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# Spatio-temporal changes in water-related ecosystem services provision and trade-offs with food production

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A B S T R A C T

A key challenge for sustainability is protecting water-related ecosystems and the services (WESs) they provide while enhancing food security. Food production usually drives land use change, which results in ecosystem services provision being altered. However, the underlying mechanisms are still unclear and relevant research is scarce. In this study, a spatio-temporal assessment framework was developed to assess the impact of food production-driven land use change on WESs and to analyze tradeoffs between food production and WESs provision, taking Songhua River Basin (SRB) as a case study. The results showed that: 1) food production increased from $0.497 \times 10^8 tons$ to $0.798 \times 10^8 tons$ despite area of cultivated land decreasing from $23.61 \times 10^4 km^2$ to $23.40 \times 10^4 km^2$ during the study period (2000–2015). 2) Water yield and soil retention both showed a downward trend, while nitrogen and phosphorus exports showed an increasing trend, in 2000–2015.3) Food production showed a trade-off relationship with soil retention and water yield, but a synergistic relationship with nitrogen and phosphorus export. This is important empirical evidence of the impact of food production-driven land use change on WESs. For simultaneous development of food production and WESs, a form of sustainable agricultural production must be established, with intensification of existing land use and establishment of farmland shelterbelts. This critical knowledge can be applied in developing practical ecosystem protection measures and land management strategies for food security in China and beyond.


## 1. Introduction

Water-related ecosystem services (WESs), mainly including water yield, soil retention, water purification, climate regulation, and biodiversity, are the products of interactions between water ecosystems and their surrounding terrestrial ecosystems (Chen et al., 2018a; Schmalz et al., 2016). WESs makes important contributions to the natural environment and to human well-being (Sahle et al., 2019; Yang et al., 2015). For example, water yield can act on irrigation water supply (Ghimire and Johnston, 2019), while soil retention is beneficial for maintaining a healthy agricultural environment (Shi et al., 2017). Given the importance of WESs, people are increasingly recognizing their value and research in the area has been growing rapidly in recent years, especially within sustainable development (Romulo et al., 2018). Inevitably, with human activities and economic development, the land cover on the Earth's surface has changed greatly, and the ability for WESs provision has been weakened (Hao et al., 2019; Zijp et al., 2017). This has resulted in impaired water purification (Gounand et al., 2018), soil erosion (Borrelli et al., 2017), unstable biodiversity maintenance (Schuldt et al., 2018), and decreased soil carbon storage (Lal, 2004). In addition, increasing some supply services may cause a decline in other regulating services (Bai et al., 2019). Therefore, it is necessary to better understand the mechanisms of WESs change

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and the driving factors.

Land use change has been identified as a main factor driving WESs change, as it can alter the function and process of WESs (Liu et al., 2019). Many researchers have studied the impact of land use change on WESs (Bai et al., 2016a). A great number of studies have reported real-world ecosystem problems, such as decreasing biodiversity maintenance (Dainese et al., 2019), habitat loss (Auffret et al., 2018), degrading water availability and quality (Camara et al., 2019; Ding et al., 2016), and soil loss (Nabiollahi et al., 2018), all caused by land use change. Thus land use change is widely accepted as the primary driver of WESs change (Gao et al., 2017; Newbold et al., 2015). However, while previous studies have clearly demonstrated that changes in land use influence biophysical processes, which further affect WESs provision, the real question is what is hidden behind land use changes.

In previous studies, changes in land use have been attributed to the impact of socio-economic development (Tesfaw et al., 2018), population growth (Mumba et al., 2017), urban expansion (Bai et al., 2016b), industrial construction (Chen et al., 2018b), food production (Rega et al., 2019), tourism (Li et al., 2020a), and recreational activities (Fisher et al., 2018). However, identifying the driving factors for land use change is difficult and these factors are site-specific, because the key characteristics and resources in each region are different (Kindu et al., 2016). This poses challenges for policy makers, because these drivers must be identified and fully taken into account for optimal land use management.

The continuous future increase required in global food production may be challenged due to the impact of COVID-19 and other uncertain risks, such as natural disasters (Lenderking et al., 2020) and tensions in international food trade (Wood et al., 2018). Given those uncertainties, food supply must be secured to ensure the well-being of mankind around the world. Increasing future food production will be one of the important driving factors in land use change, which may have far-reaching effects on WESs (Bonhommeau et al., 2014; Heuvel et al., 2020).

Food production inevitably drives conversion of forest, grassland, wetland, and other land use types to cultivated land. Combined with fertilizer application, food production can lead directly to water quality pollution and soil fertility degradation, which can cause permanent damage to WESs (Jelic et al., 2015). However, previous studies have mainly explored how to improve ecosystem services to ensure food production and increase yield (Chen et al., 2019), while the potential impact of food production on WESs has been neglected (Bartual et al., 2018). Therefore, quantifying, mapping, and identifying tradeoffs in the impacts of food production-driven land use change, and revealing material flows and spatio-temporal changes in WESs, are urgently needed for better decision making.

Songhua River Basin (SRB) is a typical food production base in China, producing 20% of the country's food (Yang et al., 2020), and is also one of only three black soil regions in the world. A key problem is that local governments only consider short-term high yields in food production, ignoring the potential long-term ecological impact. According to the literature, a 0.3–1.0 cm thick surface layer is lost every year in the black soil area in SRB (Wei et al., 2016). Thus soil fertility has decreased and water quality is deteriorating in the basin (Han and Zou, 2018). However, there is a research gap concerning the impact of land use change driven by food production and trade-offs between food production and WESs provision in SRB.

Specific objectives of the present study were thus to: 1) identify land use changes caused by food production in SRB; 2) evaluate the spatiotemporal changes in WESs caused by food production-driven land use change; and 3) identify trade-offs between food production and WESs. The overall aim was to help decision makers understand the mechanisms of WESs change caused by food production-driven land use change and to develop a theoretical framework and technical support for optimal agricultural production and land use planning.

## 2. Materials and methods

### 2.1. Study area

Songhua River Basin is located in northeast China ($41°42'N - 51°38'N, 119°52'E - 132°31'E$) (Fig. 1). The basin occupies an area of $55.68 \times 10^4 km^2$. The Songhua River has two sources: a southern source, the Western Songhua River (formerly the second Songhua River), which originates in Tianchi, Changbai Mountains, and a northern source, the Nenjiang River, which originates in the Yile Huli Mountains within the Great Hinggan mountain range. These two rivers merge in Sanchahe Town, Jilin Province, and the Songhua River then flows eastward to Tongjiang City and into Heilongjiang River. The highest point in SRB is 2667 m above sea level (asl) and the lowest point is 43 m asl. The basin encompasses Inner Mongolia, Jilin, and Heilongjiang provinces, and is located in the north temperate monsoon climate zone, with distinct seasons comprising warm and rainy summers, cold and dry winters, mean annual temperature ranging from 3 to 5 °C, and mean annual precipitation of around 500 mm.

SRB contains a vast area with fertile black soil, which is suitable for agricultural production. Large areas of soybean, maize, sorghum, wheat and other crops are grown in the basin, making it an important food production base in China. In 2019, the total grain output of China was about $6.64 \times 10^8 tons$, and the grain output of SRB was about $1.38 \times 10^8 tons$, accounting for about 20.8% of national production. The watershed also contains large areas of wetland, virgin forest, mountain, and other natural ecosystems. Within SRB, there are 28 prefecture-level municipal administrative regions and the National Material Reserve Bureau has offices in Heilongjiang Province, Jilin Province, and Inner Mongolia Autonomous Region.

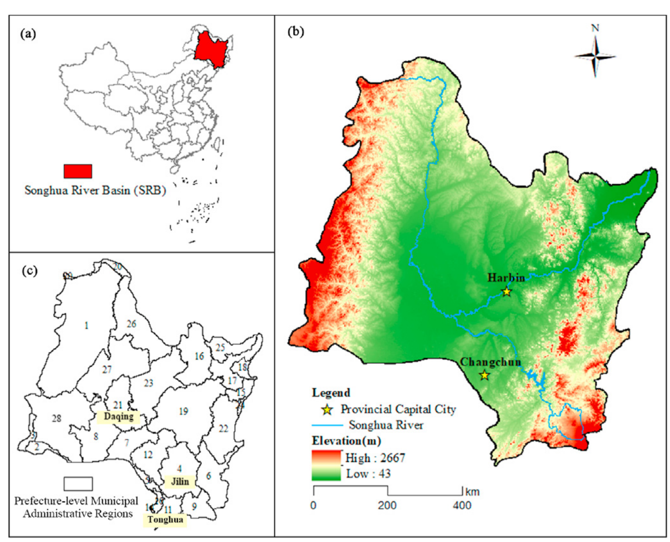


**Fig. 1.** (a) Location of the Songhua River Basin in northeast China, (b) relief map of the basin, and (c) map showing the 28 administrative regions in the basin established within the Chinese administrative system for regional food production analysis.

### 2.2. Operational framework

An operational framework showing the potential impact of land use change driven by food production on WESs and trade-offs between food production and WESs was developed (Fig. 2). First, land use change in SRB was analyzed using a remote sensing artificial interpretation dataset for 2000–2015. Statistical yearbook data were used to analyze temporal variations in food production and soil fertilization. The InVEST model was then used to assess the ecosystem services under alternative land use and fixed climate change. Next, the trade-offs between food production and WESs were analyzed by Pearson correlation. Finally, the implications of the results for land use policy were assessed. The focus was mainly on the different ways in which land use by humans results in spatial and temporal changes in WESs.

### 2.3. Land use and food production change

Based on the characteristics of SRB and the study region, the period 2000–2015 was selected for analysis of land use/land cover (LULC) change. Following the system of remote sensing investigation and assessment of changes in ecological environments in China, land use types were divided into seven categories: forest, shrubland, grassland, wetland, cultivated, developed, and bare land.

Food production data for the 28 administrative regions in SRB were taken from the statistical yearbooks for Heilongjiang, Jilin, and Liaoning Province from 2000 to 2015. Based on the cultivated land area in each administrative district, food yield per unit of cultivated land in the 28 administrative districts in 2000 and 2015 was calculated. The increase/decrease in food production per unit area between 2000 and 2015 was also calculated.

### 2.4. Modeling WESs and model validation

Both local government concerns and the interests of basin inhabitants were considered when assessing changes in WESs. The focus was on three kinds of WESs: water yield, soil retention, and water purification. In particular, the influence of LULC on provision of these WESs in SRB from 2000 to 2015 was evaluated.

The Water Yield module in the InVEST model was used to evaluate spatial-temporal changes in the water provision service in SRB, the Sediment Delivery Ratio module in InVEST was used to evaluate spatial-temporal changes in the soil retention service, and the Nutrient Delivery Ratio module in InVEST was used to evaluate spatial-temporal changes in the water purification service. The InVEST suite of tools (Version.3.6.0; see Supplementary Information (SI) part 1) enables decision makers to assess trade-offs between ecosystem services and to compare the consequences of different future change scenarios, like land use and climate change. Details of these model and their governing equations are provided in parts 1.1–1.3 in SI. The availability and sources of the data used, and relevant input parameters, are shown in Tables S1–S3 in SI. All spatial data required by the model were prepared by ArcGIS 10.2.

The Water Yield module is an estimation method based on water balance where the precipitation in each pixel minus the actual evapotranspiration is taken as water yield. Actual evapotranspiration is calculated using an algorithm based on Budyko's hypothesis of water-heat coupling equilibrium (Zhang et al., 2001). Soil retention refers to the capture of rain-eroded soil by vegetation or forest cover, which is used to protect soil resources and water quality. The Sediment Delivery Ratio module in InVEST uses a sediment transport model to represent the process of soil sediment generation and transport to rivers. For water purification, based on land use change and different nitrogen and phosphorus loading capacity, the nutrient sources in the whole landscape are determined in the Nutrient Delivery Ratio module, and the amount of nitrogen and phosphorus transported to rivers is calculated to assess the change in water quality. Water pollution is reduced by reducing the amount of nitrogen and phosphorus flowing into rivers.

The results of the three sub-modules of the InVEST model were validated with other reference data for SRB, which revealed that the results of the model were good enough to simulate the WESs (SI, part 2). The Water Yield module adopts the value of actual evapotranspiration (AET) for validation. The results showed that the modeled values and observed values for AET showed excellent linear regression, with $R^2$ values of 0.90 (Fig. S1). The Sediment Delivery Ratio model uses the average erosion modulus calculated by the Universal Soil Loss Equation (USLE) for validation. The results showed that the modeled values and observed values for USLE showed good linear regression, with $R^2$ values of 0.66 (Fig. S2 and Table S4). The Nutrient Delivery Ratio model adopts the average total nitrogen load and total phosphorus load intensity for

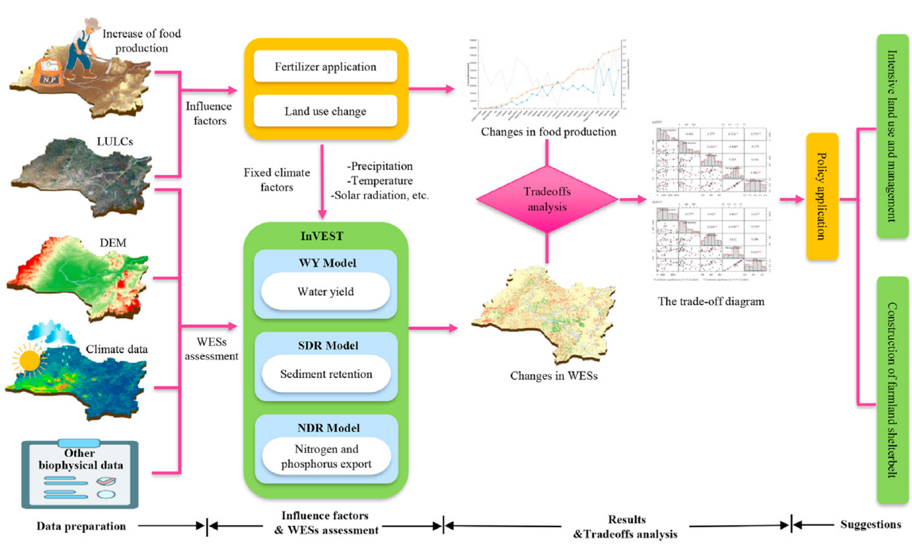


**Fig. 2.** Analytical framework applied in the present analysis. WY = water yield; SDR = sediment delivery ratio; NDR = nutrient delivery ratio).

validation. These results also showed perfect linear regression, with $R^2$ values of 0.75 and 0.68 for nitrogen and phosphorus load, respectively (Fig. S3).

### 2.5. Trade-offs between food production and ecosystem services

Correlation analysis and cluster analysis were used to identify trade-offs between food production and ecosystem services. The trade-offs identified were confirmed by Pearson test, significance tests, and a scatter plot matrix. When the correlation coefficients of two ecosystem services were negative and passed the significance test ($p < 0.05$), it was assumed that there is a trade-off between them, while otherwise a synergistic relationship was assumed (Jopke et al., 2015).

The average values of different ecosystem services in the 28 administrative regions in SRB were calculated using the Zonal Statistics function in ArcGIS. Excel software was used to create a diagram showing trade-offs between food production and ecosystem services.

### 2.6. Data requirement and preparation

The InVEST model requires multiple gridded datasets together with specific biophysical data as inputs. The data required and those used in the present study are listed in Table 1. The spatial data on SRB and other relevant data used in this study are summarized in Table S5 in SI, including a brief introduction, summary of each dataset, related model principles, and the key parameters used in the InVEST model. All raster layers have resolution 90 m × 90 m. The geographic coordinate system used is GCS_WGS_1984 and the projection coordinate system is Albers_Conic_Equal_Area. Spatial distribution data on precipitation, radiation, and temperature in 2000 and 2015 were obtained by Kriging interpolation (Fig. S4 in SI), with spatial resolution of 90 m × 90 m, in ArcGIS 10.2. Food production data and fertilizer application data for the 28 administrative regions in SRB were taken from China Forestry Statistical Yearbooks. Natural factors such as precipitation, temperature, solar radiation, etc. were set as invariants.

## 3. Results

### 3.1. Food production changes

Total food production increased from $0.497 \times 10^8$ *tons* in 2000 to $0.798 \times 10^8$ *tons* in 2015. In most of the 28 administrative regions in SRB, food production increased between 2000 and 2015, and the rate of change was very high (Fig. 3; Table S6 in SI). The growth in food production was highest (76.44%) in the Daqing administrative region. However, in a few administrative regions, such as Jilin and Tonghua, food production decreased, by −2.34% and −5.42%, respectively (Fig. 3).

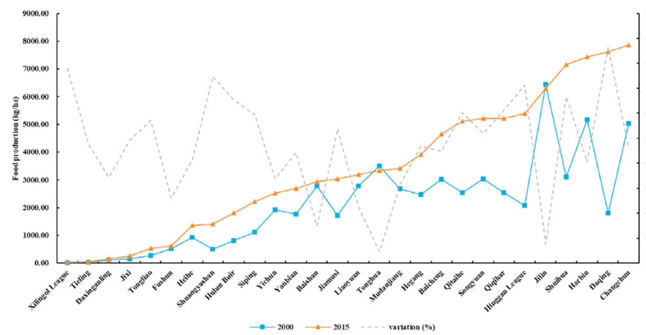


**Fig. 3.** Areal food production (kg/ha) in the 28 administrative regions in Songhua River Basin in 2000 and 2015, and (right axis) change from 2000 to 2015.

**Table 1**
Data requirements for the InVEST model (NDR = Nutrient Delivery Ratio module, SDR = Sediment Delivery Ratio module, WY = Water Yield module, LULC=land use and land cover).

| Data | Type | Data source | Note | Related model |
|---|---|---|---|---|
| Digital Elevation Model (DEM) | Raster | Geospatial Data Cloud, http://www.gscloud.cn | Resolution is 90 m × 90 m | NDR, SDR |
| Annual average precipitation | Raster | China Meteorological Data Center, http://data.cma.cn/ | Interpolated based on annual data, resolution is 90 m × 90 m | WY, NDR, SDR |
| Reference evapotranspiration | Raster | MODIS Global Evapotranspiration Project (MOD16) http://www.ntsg.umt.edu/project/mod16 | Resolution is 90 m × 90 m | WY |
| Plant-available water content | Raster | Environmental and Ecological Science Data Center for West China, http://westdc.westgis.ac.cn/ | Calculated based on the soil data (Harmonized World Soil Database) according to the model proposed by (Zhou et al., 2005), the resolution is 90 m × 90 m | WY |
| Land use/land cover | Raster | Resource and environment data cloud platform, Chinese Academy of Sciences, http://www.resdc.cn/ | LULC of year 2000, 2010 and 2015, including forest, Shrubland, grassland, wetland, developed land, cultivated land and bare land, the resolution is 90 m × 90 m | WY, NDR, SDR |
| Depth to root restricting layer | Raster | Environmental and Ecological Science Data Center for West China, http://westdc.westgis.ac.cn/ | Derived from the soil data (Harmonized World Soil Database), resolution is 1 km × 1 km | WY |
| Watersheds | Shapefile | Geospatial Data Cloud, http://www.gscloud.cn | A shapefile determined by DEM raster using ArcGIS tool | WY, NDR, SDR |
| Rainfall erosivity index | Raster | China Meteorological Data Center, http://data.cma.cn/ | Calculated based on precipitation according to the model proposed by (Zhang and Fu, 2003), the resolution is 90 m × 90 m | SDR |
| Soil erodibility | Raster | China Meteorological Data Center, http://data.cma.cn/ | Calculated based on precipitation according to the model proposed by (Cao et al., 2015), the resolution is 90 m × 90 m | SDR |
| Biophysical data | .CSV file | Literature (Wang et al., 2016; Han et al., 2016) and the InVEST user's guide (Sharp et al., 2016) | Including attributes of each LULC, $K_c$ (plant evapotranspiration coefficient), load of nutrients, efficiency of nutrient retention, etc. | WY, NDR, SDR |

### 3.2. Land use change

In 2000 and 2015, the main land use types in SRB were forest and cultivated land, which in combination accounted for 80.65% and 80.81% of the total area of the basin in 2000 and 2015, respectively. Overall, the area of forest showed an upward trend and the area of cultivated land a slight downward trend in the study period (Table 2).

From 2000 to 2015, 42,131 km$^2$ of cultivated land were created from other forests, shrubland, and wetlands (Fig. 4). However, it was found that the total area of cultivated land was 236,099 km$^2$ in 2000 but 234,006 km$^2$ in 2015, a decrease of 2093 km$^2$ in the 15-year period. From 2000 to 2015, the total area of forest increased from 228,961 km$^2$ to 231,989 km$^2$, although in the same period 17,314 km$^2$ of forest were converted to cultivated land. The increase in forest area mainly came from the transformation of 19,001 km$^2$ cultivated land to forest. Between 2000 and 2015, the total area of wetlands decreased from 50,443 km$^2$ to 43,572 km$^2$, caused by conversion to cultivated land (9753 km$^2$) and forests (7897 km$^2$).

Forests are mainly distributed around the edge of the basin and cultivated land is mainly distributed in the center (Fig. 4). From 2000 to 2015, the area of forest increased but there was no obvious spatial change. However, there were significant spatial changes in cultivated land and wetlands, which became smaller and more dispersed.

Urbanization is an important factor affecting land use change. By comparing the changes in cultivated and developed land (Fig. S5 in SI), we found that the area of cultivated land that was unchanged, increased, and decreased from 2000 to 2015 was 191,868 km$^2$, 44,231 km$^2$, and 42,138 km$^2$, respectively. The area of developed land that was unchanged, increased, and decreased in the same period was 8013 km$^2$, 10,397 km$^2$, and 7552 km$^2$, respectively (Table S7 in SI). Through the land transfer matrix, the inflow and outflow area of cultivated land and construction land were obtained. Analysis of variance showed that the variance in cultivated land was far greater than that in developed land (Table S8 in SI). This indicates that food production was the factor with the strongest influence on WESs in SRB during the study period (2000–2015).

### 3.3. Ecosystem services change

#### 3.3.1. Water yield

Total water yield displayed a downward trend during 2000–2015. In 2000, the total water yield of the basin was 136.81 billion m$^3$, while in 2015 it was 136.09 billion m$^3$ (Fig. 5, Table S9 in SI). The highest water yield in 2000 and 2015 was 716.76 mm and 731.82 mm, respectively (Fig. 5). The change in water yield was more obvious in the southern part of the basin, while water yield was low throughout in the western part. The highest levels of water yield were concentrated to southern parts. In most regions water yield showed little change and the areas with increases were widely distributed (Fig. 5c). The decline in water yield was significant mainly in the middle and southeast of SRB. The area of forest land increased, which would result in a decrease in water yield as evapotranspiration from forest is higher than from other land types (Cao et al., 2017; Han et al., 2019).

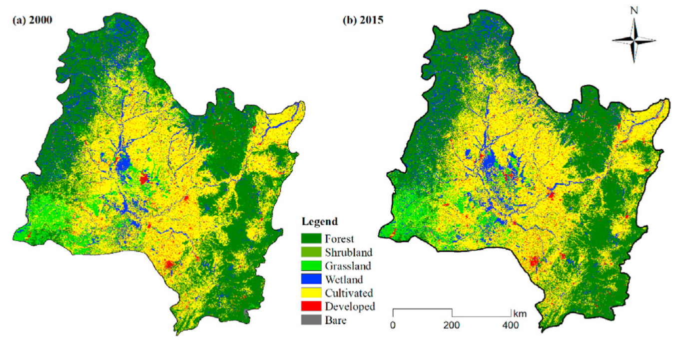


**Fig. 4.** Land use/land cover in Songhua River Basin in (a) 2000 and (b) 2015.

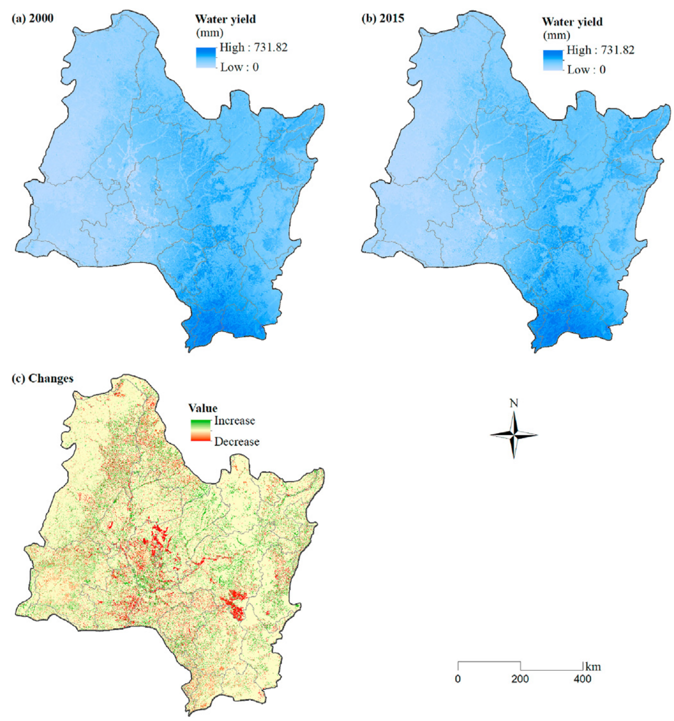


**Fig. 5.** Spatial distribution and changes in water yield from 2000 to 2015. (a) Water yield in 2000; (b) water yield in 2015; (c) change from 2000 to 2015).

**Table 2**
Land use/land cover (LULC) transition matrix for Songhua River Basin, 2000–2015 (units = km$^2$).

| | | LULC 2015 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Forest | Shrubland | Grassland | Wetland | Cultivated | Developed | Bare | Total |
| LULC 2000 | Forest | 197626 | 376 | 5642 | 7897 | 19001 | 1360 | 87 | 231989 |
| | Shrubland | 1215 | 1302 | 502 | 231 | 892 | 62 | 2 | 4207 |
| | Grassland | 5134 | 124 | 21094 | 5435 | 8990 | 751 | 937 | 42468 |
| | Wetland | 6851 | 59 | 1112 | 25939 | 8773 | 497 | 336 | 43572 |
| | Cultivated | 17314 | 444 | 6442 | 9753 | 191868 | 7594 | 584 | 234006 |
| | Developed | 701 | 11 | 479 | 494 | 5808 | 8013 | 53 | 15565 |
| | Bare | 120 | 7 | 1673 | 695 | 765 | 134 | 1433 | 4834 |
| | Total | 228961 | 2323 | 36945 | 50443 | 236099 | 18410 | 3432 | 576641 |

#### 3.3.2. *Soil retention*

Total soil retention in the basin decreased slightly, from 53.25 million t to 51.40 million t, between 2000 and 2015 (Fig. 6, Table S9 in SI). The highest soil retention rate in 2000 and 2015 was 88.87 t/ha and 81.07 t/ha, respectively (Fig. 6). The spatial changes in soil retention were basically coincident, and soil retention in the west and east of the basin was higher than that in the central part. Overall, soil retention was highest in the southern part. In most regions of SRB soil retention showed little change and the areas showing an increase were widely distributed in the west and east (Fig. 6c). A significant decline in soil retention was seen mainly in the southwest of SRB (Fig. 6c). Soil retention decline is mainly due to the interaction of natural conditions and unsustainable human activities (Borrelli et al., 2017; Li et al., 2019). Climate change, fertile farmland development, and vegetation destruction may be the main reasons for the decline in soil retention in SRB (Li et al., 2009; Zhong et al., 2019).

#### 3.3.3. *Nitrogen and phosphorus export*

Total nitrogen export from SRB increased from 56,161.80 t to 57,007.05 t between 2000 and 2015 (Fig. 7, Table S9 in SI). It was found that from 2000 to 2015, the highest nitrogen export rate was 9.40 kg/ha (Fig. 7). The spatial changes in nitrogen export were basically coincident and increases in nitrogen export were concentrated in the central part of the basin.

Total phosphorus export from the basin was 13,153.47 t in 2000 and 13,654.12 t in 2015 (Fig. 8, Table S9 in SI). Thus total phosphorus export also showed an upward trend. In 2000–2015, the highest export rate was 3.99 kg/ha (Fig. 8). The spatial changes of phosphorus export were basically coincident and increases in phosphorus export were concentrated in the center of the basin. In general, nitrogen and phosphorus export generally showed the

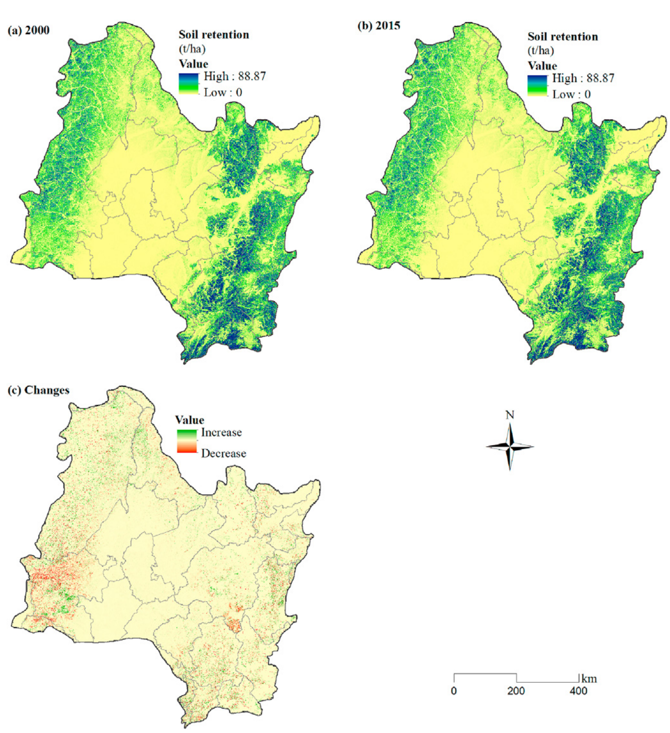


**Fig. 6.** Spatial distribution and changes in soil retention from 2000 to 2015. (a) Soil retention in 2000; (b) soil retention in 2015; (c) change from 2000 to 2015.

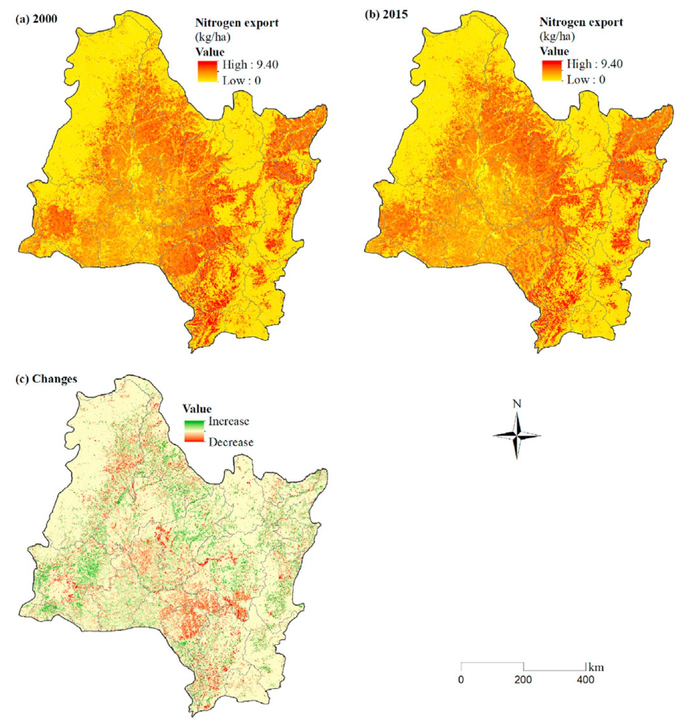


**Fig. 7.** Spatial distribution and changes in nitrogen export from 2000 to 2015 (a) Nitrogen export in 2000; (b) nitrogen export in 2015; (c) change from 2000 to 2015.

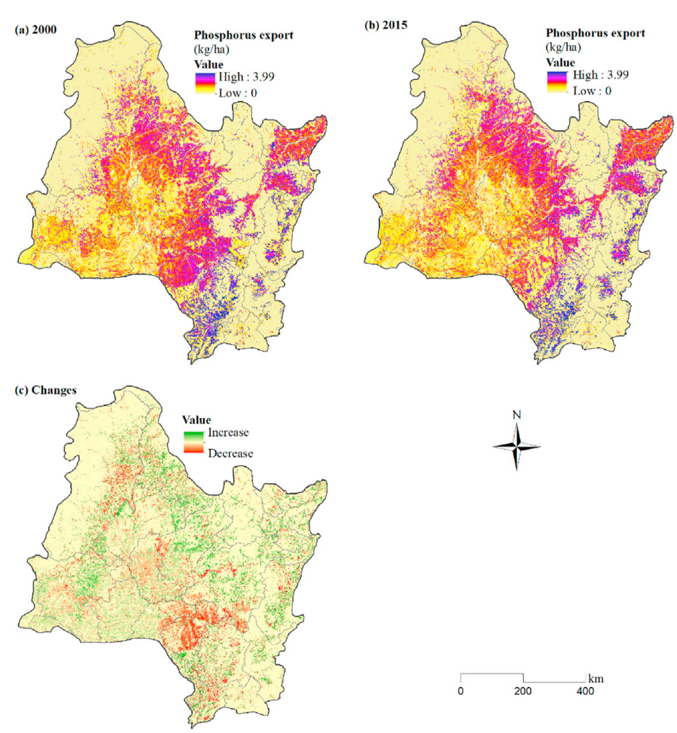


**Fig. 8.** Spatial distribution and changes in phosphorus export from 2000 to 2015. (a) Phosphorus export in 2000; (b) phosphorus export in 2015; (c) change from 2000 to 2015.

same pattern of change from 2000 to 2015 (Figs. 7 and 8). Overall, these findings are in agreement with previous reports of increasing nitrogen and phosphorus exports in SRB, mainly caused by increasing use of fertilizers, pesticides, and other human pollutants (Goyette et al., 2016; Hu et al., 2020; Pastuszak et al., 2018).

### 3.4. Trade-off analysis

Food production was negatively correlated with soil retention and positively correlated with water yield, but the correlations were not significant in 2000 (see Table S10 in SI for original data). Food production was positively correlated with nitrogen and phosphorus export (Fig. 9a). In 2015, there was a significant negative correlation between food production and soil retention, and a non-significant negative correlation between food production and water yield (see Table S11 in SI for original data). There were significant positive correlations between food production and nitrogen and phosphorus export, but the correlation was weaker in 2015 than in 2000 (Fig. 9b). Previous studies have shown that forest plays a significant role in retention of soil nitrogen and phosphorus (Aguirre-Gutiérrez et al., 2020; Ren et al., 2016). Due to the implementation of government policies in recent years on afforestation and returning farmland to forest (Wang et al., 2017), the area of forest in SRB is increasing, which would alleviate the export of nitrogen and phosphorus and weaken the correlation. Increased food production was associated with a decline in soil retention service, i.e., a trade-off relationship. Increased food production led to an increase in nitrogen and phosphorus export, i.e., a synergistic relationship.

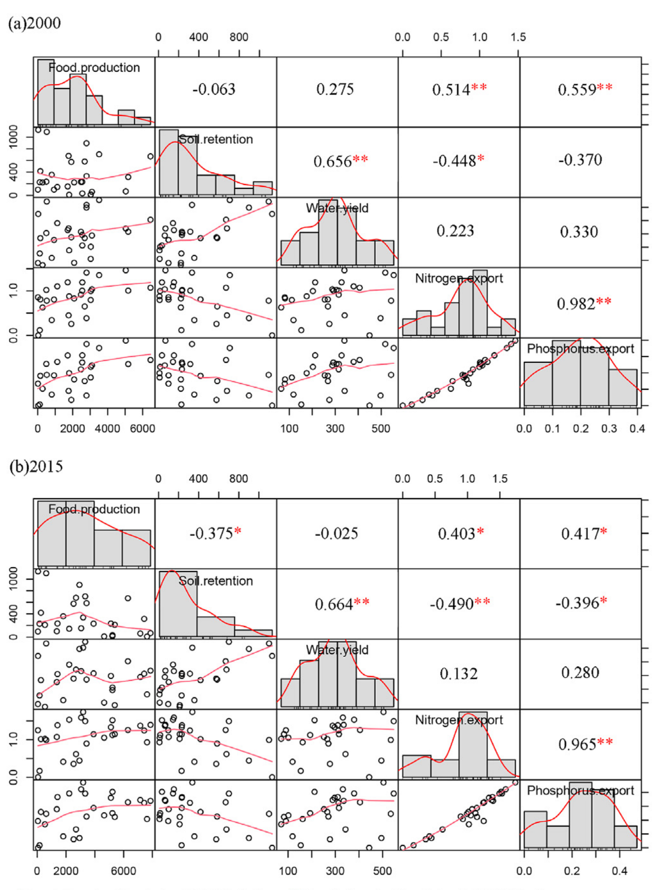


**Fig. 9.** Pearson correlation coefficient ($R^2$) between different ecosystem services in SRB in (a) 2000 and (b) 2015.

## 4. Discussion

### 4.1. Changes in land use and food production

In response to the "Project planning for returning farmland to forest" policy for northeast China, the area of cultivated land returned to forest during the period 2000–2015 exceeded the area of forest converted to cultivated land. The underlying policy seems to be based on optimizing allocation of resources to restore eroded or destroyed soil, by means of ecological compensation measures such as afforestation, land renovation, irrigation, and water replenishment (Ren and Li, 2018). As a result, the area of forest in SRB increased and the area of cultivated land decreased by 2015.

Although the area of cultivated land area was smaller in 2015 than in 2000, food production showed an increasing trend between the years. This agrees well with previous findings of increasing food yield in northeast China in recent decades (Li et al., 2020b). Change in the area of cultivated land is usually the main factor explaining increases and decreases in food production (Yang and Li, 2000). However, other important factors also influence food production, such as planting density, use of modern crop varieties, better mechanization of sowing and so on. The amount of fertilizer applied may also be a key factor in the rate of food production change (Jiang et al., 2018). The present analysis showed that, between 2000 and 2015, use of fertilizer increased in 90% of the 28 administrative regions in SRB and the amount of fertilizer increased from $9.25 \times 10^6 tons$ in 2000 to $11.49 \times 10^6 tons$ in 2015 (Table S12 and Fig. S6 in SI). With limited farmland, the amount of fertilizer applied in the northeast China Plain has been increased to support high grain yields (Hui et al., 2017; Zhou et al., 2019). This largely explains the increase in total food production despite the decrease in cultivated land.

### 4.2. Potential water-related ecological risks and tradeoffs

In SRB, WESs appeared to be gradually weakening during the 15-year study period. First, water yield was found to have decreased which indicates that evapotranspiration increased, since precipitation remained constant during the study period. Forest, grassland and cultivated land have lower evaporative losses and runoff, and thus better water retention, than developed land and bare land. Therefore the decline in water yield observed in SRB reflects the fact that the area of developed land or bare land in the basin increased. Second, soil retention in SRB declined from 2000 to 2015 (see Table S9 in SI for original data), indicating that soil erosion has increased. A serious consequence of this is loss of black soil and a decline in soil fertility in northeast China (Fang and Sun, 2017). Finally, with the increasing demand for food production in the region and the increasing use of fertilizers, nitrogen and phosphorus exports from the basin increased from 2000 to 2015, creating a potential risk of increased water pollution in SRB. Fertilizer application in agriculture has been shown to be the main source of nutrient pollution in many places in China, such as Taihu River Basin (Li et al., 2008) and Haihe River Basin (Zhou et al., 2015). These results obtained in this study indicate that improving food production may compromise provision of ecosystem services in SRB, through causing frequent land use changes. The ecological security of water is the basis of food security, and thus of human survival (Karen, 2012). The present study confirmed previous findings regarding the potential water-related ecological risks caused by food production. This contradicts findings in other studies that food production probably has little impact on ecosystem services compared with industry and services (Tchalala et al., 2019; Yue et al., 2017).

Balancing food security and ecological security is a major problem that needs to be solved (Shindell et al., 2012). Therefore, it is necessary to make trade-offs between food production and other important ecosystem services. In this study, it was found that food production in SRB increased in the period 2000–2015, but also caused potential water pollution and declining soil retention, resulting in an increasingly prominent trade-off between food production and WESs (Table S13 and Fig. S7 in SI). The trade-off analysis results confirmed the findings that WESs should be conserved while simultaneously strengthening food production. However, previous studies only considered the one-sided importance of ecological improvements in increasing food production (Bardgett and Gibson, 2017; Turyansky et al., 2018), or used land sparing/sharing achieve a trade-off between agricultural production and ecology (Green et al., 2005; Wittman et al., 2017). WESs are facing unprecedented risks and need to be regulated. Therefore, accurate knowledge of the spatial pattern and trade-off relationship with regional WESs is an important prerequisite for achieving both ecological protection and agricultural sustainability, which are critical to human well-being.

### *4.3. Strategies and implications*

#### *4.3.1. Intensive land use and management*

Because of the finite amount of land available, there is competition for land between food production and economic construction. Therefore use of existing land should be intensified in order to meet the growing demand for food production and achieve the goal of arable land protection (Peltonen-Sainio et al., 2019). Intensive use of land resources can also alleviate ecological deterioration (Godfray and Garnett, 2014). Therefore, a strategy of intensive land use is suggested for SRB and other critical food producing regions.

Three-dimensional cultivation could be used to extend into the air and create a vertical crop growing space with integrated technology for optimization of water and fertilizer supply (Kovács-Hostyánszki et al., 2017). This would maximize the use of the existing land area, decrease the spread of chemical fertilizers and reduce pollution. Meanwhile, advances in science and technology could allow food production to be expanded to underground spaces, in a modification of the three-dimensional cultivation approach, further maximizing land use and promoting multi-dimensional development of land resources. Therefore, land-use planning could reasonably allocate various types of land and scientifically delimit “cultivated land red line” and “ecological red line” to support strategic management and planning of WESs (Bai et al., 2018).

#### *4.3.2. Construction of farmland shelterbelts*

Construction of shelterbelts on farmland could be another effective measure to improve WESs (Deng et al., 2015). The purpose of shelterbelts is to prevent soil erosion and improve climate and hydrological conditions, by creating an artificial ecosystem that is conducive to plant growth, while also intercepting surface runoff (Sun et al., 2018), regulating underground water level (Szajdak and Życzyńska-Bałoniak, 2013), and mitigating water pollution (Qiao et al., 2016). Generally, when shelterbelt trees reach mature height, the farmland protected by the shelterbelt can increase its average yield by 20–30% compared with adjacent areas before or without the shelterbelt (Shi et al., 2016), and may even increase average yield by up to 100% (Guo, 2017).

SRB is a region of mountains and plains. There are many ditches and rivers, and there is a high-density road network. The cultivated land is mainly distributed on the plains, which have good soil texture and rich black soil (Gu et al., 2018). In order to prevent loss of soil fertility, a grid of farmland shelterbelts is needed, including field belts, canal belts, road belts, and belts around villages, drainage ditches, and rivers (Wu et al., 2018). It is also important to increase the level of forest coverage in plains areas and use a combination of needle/broadleaf trees and shrubs to improve the efficiency of farmland protection and pollutant interception, and maintain ecological benefits. Through the use of shelter forests around cultivated land planted with grain, losses of nitrogen and phosphorus caused by fertilization could be effectively blocked. This would improve soil fertilizer use efficiency and also minimize water pollution and protect the ecological environment in SRB.

### *4.4. Implications and limitations*

With global population growth, accompanied by e.g., COVID-19 and natural disasters, increasing food yield has become a major concern worldwide. Food production has expanded dramatically in recent years in many countries like China, United States, Russia, Japan, Indonesia, and Switzerland (Laborde et al., 2020). However, the links between food production and local land-use driven WESs changes remain underestimated and unrevealed. The sustainability of food production worldwide urgently needs to be improved, in order to protect natural resources and WESs. This study demonstrated that integrating the InVEST model with agriculture data in a novel approach can effectively estimate and visualize the multiple impacts of food production-driven land use changes on WESs and associated tradeoffs. This provides useful data support for decision makers, improving their understanding of the mechanisms of WESs, and indicates new ways to combine future food production with ecological protection.

With the development of geographic information service, remote sensing, and other technologies, a mature InVEST model has emerged (Bai et al., 2011). The model has been widely verified to be reliable after proper validation. It can be used to assess the positive and negative impacts of different policies on ecosystems and also provides a practical, low-cost approach to quantifying ecosystem services compared with other models (Butsic et al., 2017). The InVEST model was used here to simulate temporal and spatial changes in ecosystem services in SRB. The model is concise and efficient after proper validation, and provides great advantages in quantitative assessment of various ecosystem services (Redhead et al., 2018). Here, the model results were validated against measured data from hydrological stations in SRB and there was good agreement between calculated and measured values, indicating good applicability of the model for the basin. However, this study did not take into account the actual needs of the basin when assessing spatial and temporal changes in ecosystem services. The value of WESs can only be determined by linking the supply and demand of these ecosystem services, which should be explored in future research.

## 5. Conclusions

The InVEST model was used to study spatial and temporal changes in WESs in SRB, and a trade-off analysis was made on whether changes in food production have affected WESs. The results showed that, from 2000 to 2015, the area of forest, shrubland, and grassland in SRB all increased, while the area of cultivated land and wetland decreased. Overall, the status of WESs declined slightly. Improving food production was thus based on sacrificing ecosystem services, posing potential ecosystem risks in SRB. Future increases in food production will bring about further changes in land use, as well as affecting ecosystem services. This in turn will result in accelerated soil losses and changes in WESs, affecting food production capacity, indicating an urgent need for ecosystem protection measures in SRB. We suggest a management strategy that combines intensification of land management with establishment of farmland shelterbelt, as part of a sustainable development path aiming at ensuring ecological protection and food security. The results obtained in this study can be of help in management and decision making for SRB and other regions worldwide.

## CRediT authorship contribution statement

**Shiliang Yang:** Data curation, Formal analysis, Roles, Writing - original draft, Writing - review & editing. **Yang Bai:** Conceptualization, Funding acquisition, Supervision, Validation, Roles, Writing - original draft, Writing - review & editing. **Juha M. Alatalo:** Roles, Writing - original draft, Writing - review & editing. **Huimin Wang:** Writing - review & editing. **Bo Jiang:** Writing - review & editing. **Gang Liu:** Writing - review & editing. **Junyu Chen:** Writing - review & editing.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125316.

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