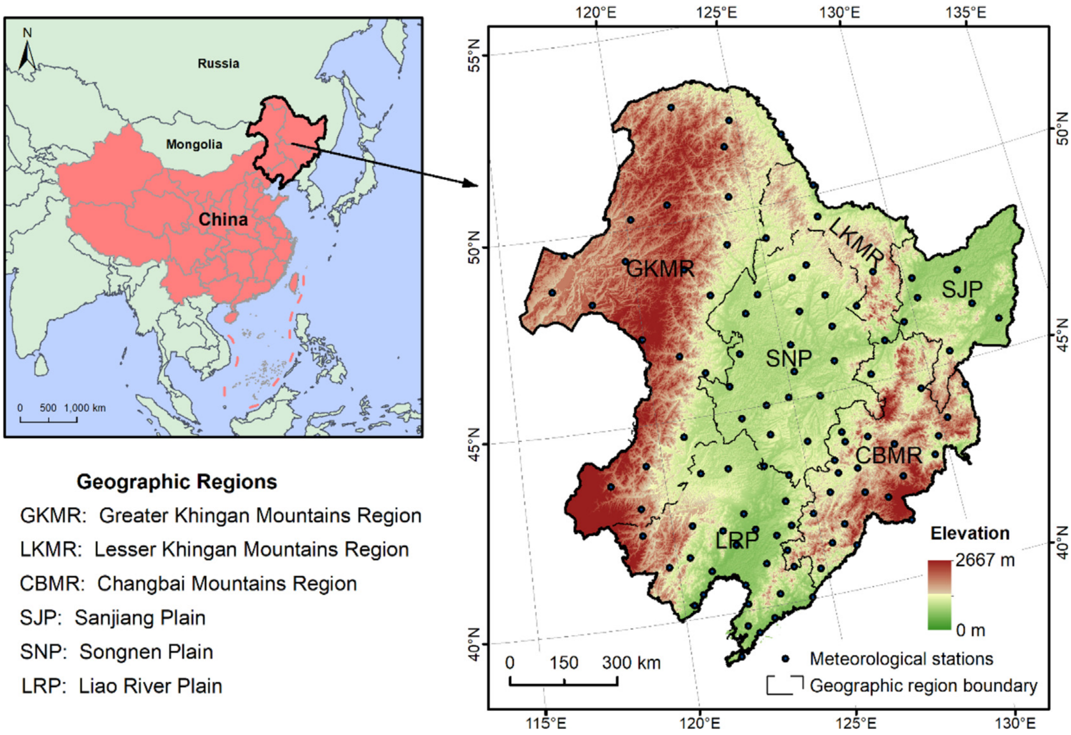

Fig. 1. Geographic location of Northeast China and general geographic features.

environmental features were used to classify the objects into certain land cover categories. A series of spectral indices and parameters were applied to develop decision rules. For example, the normalized differential vegetation index (NDVI) and brightness were used mostly to separate the land covered by vegetation or no vegetation. The normalized difference water index (NDWI) was used to identify wetland, while the normalized differential built-up index (NDBI) and the ratio of length to width were used to recognize built-up land. Texture, shape index, and phenology were combined to classify cropland. Prior knowledge about the landscape pattern over the study area is important to this process. In addition, vegetation map, DEM, and historical land use datasets contributed to the identification of different land cover categories (Mao et al., 2018b). The preliminary classification results were revised according to visual interpretation and ground survey samples (36,750 samples). Lastly, based on the ground truth points for validation (7689 for 2000 and 8130 for 2015), overall accuracy for land cover datasets in 2000 and 2015 was assessed to be 92% and 94%, respectively. Fig. 2 shows the spatial pattern and composition of the land cover categories in 2015 over Northeast China.

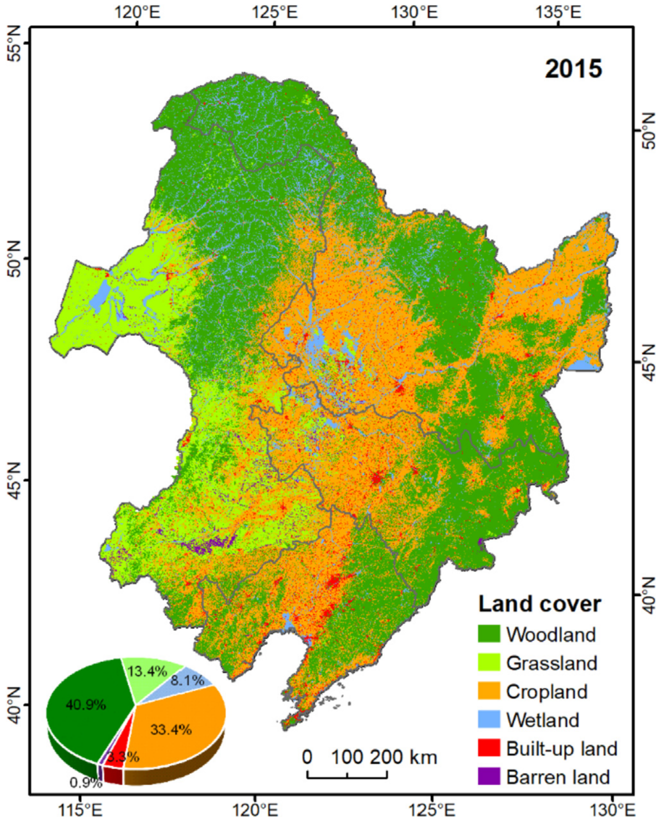

Fig. 2. Spatial pattern of land cover categories in Northeast China.

2.4. Quantifying ecosystem services

As the ecological barrier in northern China and grain base, Northeast China requires sustainable ecosystem management because the ecosystem services are important to human in this region, even in the whole country. Considering the dominant ecosystem types as described above, water yield, ecosystem carbon storage, soil retention, sandstorm prevention, habitat provision, and food production are recognized to be major types of ecosystem services in Northeast China. Therefore, besides the land cover change analysis, the ecosystem service changes were also performed to assess ecosystem changes. Specifically, we quantified the patterns and changes in six ecosystem services between 2000 and 2015 over the study area. Moreover, to compare the dynamics of ecosystem services and their relationships in six geographic regions, the numerical values for each ecosystem service in 2000 and 2015 were normalized ranging from 0 to 1 by dividing each service value to the largest value between the two years. Methods used to quantify the ecosystem services are documented as follows.

2.4.1. Water yield

Water yield characterizing hydrological regulation was estimated from precipitation and actual evapotranspiration (AET) based on Equation (1) (Wang et al., 2015). Precipitation was interpolated from the meteorological records using the ANUSPLIN software (Wang et al., 2015). AET was estimated using a remote sensing flux algorithm named SEBAL model (Bastiaanssen et al., 1998) combined with MODIS products and meteorological records on the monthly scale. The SEBAL model was calibrated and estimated AET was also validated by the eddy covariance measurements from the Sanjiang Wetland Experimental Station, Chinese Academy of Sciences (Wang et al., 2015).

$$\mathrm{WY}_i = \sum_{i=1}^{j} (\mathrm{P}_i - AET_i) \times A_i \tag{1}$$

where WY_i, P_i, AET_i, and A_i are water yield (mm), annual precipitation (mm), annual AET (mm), and area (km^2), respectively, in corresponding pixel *i*.

2.4.2. Ecosystem carbon storage

Regional ecosystem carbon storage in 2000 and 2015 was estimated using the InVEST (Nelson et al., 2009). The detailed quantification approach and coefficients were referenced from the study of Xiang et al. (2018). As shown in Equation (2), ecosystem carbon storage was calculated from carbon density and area.

$$\mathrm{CS}_i = \mathrm{CD}_i \times \mathrm{A}_i \tag{2}$$

where CS_i is carbon storage ($\mathrm{t \cdot km^{-2}}$) in pixel *i*; CD_i is carbon density ($\mathrm{t \cdot km^{-2}}$) in pixel *i*; and A_i ($\mathrm{km^{-2}}$) is the area of a pixel.

2.4.3. Soil retention

The Universal Soil Loss Equation (USLE) shown as Equation (3) was used to evaluate the capacity of soil retention in 2000 and 2015 over Northeast China. The soil retention capacity (SC, $\mathrm{t \cdot km^{-2}}$) is affected by four important factors including rainfall erosivity (R), soil erodibility (K), topography (LS), and vegetation coverage (*C*).

$$\mathrm{SC} = \mathrm{R} \times \mathrm{K} \times \mathrm{LS} \times (1 - \mathrm{C}) \tag{3}$$

A detailed introduction for this model can be found in the study of Jiang et al. (2018). *R* is calculated from the raster data of annual precipitation, while *K* is quantified based on the soil map covering Northeast China, which was provided by the Resource and Environment Data Cloud Platform, Chinese Academy of Sciences. DEM was used to generate slope length and gradient for assessing *LS* in the study area. The *C* factor, characterizing the positive effect of vegetation on soil erosion, was assigned values based on the vegetation structure and cover type.

2.4.4. Sandstorm prevention

We used the Revised Wind Erosion Equation (RWEQ) to quantify the sandstorm prevention service which refers to the sand retained in ecosystem within a given period (Jiang et al., 2018). Sandstorm prevention is an important goal of some important ecological projects in Northeast China such as the Three North Shelter Forest System Project (TNSP). RWEQ has been widely used, and its detailed introduction can reference the study of Ouyang et al. (2016). We can estimate the sandstorm prevention (*SP*) as a function of several factors (Equations (4)–(6)) including the weather factor (*WF*), soil erodibility (*EF*), the soil crust factor (*SCF*), surface roughness (*K*′), and vegetation cover (*C*).

$$\mathrm{SP} = \frac{2Z}{S^2} \times Q_{max} \times e^{-(Z/S)^2} \tag{4}$$

$$S = 150.71 \times \left(WF \times EF \times SCF \times \mathrm{K}' \times C\right)^{-0.3711} \tag{5}$$

$$Q_{max} = 109.8 \times WF \times EF \times SCF \times \mathrm{K}' \times C \tag{6}$$

where SP ($\mathrm{t \cdot km^{-2}}$) is the capacity for sandstorm prevention; *S* is the critical field length; Z is the distance from the upwind edge of the field; and Q_{max} is the maximum transport capacity. In this study, the value of *Z* is assigned to be the same as *S*.

2.4.5. Habitat suitability

To assess habitat suitability, we used a habitat suitability index (HSI, Wang et al., 2015) to characterize habitat changes. HSI is developed from four key indicators, which directly affect habitat quality, including food abundance, water availability, disturbance, and shelter condition (Equation (7)). Food abundance is characterized by normalized differential vegetation index (NDVI), which is an important index reflecting vegetation growth and coverage. Water availability is characterized by the density of lakes and rivers, which is extracted from the land cover datasets. Disturbance is mostly from human activities and thus is characterized by the density of roads and residences. Land cover and slope reflecting the habitat safety of shelters are used to characterize the shelter condition. The values for each indicator were normalized, ranging from 0 to 100. Finally, HSI was integrated from the four indicators with a weighting coefficient of 0.3 for both food abundance and water availability, and 0.2 for both disturbance and shelter condition. The weighting coefficients for those factors were determined using the analytic hierarchy process approach (Tian et al., 2019).

$$HSI = \sum_{i=1}^{4} W_i \times F_i \tag{7}$$

where W_i is the weighting coefficient for factor *i*, while F_i is the value of factor *i*.

2.4.6. Grain production

Food production refers to the food produced by ecosystems. Because grain, including rice, wheat, corn, and soybean, is the dominant food product in Northeast China, we chose grain production as the proxy for the food provisioning service. The amount of produced grain (t) in each county collected from statistical yearbooks was mapped in ArcGIS software. In addition, the amount of produced grain in all the counties of each geographic region was accumulated.

3. Results

3.1. Land cover changes in Northeast China

Notable land cover conversions were identified between 2000 and 2015 (Fig. 3) due to human and climatic drivers. Extensive deforestation was observed in the six geographic regions and most of the grasslands were lost in the GKMR and SNP. Remarkable wetland losses were examined in both the SNP and SJP, while barren land was clearly reduced in the SNP. Losses of cropland were observed mostly in plains, including the SJP, SNP, and LRP (Fig. 3A). However, afforestation was also clearly found in all of Northeast

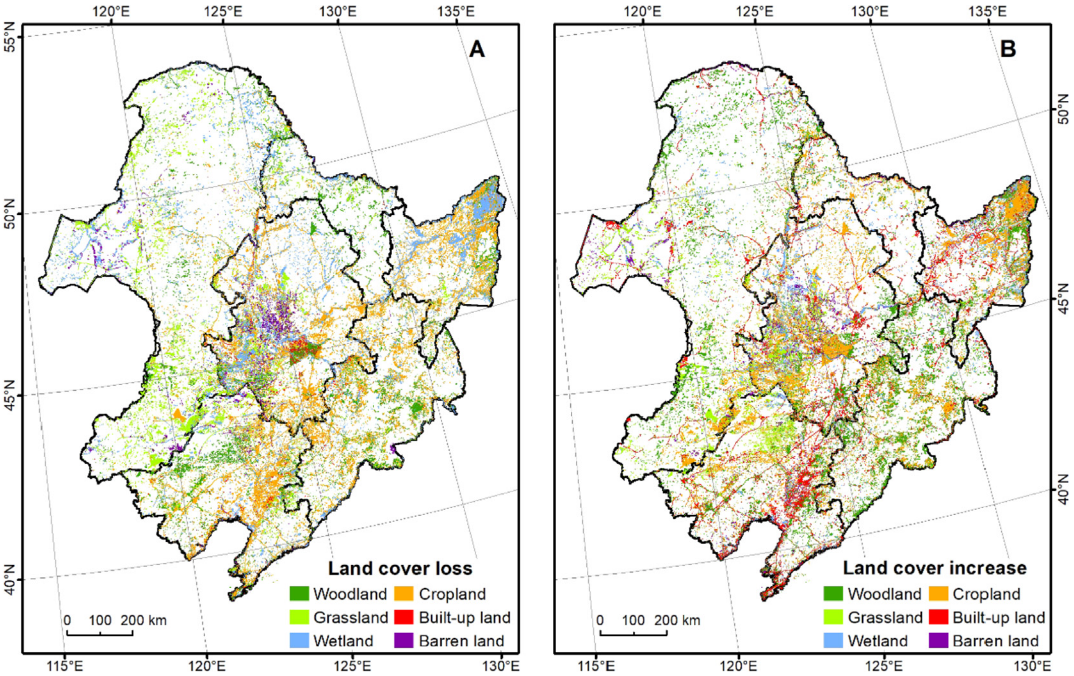

Fig. 3. Pattern of land cover changes in Northeast China from 2000 to 2015: A, land cover loss; B, land cover increase.

China, while grassland restoration was implemented in the northern LRP and western SNP. A little area of wetlands were restored in the southeast SJP and west SNP, while land salinity/sodicity amelioration was developed in the western SNP. Notable cropland and built-up land expansions occurred in the SJP, SNP, and LRP (Fig. 3B).

To determine the specific land cover conversions, a statistic of the transition matrix was created (Table 1). During the first 15 years of the 21st century, woodland increased by 2256 km^2, while grassland and wetland decreased by 3378 and 4828 km^2, respectively. Cropland and built-up land expanded by 1855 and 5732 km^2, respectively, while barren land was reduced by 1236 km^2. Agricultural cultivation was the dominant force driving the losses of woodland, grassland, and wetland, while the expanded croplands were cultivated mainly from wetlands (7120.5 km^2). Expanded built-up lands were primarily converted from croplands (62.8%) and encroached upon large areas of woodland, grassland, and wetland. Additionally, ecological restoration has been notably implemented in China. For example, 4140, 1120, and 2949 km^2 of croplands were converted into woodland, grassland, and wetland, respectively. There were 925 km^2 of grasslands and 1039 km^2 of wetlands rehabilitated from barren lands.

3.2. Spatial pattern of ecosystem services over Northeast China

Spatially explicit ecosystem services quantified in 2015 are shown in Fig. 4. For water yield, large values (>20 $m^3\ km^{-2}$) were identified in eastern parts and especially in the central CBMR which were mostly covered by broadleaved deciduous forest, while the low values were in the west (Fig. 4A). The pattern of ecosystem carbon density was largely related to the distribution of land cover. The three geographic regions (the GKMR, LKMR, and CBMR) dominantly covered by woodland had large ecosystem carbon density (>15×10^9 gC·km^{-2}), while areas in the GKMR, SNP, and LRP covered by grassland showed medium values, and the SJP, SNP, and LRP covered by cropland presented low ecosystem carbon density (Fig. 4B). The pattern of soil retention revealed that the capacity for soil retention was linked primarily to terrain features. In Northeast China, larger values over the mountain areas were observed than over the plain areas (Fig. 4C). Three hotspot areas with high capacity that were mostly covered by sparse vegetation were identified for sandstorm prevention, including the Hulun Buir Plateau in the west GKMR, Horqin Sandy Area in the north LRP, and the ecotone between the SJP and CBMR (Fig. 4D). In general, the study area provided good habitat. However, low suitability indicated by HSI was dominantly observed in the southwestern regions (the southern GKMR and northern LRP) that were covered by sparse grassland and have a relatively drier climate (Fig. 4E). Grain production was dominantly identified in the three plains, especially in most areas of the SNP with annual yield larger than 0.8×10^6 t (Fig. 4F).

Table 1
Transition matrix of land cover categories from 2000 to 2015.

Area (km^2)	Woodland	Grassland	Cropland	Wetland	Built-up land	Barren land	Total
Woodland	501,655.7	944.5	3234.0	852.5	702.5	65.5	507,454.7
Grassland	2584.7	161,251.8	3052.3	1607.6	963.7	444.7	169,904.8
Cropland	4139.7	1120.1	400,671.1	2949.0	3795.7	208.3	412,883.9
Wetland	1113.7	1862.0	7120.5	94,366.6	526.0	707.3	105,696.1
Built-up land	42.4	23.3	176.2	53.5	34,522.4	13.3	34,831.1
Barren land	174.4	925.2	484.4	1038.9	52.6	9755.8	12,431.3
Total	509,710.6	166,126.9	414,738.5	100,868.1	40,562.9	11,194.9	1,243,201.9

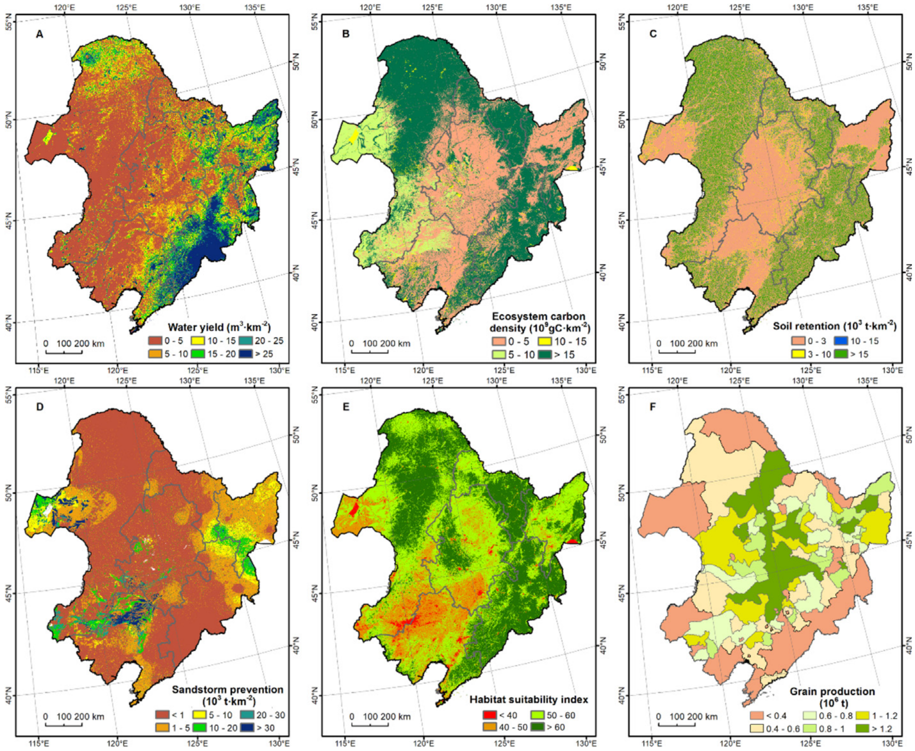

Fig. 4. Spatial pattern of ecosystem services: A, Water yield; B, Ecosystem carbon density; C, Soil retention; D, Sandstorm prevention; E, Habitat suitability; F, Grain production.

3.3. Temporal changes in ecosystem services from 2000 to 2015

For the whole study area, three ecosystem services were reduced, but two of the ecosystem services changed slightly (Table 2). Specifically, the amount of water yield decreased by 10.8 million t (11.8%) from 2000 to 2015. The ecosystem carbon storage and soil retention declined slightly with the change percentage smaller than 1%. The other three ecosystem services have been improved. As stated in Table 2, the capacity for sandstorm prevention was enhanced by 45.9 t km^{-2}, and its total amount increased by 1.3%. Area in good suitability (HSI > 50) increased by 61.4 thousand km^2 or 6.7%. Striking increase was identified for annual grain production with an amount of 81.5 million t or by 139%.

For a specific assessment of the dynamic ecosystem services, the changes in the six normalized ecosystem services over the six geographic regions are compared in Fig. 5. Water yield service diminished in 5 geographic regions except the LKMR, when the SNP experienced the largest decease (Fig. 5A). Ecosystem carbon storage declined in 5 geographic regions especially in the SJP, but the CBMR showed a slight increase (Fig. 5B). Soil retention (Fig. 5C) was slightly weakened in three geographic regions (the GKMR, SJP, and LRP), but was slightly enhanced in the other 3 regions (the LKMR, CBMR, and SNP). The capacity for sandstorm prevention (Fig. 5D) was obviously enhanced in three western regions (the GKMR, LRP, and SNP), but decreased slightly in three eastern regions (the LKMR, CBMR, and SJP). Habitat suitability was markedly improved in the GKMR, LRP, and SNP, while other three regions experienced small changes (Fig. 5E). Grain production was substantially increased in all the 6 geographic regions in Northeast China (Fig. 5F).

4. Discussion

4.1. Land cover changes driven by polices

Remarkable policy-driven bidirectional conversions of land cover were observed in this region during the period of 2000–2015 (Table 1). Northeast China played critical roles in proving food, timber, and mineral resources for a long time. Based on our estimation, there were still 3234 km^2 of woodland, 3052 km^2 of grassland, and 7121 km^2 of wetland replaced by cropland expansion during the 15 years observed. As reported by Mao et al. (2018a), a series of policies in China were developed to stimulate agricultural development for grain production from the 1980s (Fig. 6A). For example, the second round of the household responsibility system (1997–2027) coupled with the rescission of the agricultural tax in 2005 have triggered large numbers of illegal

Table 2
Value changes in ecosystem services from 2000 to 2015.

Ecosystem services (unit)	Value in 2000	Value in 2015	Change percentage
Water yield (10^9 m^3)	125.7	110.9	−11.8%
Ecosystem carbon storage (Tg)	19,146.0	18,960.5	−0.97%
Soil retention (10^6 t)	63,222.9	63,212.1	−0.02%
Sandstorm prevention (10^9 t)	4423.4	4480.5	1.3%
Area of good habitat (10^3 km^2)	923.0	984.4	6.7%
Grain production (10^6 t)	58.8	140.3	139%

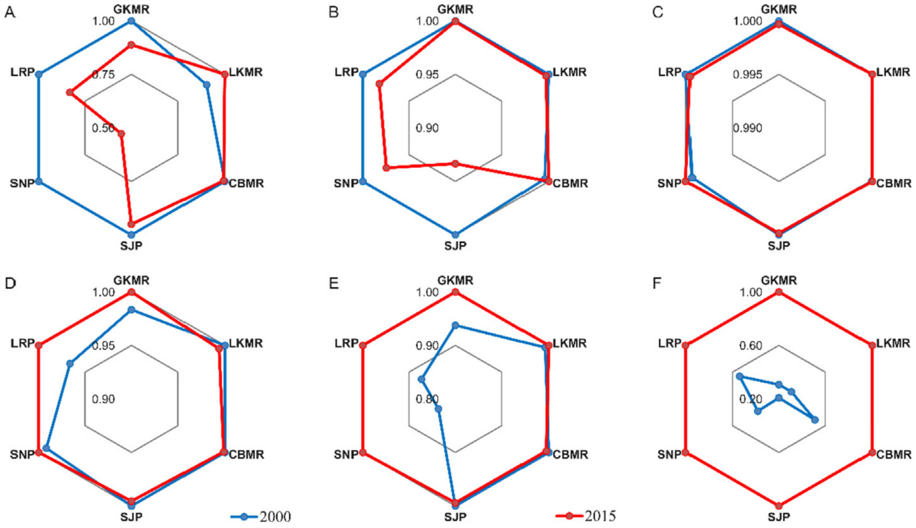

Fig. 5. Changes in normalized values of ecosystem services in six geographic regions from 2000 to 2015: A, water yield; B, ecosystem carbon storage; C, soil retention; D, sandstorm prevention; E, area of good habitat suitability; F, annual grain production.

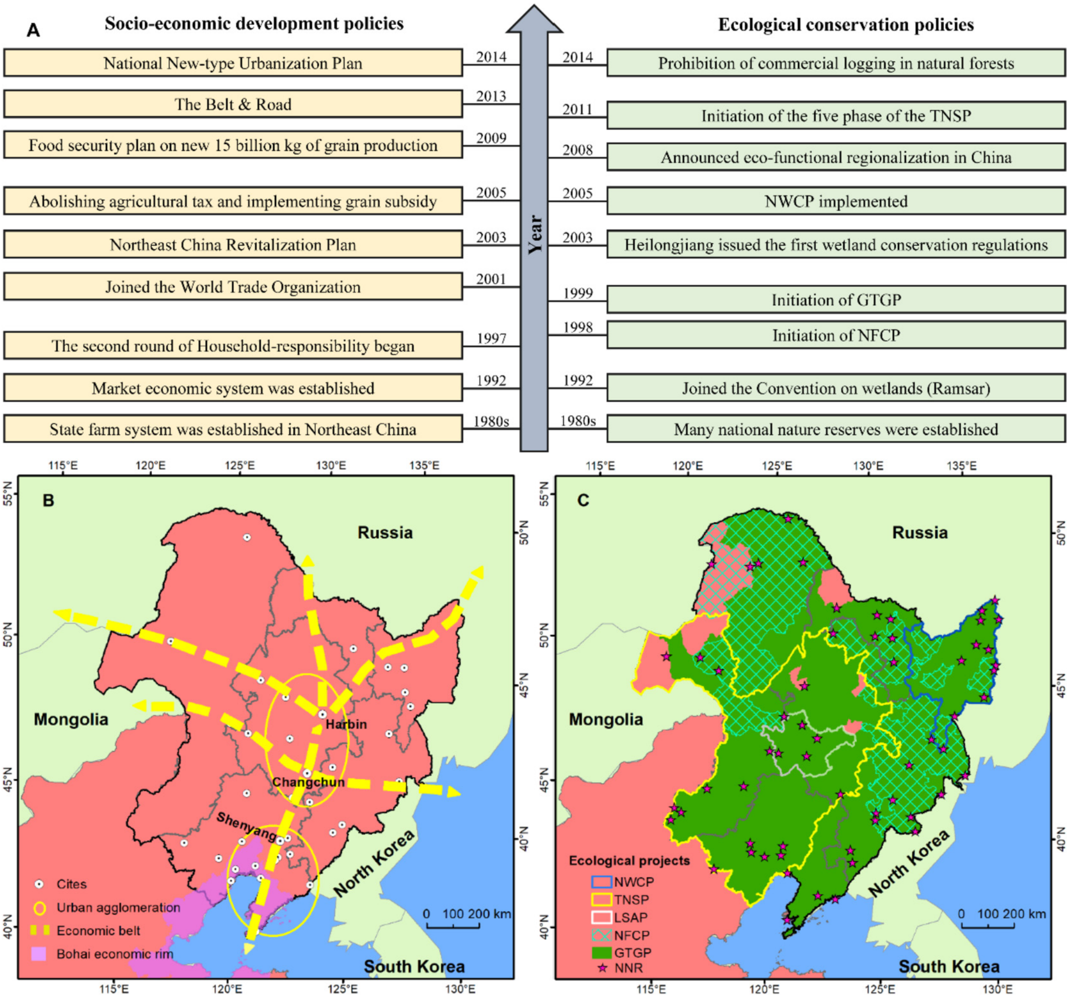

Fig. 6. A summary of bidirectional policies in Northeast China for socio-economic development and ecological conservation: A, different policies for socio-economic development and ecological conservation from 1980s; B, distribution of urban agglomeration, economic belt or rim in the Northeast China; C, distribution of various ecological projects; NWCP, natural wetland conservation project in the Sanjiang Plain; LSAP, land salinity/sodicity amelioration project in the Songnen Plain; NFCP, natural forest conservation project; GTGP, grain to green project; TNSF, three north shelter forest system project; and NNR, national nature reserves.

cropland cultivations from natural ecosystems. In 2009, China launched a food security program to achieve an additional 50 million tons of grain yield. Northeast China undertook critical roles (30%) in this program, especially in Heilongjiang Province. In addition to these agricultural policies, expanded grain markets after joining the World Trade Organization (WTO) promoted the farming profits and contributed largely to the area increase in cropland. Except for the direct encroachment, policy-driven conversion from dry farmland to paddy field also caused water shortages (Chen et al., 2015a), which further led to loss and degradation of wetland and grassland.

In addition to agricultural encroachment, regional urbanization and industrialization largely linked to policies also removed large areas of natural land cover (Table 1). Murray et al. (2014) documented that extensive losses of tidal flats along the Yellow Sea associated with unprecedented coastal development occurred before the 2000s. However, Northeast China, the past economic locomotive, has experienced a serious economic downturn during recent decades. Although there was an increase in GDP, significant decline in the contribution to China's total amount of GDP (from 19.1% to 7.1%) was identified (Fig. 7). Currently, the economic development in Northeast China was a matter of extensive concern by the central and local governments. The policy of “Revitalizing the Old Industrial Base of Northeast China” proposed in 2003 greatly promoted urban expansion in Northeast China. In the National Thirteenth Five-Year Plan (2015–2020), development of two urban agglomerations (Fig. 6B), Harbin-Changchun and Central-South Liaoning, in Northeast China were strongly supported (Mao et al., 2018b). The grand policy of “the Belt and Road” initiative also attempted to enhance the economic cooperation between Northeast China and other countries in Northeast Asia. The economic corridor among China-Mongolia-Russia was designed to revitalize regional economy (Fig. 6B). Under the background of these national policies (Fig. 6A, and B), great challenges thus still exist for sustainable utilization of land resources and ecosystem management.

From the 1980s, serious ecological problems have been recognized, and many ecological policies were thus made to protect and restore natural ecosystems (Fig. 6A). For reducing water loss, soil erosion, and desertification, TNSF was developed from 1979. To respond to large amount of deforestation and associated ecological issues (e.g., flood in 1998), the natural forest conservation project (NFCP) and the grain to green project (GTGP) were implemented, especially in Northeast China (Fig. 6C). From the implementation of these two projects, China stopped the commercial logging in natural forests, and large areas of afforestation can be observed (Fig. 3). Our results reveal that the GTGP has achieved reconversion of 4140 km^2 of cropland into woodland from 2000 to 2015. Different from the shrinkage in grassland and wetland, the total area in woodland had a net areal increase by 2256 km^2 in Northeast China after 2000 rather than a decline before 2000. Despite a net loss in area, the conservation and rehabilitation of grassland and wetland have been largely enhanced (Mao et al., 2018a). A natural wetland conservation project (NWCP) was performed in the largest marsh distribution area, the SJP. The government of Heilongjiang Province issued the first provincial wetland conservation ordinance in China. Jilin Province developed land salinity/sodicity amelioration project (LSAP) in the SNP to restore grassland. The conversions from cropland to grassland (1120 km^2) and wetland (1862 km^2) between 2000 and 2015 are related mostly to these two projects. Although extensive areas of cropland have been reconverted into woodland, grassland, and wetland, the restoration in the ecosystem functions and services needs a longer time and falls short of their natural levels (Chazdon, 2008; Zedler, 2003). Therefore, better understanding of changes in ecosystem services in terms of diverse policies is necessary for sustainable ecosystem management.

4.2. Dynamic ecosystem services across scales in terms of diverse policies

Land cover changes altered ecosystem structure and thus influenced ecosystem services. At the country scale, Ouyang et al. (2016) reported improved ecosystem services from 2000 to 2010 including food production, carbon sequestration, soil retention, sandstorm prevention, water retention, and flood mitigation, except the habitat provision. Differently, our results indicated that, on the scale of Northeast China and in the period of 2000–2015, the three kinds of services, including sandstorm prevention, habitat provision, and grain production, have been substantially enhanced, while the services of water yield have been markedly weakened. Although both the value of soil retention and carbon sequestration decreased from 2000 to 2015, their change percentages were very small. At both the scales of China and Northeast China, geospatially varied changes in multiple ecosystem services were identified due to heterogeneous ecosystem patterns and diverse policies.

In terms of land cover conversions, it is evident that a conspicuous increase in grain production can be attributed mostly to extensive cropland expansion (Morton et al., 2006; Wang et al., 2015). Enhanced sandstorm prevention is largely related to the policy-driven afforestation such as the TNSP, specifically why sandstorm prevention was enhanced in the three western geographic regions where the major covering regions of TNSP

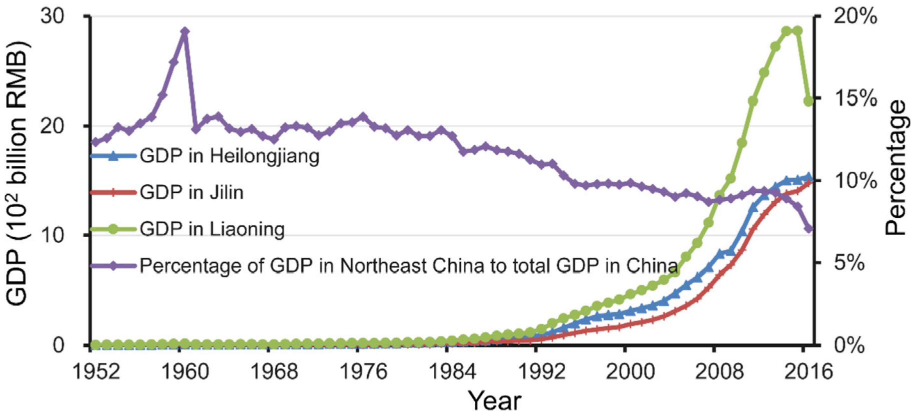

Fig. 7. Changes in annual GDP of three provinces and their contribution to total China's GDP. (Due to the administrative division changes and low values of GDP for eastern Inner Mongolia, its data were excluded in this analysis).

(Fig. 6B) are, rather than the eastern three regions. Evidence was also found in the study of Zhang et al. (2012), which reported that the ecological restoration greatly contributed to the increased vegetation cover and prevented sand dune expansion in the Horqin Sandy Land in Northeast China. The area of good habitat suitability obviously increased, probably caused by the multiple ecological projects, including the GTGP, NSCP, NWCP, etc. Great protection and restoration on the natural ecosystems was achieved in the western three regions. Notable increase in forest NPP over the western part of Northeast China has been confirmed by Mao et al. (2014), indicating improved ecosystem services. Specific to the CBMR and SJP, the degraded habitat suitability was identified. In addition to the losses in forest and wetland, habitat fragmentation and human disturbances were the important driving forces (Tao et al., 2017; Wang et al., 2015).

However, Northeast China experienced evident declines in water yield during 2000–2015. Because an increased annual precipitation and a decreased annual mean temperature were observed in Northeast China after 2000. We thus argue that such a decline can be attributed to increased vegetation cover. The increased vegetation caused the substantial enhancement of evapotranspiration, and thus led to a decline in water yield. Similar arguments could also be found for the Loess Plateau, which is one of the important areas for converting cropland to woodland (Feng et al., 2016). Specific to the LKMR which lost some forests during 2000–2015 (Fig. 3), water yield in the LKMR thus increased. In addition, there were slight decreases in soil retention and carbon storage for the whole Northeast China, which were strongly correlated to human-induced loss and degradation of natural ecosystems (Ouyang et al., 2016; Wang et al., 2015). Gong et al. (2017) documented that vegetation restoration obviously increased soil carbon stocks in China. Such evidence can be found in the CBMR where a slight increase in ecosystem carbon density was identified (Fig. 3B). However, ecological restoration in other regions of Northeast China did not offset the decline in ecosystem carbon storage caused by climate change and human disturbance, especially in the SJP. Mao et al. (2015) reported that wetland has larger soil organic carbon density than other land covers in the SJP. Thus, the most significant decline in ecosystem carbon storage in the SJP can be strongly clarified by its extensive wetland loss (4828 km^2), despite the NWCP implemented here. Considering these changes in multiple ecosystem services, it is urgently necessary to reduce the policy-driven natural ecosystem losses and to improve the effectiveness of ecological projects in Northeast China.

4.3. Balancing policy impacts for a sustainable Northeast China

In Northeast China, diverse policies were implemented. On the one hand, many policies such as “Revitalizing Old Industrial Base of Northeast China”, “Food Security Program”, and the “Economic Corridor among China-Mongolia-Russia” were formulated to promote socioeconomic development (Fig. 6A). These policies caused notable expansion in cropland and built-upland and accompanied encroachment into woodland, grassland, and cropland. Furthermore, these policy-driven land cover changes further induced distinct ecosystem service degradation, including decreased ecosystem carbon sequestration, water yield, and soil retention (Fig. 5). On the other hand, many policies were developed to protect and restore natural ecosystems (Fig. 6A). These ecological projects supported by policies largely contributed to the increase in woodland, and the restoration of grassland and wetland from cropland and barren land. Meanwhile, the ecological conservation network was designed to protect important habitats and species. China has established numerous nature reserves including 62 at the national level and 89 at the provincial level to protect natural ecosystems in Northeast China. Therefore, multiple ecosystem services were enhanced in specific regions of Northeast China (Fig. 5). Comprehensively considering regional sustainability both in social-economy and ecological security, we need to rethink the policies performed in this important region.

First, we should reduce emphasis on food production, which was categorized as the most important underlying driver for shrinkage and degradation of natural ecosystems. Notable impacts of agricultural cultivation on ecosystem services have been observed in this study (Table 1). In addition, the population increase rate has remarkably slowed in the recent decade, and the grain yield per unit area has been enhanced more than in previous decades. At present, it is really bad to increase grain production through expanding cropland area. Green agriculture should be enhanced to reduce the influence of agricultural activities on other ecosystems (Chen et al., 2015a).

Second, scientific strategies are necessary for urbanization. We should not focus only on extensive urban expansion, but we should also focus on the enhancement of urbanization quality. In the process of urbanization, large areas of croplands with high-quality soil were destroyed, which affected food security (Chen, 2007). Additionally, urbanization also impose great pressure on water resources, carbon sequestration, and other services, especially in the drylands (Li et al., 2017). Therefore, Northeast China must get rid of the unscientific policies, such as “Grow First, Clean up Later”. The ideology of “Green hills and clear waters are gold & silver mountains” said by the President Jinping Xi should be practiced.

Third, effectiveness of ecological projects and protected areas should be enhanced. Although large areas of croplands have been converted into natural land covers, the declines in multiple ecosystem services were not reversed. For example, an increased area in woodland was identified in Northeast China. However, woodland ecosystem quality should be improved to mitigate limited or inappropriate species in the afforestation (Cao et al., 2011). Lu et al. (2016) assessed the conservation effectiveness of 28 wetland protected areas in Northeast China and found that the conservation effectiveness in most of reserves decreased due to human disturbances between 2000 and 2012. Improving the effectiveness of ecological projects and protected areas is a matter of priority.

In this study, geospatially varied changes in multiple ecosystem services were identified. Although we do not investigate the synergies and trade-offs between coupled ecosystem services, the opposite changes among them indicate that we should be concerned about their relationships in specific regions. For example, Chen et al. (2015b) reported that the GTGP of China has greatly increased vegetation cover and reduced soil erosion on the Loess Plateau. However, they argued that the vegetation should be maintained but not expanded further due to limited water resources. In Northeast China, the SNP, which is dominant in the drier climate, showed an improved soil retention, sandstorm prevention, and habitat suitability, but a declined water yield. Therefore, the resilience of regional water resources must be evaluated. Ecosystem changes impacted by diverse policies were evident not only in Northeast China, but also in a lot of areas in China (Mao et al., 2018c; Zhang et al., 2018). Therefore, optimal land management for China's sustainability requires to balance the impacts of diverse policies on ecosystems by investigating the land cover and ecosystem service changes at different scales. Additionally, the implications stated above should be primarily considered for the eco-fragile regions.

5. Conclusions

Integrating multi-source remote sensing, meteorological records, and statistical data, our study documented the policy-driven land cover changes in Northeast China, where important ecosystem services originate and are changing on different scales during 2000–2015. Northeast China experienced significant area increases in woodland, cropland, and built-up land, simultaneous declines in grassland and wetland. Sandstorm prevention, habitat suitability, and grain production were significantly enhanced, while the capacity for water yield decreased markedly, and soil retention and ecosystem carbon sequestration decreased slightly. Additionally, geospatially varied changes in multiple ecosystem services were also identified due to heterogeneous ecosystem patterns and diverse policies. Agricultural cultivation was still the dominant driver for losses in the natural ecosystems and degradation in ecosystem services during the observed 15 years, while urbanization and industrialization contributed largely to these changes. Although policies enhanced ecological conservation and achieved improvement in specific ecosystem services, great challenges still exist in terms of the present policies for social-economic development. Balancing grain production and ecological conservation and developing place-based management policies are especially urgent goals for this eco-sensitive region.

Author contributions

D.M., X.H., and Z.W. conceived and designed the study. Y.T., H.X., H.Y., and W.M. performed the estimation of ecosystem services. M.J., C.R., and H.Z. performed the image classification and collected the statistical dataset including the GDP and grain production. D.M. performed the data analysis and wrote the manuscript. Z.W., X.H. revised the paper.

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