Global Spatio-Temporal Assessment of Changes in Multiple Ecosystem Services Under Four IPCC SRES Land-use Scenarios

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Abstract Social development and technological advancement have led to land use changes, influencing the structure of ecosystem services and severely impacting ecological balance. This study spatially and quantitatively assesses the effects of land-use changes on ecosystem services based on the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) and using the Integrated Valuation of Ecosystem Services and Tradeoff (InVEST) model. This model, applied on a global scale, was used to quantify the changes in three ecosystem services, namely, carbon storage, water yield, and sediment retention, 2010 and 2100 under four land use scenarios (A1B, A2, B1, and B2) and to evaluate the impact of land use changes to these services. The results indicate that (1) sediment retention and carbon storage under scenario B1 increase more than under other scenarios, with average global increases of 175.74 t/km² and 913.60 Mg/km², respectively; water yield increase only under scenario A2 between 2010 and 2100, with average global increase of 3.51 mm; (2) forest and grassland are the principal land types providing three ecosystem services globally, and decreasing the area of barren contributes to increases in three ecosystem services; and (3) when barren is converted to forest, grassland, cropland, and urban, ecosystem services all increase, strengthening the utilization of barren land can increase ecosystem services greatly. This study provides a reference for further research and the sustainable development of ecosystem services.

Plain Language Summary Analyzing the effects of land use changes on ecosystem services on a global scale is vital for the promotion of the sustainable development of ecosystems, especially in little-studied areas. Many studies have mapped and analyzed ecosystem services, but most have considered only local regions. There is no global research on this subject using IPCC SRES scenarios. This study aims to predict how different development scenarios (A1B, A2, B1, and B2) affect land use changes and to analyze the impact of corresponding land use changes on the ecosystem services of carbon storage, water yield, and sediment retention from a global perspective. We found that sediment retention and carbon storage under scenario B1 increased more than under other scenarios, with average global increases of 175.74 t/km² and 913.60 Mg/km², respectively; water yield increased only under scenario A2 between 2010 and 2100, with average global increase of 3.51 mm; when barren is converted to forest, grassland, cropland, and urban, ecosystem services all increase, strengthening the utilization of barren land can increase ecosystem services greatly.

1. Introduction

Ecosystem services mean the welfare and benefits derived from ecosystems directly or indirectly supporting human survival and development (Costanza et al., 1997). Ecosystems provide various benefits such as water yield, carbon storage, food supplies, climate regulation, and entertainment (Yang et al., 2015). Since ecosystems can self-regulate, they can provide services consistently as long as external disturbances do not exceed a threshold (Liu et al., 2016). As human activity and the social economy increase, the ecological environment becomes more and more vulnerable (Halpern et al., 2007; Laurance et al., 2011). Once external disturbance exceeds an acceptable level, ecosystems are vulnerable and can even disintegrate and no longer provide sufficient benefits (Feng-jin & Hua, 2002; Yu et al., 2013). Land is a complex dynamic system developing and evolving under the influence of long-term interactions between nature and human activity (Lambin et al., 2003, 2001), and land use changes are a direct result of human activity, affecting ecological systems and services (Gashaw et al., 2018; Khaledian et al., 2016; Ligate et al., 2018; Mohawesh et al., 2015; Yu et al., 2013).
et al., 2015). As a consequence, reasonable development and utilization of land is vital to the sustainable development of ecosystems, and it is essential to study the impact of land use changes on ecosystem services including their underlying ecological mechanisms (Daniel et al., 2015; Sherrouse et al., 2017).

Many studies have mapped and analyzed ecosystem services, but most have considered only local regions (Hamel et al., 2015; Nowak & Crane, 2002; Zhang et al., 2019), and many regions are sparsely studied. Of over 150 studies of ecosystem services, 50% focus on six countries (China, the United States, the United Kingdom, Sweden, Canada, and Mexico), more than half of the countries in Africa and Asia have no relevant case study (Seppelt et al., 2011); however, ecosystem service value provided by these six countries is barely 23.5% of the world total (Sutton & Costanza, 2002). Therefore, the study of ecosystem services in little-studied areas is of great value for better understanding and improving ecosystem services. This study analyze the effects of land use changes on ecosystem services on a global scale, which is vital for the promotion of the sustainable development of ecosystems, especially in little-studied areas. There is no global research on this subject using IPCC SRES scenarios. This study aims to predict how different development scenarios affect land use changes and to analyze the impact of corresponding land use changes on the ecosystem services from a global perspective.

2. Data and Methods

2.1. Data

The data for this study include the following. (1) We obtained 2010 and 2100 global land use and land-cover (LUCC) map, with a 1-km resolution, from Li et al. (2017) (available at http://geosimulation.cn/GlobalLUCCProduct.html). The LULC map has six major classes: water, forest, grassland, farmland, urban, and barren. (2) We used the FAO Harmonized World Soil Database (HWSD, version 1.2; available at http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/), with a resolution of 30 arc seconds, for data on plant root depths, plant available water content, and soil depths. (3) We obtained 2010 meteorological data from Abatzoglou et al. (2018), including precipitation, evapotranspiration, and solar radiation, with a resolution of 2.5 arc minutes, from TerraClimate data sets (available at https://doi.org/10.1038/sdata.2017.191). Monthly mean temperature was obtained from Copernicus Climate Change Service (C3S) (2017) (available at https://cds.climate.copernicus.eu/cdsapp#!/home), with a resolution of 0.25 arc degrees. (4) We obtained data on global watersheds from Lehner and Grill (2013) (available at https://www.hydrosheds.org/). (5) A digital elevation map (DEM) with a resolution of 0.5′ was obtained from HiJmans et al. (2005). (6) Validation data including soil erosion modulus data sets and runoff records of hydrological stations were obtained from National Earth System Science Data Center and local hydrological stations (available at http://www.geodata.cn). Validation data about carbon storage were obtained from Liu et al. (2019).

2.2. Scenarios

This paper considers four SRES scenarios (A1B, A2, B1, and B2) as described in the Intergovernmental Panel on Climate Change’s (IPCC’s) fourth assessment report. The IPCC has been pursuing global change research in the context of climate warming for many years. Using future scenarios proposed by the IPCC to study global change is widely accepted by researchers. The four scenarios, with A and B denoting an economic and environmental emphasis, respectively, 1 and 2 representing a global focus and a regional focus, respectively. A1 describes a world of low population growth, rapid technological innovation, very high economic growth, sprawling urban expansion, and strong biofuels demand, there are three scenarios within A1: A1B (balanced across all scenarios), A1F (fossil fuel intensive), and A1T (technological advancement in renewable resources). In this study, we have elected to consider scenario A1B. B1 storyline assumes a convergent world, with the same population growth as A1, but with compact urban expansion, medium technological innovation and low biofuels use. A2 describes a very unbalanced world with high population growth, sprawling urban expansion, medium economic growth, slow technological innovation, and medium biofuels demand. B2 describes a world with medium population growth, compact urban expansion, medium economic growth, medium technological innovation, and medium energy use (Sleeter et al., 2012; Sohl et al., 2012).
2.3. Global Ecosystem Services Under Different Scenarios

Based on the availability of data, this paper considered three ecosystem services in two ecosystem categories, a provisioning category (water yield) and a regulating category (sediment retention and carbon storage), at the same time, these three ecosystem services can also serve as representative of regulating services and provisioning services in general (Liu et al., 2016). The study used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to calculate water yield, sediment retention, and carbon storage (Tallis et al., 2011). The model has been widely used in ecological field cause its relatively little input data and strong processing abilities, it has multiple modules, such as carbon, sediment delivery ratio, water yield, and habitat quality (Bhagabati et al., 2014; Lyu et al., 2019; Yin et al., 2020). To calculate ecosystem services in 2100 under four scenarios, we lacked basic meteorological data, such as precipitation, temperature, and solar radiations. This paper assumes that meteorological data do not change, with only land use changes altering ecosystem services, and thus, in calculating ecosystem services under each scenario, only land use change is a unique variable while other factors are assumed to be the same as in 2010. In this study, first, we used InVEST model to calculate ecosystem services in 2010 and 2100 under four scenarios (A1B, A2, B1, and B2), then analyzed the change of ecosystem services between 2010 and 2100 under different scenarios at global, continental, and country scale, at last we assessed the impact of future global land-use changes on carbon storage, water yield, and sediment retention.

2.3.1. Carbon Storage

InVEST uses a simple method to map and quantify carbon storage based on four carbon pools: above ground biomass, below ground biomass, soil, and dead organic matter. Global biomass carbon stocks per unit area for each land use type and above ground biomass were both derived from the IPCC (2006) Tier 1 (Lanza et al., 2006). Below ground carbon density and dead organic matter were calculated using R (the ratio of belowground biomass and dead organic matter to aboveground biomass), also derived from the IPCC (2006) Tier 1.

2.3.2. Water Yield

Water yield estimates the annual quantity of water available to humans. The water yield module in the InVEST tool is calculated by the Budyko curve (Tallis et al., 2011). Average annual precipitation, plant root depth, soil depth, plant available water content, and land use data are required for calculations. We determined the annual water yield $Y_x$ for each pixel x as follows:

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \cdot P_x,$$

where $AET_x$ is the actual annual evapotranspiration for pixel x and $AET_x/P_x$ is an approximate value of the Budyko curve (Zhang et al., 2001) expressed using:

$$\frac{AWC_x}{P_x} = \frac{1 + w_j \cdot R_{sj}}{1 + w_j \cdot R_{sj} + (1/R_{sj})},$$

and

$$w_j = \left(\frac{AWC_x}{P_x}\right) \cdot Z,$$

where $AWC_x$ is the volumetric plant available water content and Z is a seasonal rainfall factor. The Budyko dryness index ($R_{sj}$) is expressed using:

$$R_{sj} = \frac{k_{sj} \cdot ETo_x}{P_x},$$

where $ETo_x$ is the reference evapotranspiration for pixel x and $k_{sj}$ is the evapotranspiration coefficient for LULCj.

2.3.3. Sediment Retention

The sediment retention module in the InVEST tool (Tallis et al., 2011) is a spatially explicit model calculating the average annual soil loss for each parcel of land. The amount of annual soil loss for each pixel x is expressed using the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978):

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where \( R_x \) is the rainfall erosivity for pixel \( x \) (units: MJ mm (ha h yr)^{-1}), \( K_x \) is the soil erodibility factor for pixel \( x \) (units: t ha h (MJ ha mm)^{-1}), \( LS_x \) is the slope length-gradient factor for pixel \( x \), \( C_x \) is the crop-management factor for pixel \( x \), and \( P_x \) is the support practice factor for pixel \( x \) (Renard et al., 1991). Sediment retention equals the difference between the potential soil loss (USLE) and maximum potential soil loss (RKLS), assuming the landscape is barren, and is expressed as \[ Sediment \ retention = RKLS - USLE. \]

### 2.4. Analysis of the Impact of Land use Change on Ecosystem Services

This study analyzes land use changes and their impacts on ecosystem services. To quantify the cumulative impacts on all ecosystem services, we used the ecosystem services states (ES) as proposed by Let et al. (2013). The change in each ecosystem service is expressed as

\[ ESCI_x = \frac{ES_{CUR} - ES_{HIS}}{ES_{HIS}}, \]

where \( ESCI_x \) is the Ecosystem Service Change Index for service \( x \), \( ES_{CUR} \) and \( ES_{HIS} \) are the current and historic ecosystem service state values for service \( x \) at times \( j \) and \( i \), respectively. Combining each \( ESCI \) for each ecosystem service yields the Ecosystem Service Status Index (ESSI) representing the cumulative status of all ecosystem services for a site:

\[ ESSI = \sum \frac{ESCI_x}{n}. \]

The \( ESCI \) can be used as a measure of increase or decrease for each individual ecosystem service. ESSI defines the overall regional increase or decrease in ecosystem services. Negative values for \( ESCI \) mean that an ecosystem service is diminished relative to the base year; the smaller the value, the greater is the reduction. Conversely, positive values for \( ESCI \) mean that an ecosystem service has increased relative to the base year; the greater the value, the greater is the increase. When \( ESCI \) is 0, there is no change in the ecosystem service. Similarly, ESSI represents overall increases and decreases for all considered ecosystem services. This paper employs ESSI to quantify the cumulative change status of each considered ecosystem service. The \( ESCI \) and ESSI values are quantified at the country scale, with 2010 representing historic conditions and 2100 representing current conditions under the four scenarios. This is advanced as a helpful method for determining variables for comprehensive consideration of multiple ecosystem services for future policy guidance.

### 3. Results

#### 3.1. Land use and Changes in Ecosystem Services

According to land use analysis and on a global basis, LULC has changed between 2010 and 2100 under four scenarios (Table 1). Globally, the proportion of forest area under all scenarios increased noticeably except under A2, while the greatest increases were seen under B1. The proportion of grassland decreased in all scenarios except under B1, with the greatest decreases under A2. Farmland increased under all scenarios except B1. The global proportion of urban areas increased significantly under all scenarios in the descending order A2, A1B, B1, and B2. However, barren land decreased under all scenarios in the descending order A1B, B1, A2, and B2. The area of forest converted to grassland, farmland, and urban under A2 was greater than under other scenarios, while the lowest change occurred under B1. Under B1, the area of grassland and farmland converted to forest was greater than that under other scenarios, and farmland converted to grassland was also greater than that under other scenarios (Figure S1 in the supporting information). The area of forest and grassland increased most, but farmland decreased under B1 relative to other scenarios, mainly because B1 advances an environmental emphasis on a global orientation. Conversely, forest and grassland showed the greatest decreases while urban area and farmland showed the greatest increases under A2, representing...
an extremely unbalanced world with high population growth and urban expansion combined with slow technological innovation.

This paper selected nine basins in China as the validation region to assess the accuracy of ecosystem services calculated by InVEST in 2010, the actual validation data including soil erosion modulus data sets and water yield obtained from runoff records of hydrological stations were used to test the accuracy of sediment retention and water yield calculated by InVEST model, respectively, soil erosion modulus refers to the amount of erosion per unit time and area, which is consistent with the value calculated by USLE in InVEST model. The correlation between actual validation data (average water yield and average soil erosion modulus) of each basin and the data calculated by InVEST model were analyzed (Figure S2). This paper used carbon storage calculated by Liu et al. (2019) to assess the accuracy of carbon storage we calculated. The results showed that the water yield and sediment retention calculated by InVEST model had a significant correlation with the validation data ($P < 0.01$), the above ground carbon storage and soil carbon storage in China calculated in this paper were 14.96 and 45.93 Pg, respectively, and corresponding value of them calculated by Liu et al. (2019) were 15.37 and 45.18 Pg, respectively. Therefore, the ecosystem services calculated in this paper can meet the accuracy requirements.

Ecosystem services are unevenly distributed among land use types (Table 1). Forest is the greatest contributor of ecosystem services across the LULC, although the proportion of forest area is not the greatest. In 2010, forest provided 39.63% of global water yield and over 50% of carbon storage and sediment retention, while forest only represented 21.05% of the total area. Grassland is the second ranking contributor of ecosystem services, although grassland is the most extensive land use category. The third ranking provider of ecosystem services is farmland. The proportion of global area devoted to farmland is 5.14% less than that of forest and grassland. Although the proportion of barren area is almost as great as that of grassland, barren provides very minor ecosystem services: providing less than 10% of carbon storage, less than 3% of sediment retention and less than 1% of water yield. Less than 3% of all ecosystem services in all scenarios are provided by the urban and water land uses, and they exhibit similar patterns of land use distribution. We can see that Amazon basin and central Africa are rich in carbon storage and water yield, all three ecosystem services are abundant in southeast China (Figure S3).

This paper analyzes the global impacts of land use conversion to ecosystem services changes between 2010 and 2100 under four scenarios (Figure 1). For carbon storage, we can see that when water was converted to other land uses, carbon storage increased, in the following descending order of increase under all scenarios:
forest, grassland, farmland, barren, and urban. When forest was converted to other land uses, carbon storage decreased under all scenarios, with the greatest decreases occurring when converted to water, urban and farmland. When barren was converted to forest, grassland, farmland, and urban, carbon storage increased. When land uses other than forest and farmland were converted to grassland, carbon storage increased. The total change in carbon storage between 2010 and 2100, considering all land use conversions, increased under A1B, B1, and B2, with average global changes of 573.71, 913.60, and 445.28 Mg/km², respectively, and decreased under A2 with an average global change of −788.77 Mg/km² (Table 2). For water yield, when forest was converted to water and barren, both exhibited a decrease in water yield under all scenarios. When forest

![Figure 1. Changes in ecosystem services caused by alterations in land use between 2010 and 2100 under four scenarios. (Numbers 1, 2, 3, 4, 5, and 6 represent water, forest, grassland, farmland, urban, and barren, respectively. 1, 2, 3, 4, 5, or 6 represent conversions from water to other land uses).](image)

| Table 2 |
| Global Densities of Carbon Storage (CS), Water Yield (WY), and Sediment Retention (SR) |
| --- | --- | --- | --- | --- |
| ES | 2010 | A1B | A2 | B1 | B2 |
| CS (Mg/km²) | 9,748.92 | 10,322.63 | 8,960.15 | 10,662.52 | 10,194.20 |
| WY (mm) | 628.33 | 622.56 | 631.84 | 626.11 | 627.97 |
| SR (t/km²) | 3,880.77 | 4,018.84 | 3,801.73 | 4,056.51 | 3,961.64 |

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was converted to grassland, farmland, and urban, water yield increased. When grassland was converted to other land uses, all showed a decrease under all scenarios. When farmland was converted to urban and barren, water yield decreased. The total global results for water yield between 2010 and 2100 considering all land use conversions showed increases under A2 with average global change of 3.51 mm and decreases under A1B, A2, and B2, with average global changes of $-5.77$, $-2.22$, and $-0.36$ mm, respectively (Table 2). Sediment retention increased when water was converted to other land uses under all scenarios except when water was converted to barren under scenario B2. When barren was converted to forest,
grassland, farmland or urban, the sediment retention increased, and when barren was converted to forest and grassland, sediment retention showed the greatest increases. When forest was converted to other land uses, all showed large decreases in sediment retention. The total global results for sediment retention between 2010 and 2100 considering all land use conversions showed increases under A1B, B1, and B2, with average global changes of 138.06, 175.74, and 80.87 t/km², respectively, and decreases under A2 with an average global change of −79.05 t/km² (Table 2). Most importantly, at a global scale, although water yield decreased between 2010 and 2100 under scenario B1, the increase of sediment retention and carbon storage under B1 were more than A1 and B2 scenarios, A2 was the worst scenario showing increases in water yield and decreases in sediment retention and carbon storage, making B1 the most beneficial scenario on a global scale considering all three ecosystem services.

Table 3
The Densities of Carbon Storage (CS), Water Yield (WY), and Sediment Retention (SR) on All Continents

| ES          | Year | Scenario | NA   | OA   | AF   | SA   | EU   | AS   |
|-------------|------|----------|------|------|------|------|------|------|
| CS (Mg/km²) | 2010 | A1B      | 9,266.16 | 4,902.11 | 6,560.43 | 17,801.41 | 12,468.09 | 9,299.43 |
|             | 2100 | A1B      | 9,544.30 | 5,144.05 | 7,226.46 | 18,211.50 | 12,675.99 | 10,180.24 |
|             |      | A2       | 8,792.76 | 4,297.37 | 6,874.49 | 13,661.45 | 11,564.68 | 8,948.82  |
|             |      | B1       | 9,854.35 | 5,409.18 | 7241.40  | 19,280.56 | 13,568.02 | 10,357.66 |
|             |      | B2       | 10,204.36 | 5,432.55 | 6,499.64 | 18,807.36 | 13,200.34 | 9,558.75  |
| WY (mm)     | 2010 | A1B      | 517.56  | 522.88 | 523.73 | 1,223.98 | 557.40 | 549.65 |
|             | 2100 | A1B      | 514.98  | 522.93 | 514.71 | 1,209.71 | 554.54 | 545.94 |
|             |      | A2       | 516.41  | 523.02 | 523.30 | 1,241.95 | 557.86 | 553.87 |
|             |      | B1       | 517.10  | 520.90 | 522.42 | 1,218.23 | 554.48 | 547.67 |
|             |      | B2       | 516.65  | 520.70 | 523.84 | 1,219.86 | 555.21 | 551.70 |
| SR (t/km²)  | 2010 | A1B      | 3,659.33 | 1,485.19 | 1,239.17 | 4,993.97 | 1,882.18 | 6,197.65 |
|             | 2100 | A1B      | 3,866.97 | 1,504.76 | 1,269.41 | 4,884.22 | 1,953.19 | 6,509.23 |
|             |      | A2       | 3,866.97 | 1,504.76 | 1,269.41 | 4,884.22 | 1,953.19 | 6,509.23 |
|             |      | B1       | 3,860.60 | 1,514.55 | 1,284.81 | 5,143.92 | 1,971.03 | 6,504.36 |
|             |      | B2       | 3,846.36 | 1,519.98 | 1,207.82 | 5,022.77 | 1,965.52 | 6,330.66 |

Note: NA, SA, OA, AF, EU, and AS refer to northern part of America, southern part of America, Oceania, Africa, Europe, and Asia, respectively.

Figure 3. Spatial sediment retention change across the world between 2010 and 2100 under four scenarios. The unit of sediment retention is t/km².
Globally, changes in temporal and spatial ecosystem services caused by land use changes showed a mixture of increases and decreases between 2010 and 2100 under all four scenarios (Figure 2). For carbon storage, there were increases in the Amazon Basin, eastern Asia, Russia, eastern Australia, and central Africa under A1B, B1, and B2 scenarios. A2 exhibited the worst performance in the Amazon Basin and the eastern part of Asia. For water yield, there were decreases in the Amazon Basin under A1B, B1, and B2 scenarios. Water yield performed best under A2 scenario globally. Sediment retention exhibited almost the same variation under all scenarios with gains in the area of dense vegetation such as the Amazon Basin, southern North America and the northern portions of Africa and Asia. For desert areas, there were almost no variation in sediment retention under all scenarios between 2010 and 2100.

Considering analysis on a continental scale (Table 3), carbon densities under scenario B1 were higher than under other scenarios for all continents except for Oceania and northern part of America, where carbon densities under scenario B1 were lower than for B2. There were increases in carbon density between 2010 and 2100 under A1B and B1 scenarios for all continents. Carbon density for southern part of America was much higher than for other continents in 2010 and 2100 under all four scenarios, while carbon density for Europe was the worst among the all continents. Water yield in Europe, Oceania, and southern part of America under A2 were higher than for other scenarios in 2100 and higher than in 2010 as well. Europe had the worst water yield in 2100 under scenario B1, and the 2100 water yield for northern part of America under all four scenarios were all lower than those in 2010. The water yield for southern part of America was higher than for other continents in both 2010 and 2100 under all four scenarios, and northern part of America was the worst among the all continents. For sediment retention, B1 performed best of all four scenarios for Africa, southern part of America and Europe, and there were increases in sediment retention between 2010 and 2100 under all scenarios for northern part of America, Africa, and Europe. Oceania, northern part of America and Asia all had increases between 2010 and 2100 under scenario B1. Sediment retention in Asia was higher than for other continents, and Africa had the lowest values for both 2010 and 2100 under all four scenarios.

Globally, although water yield decreased between 2010 and 2100 under scenario B1, the increase of sediment retention and carbon storage under B1 were more than under other scenarios, this paper choses B1 as a representative scenario for analyzing the impact of land use change to ecosystem services at country level. This paper analyzed top 10 countries of carbon storage and sediment retention and top 10 basins of water yield in 2010 and their changes between 2010 and 2100 under scenario B1 (Figure 3). For carbon storage, India and Indonesia declined 9.38% and 1.44%, respectively. The other eight countries increased, and China increased most, which has increased 29.08%. The combined carbon storage of Russia and Brazil, the largest and the second largest respectively, providing over 1/4 of the world total, and they also rose obviously by 15.56% and 7.08%, respectively. For water yield, Amazon provided most water yield,
Figure 5. Ecosystem Service Change Index (ESCI) under four scenarios, 2100.
accounted 15.37% of global total, which increased 0.09%. Yangtze River decreased most in top 10 basins which declined 1.16%, removing top 10 basins, it should be noted that water yield provided by rest basins declined 16.80%. For sediment retention, China provided the most amount of sediment retention in the world, about 16.60% of the world total in 2010, which has increased 29.08% between 2010 and 2100 under B1 scenario. The United States increased most in top 10 countries which has increased 10.5%. The amount of sediment retention provided by combined top 10 countries exceeded over 1/2 of the world total (Figure 4).

3.2. Analysis of Ecosystem Services Status

There is a complex and nonlinear relationship among ecosystem services. To consider the cumulative impacts of all services, ESCI and ESSI for all scenarios were analyzed at the country scale (Figures 5 and 6). We can see that there were a mixture of increases and decreases in the ESCI among countries under all scenarios. ESCI and ESSI in each country are quite different. Under scenario B1, for carbon storage, except for the decline of Uruguay (ESCI = −0.023), all other countries in southern part of America increased. Countries in northern Africa performed poorly, and most were in a state of decline. In Europe, Ireland, Denmark, and Andorra decreased significantly (ESCI = −0.249, −0.106, and −0.231, respectively), while Serbia, Lithuania, and Poland increased substantially (ESCI = 0.472, 0.396, and 0.271, respectively). In Asia, the performance of the ESCI in the countries of southwestern Asia such as Pakistan, India, and Myanmar were poor (ESCI = −0.128, −0.094, and −0.080, respectively), while China and Russia increased substantially (ESCI = 0.291 and 0.156, respectively). For water yield, Qatar, Oman, Saudi Arabia, and India in southern Asia decreased significantly (ESCI = −0.999, −0.642, −0.559, and −0.465, respectively). Togo, Algeria, and Cameroon in northern part of Africa performed poorly (ESCI = −0.382, −0.156, and −0.108, respectively). Figure 7. The increase and decrease of carbon storage (CS), water yield (WY), and sediment retention (SR) in each country between 2010 and 2100 under scenario B1.
respectively). Except for a slight increase in the Solomon Islands in Oceania (ESCI = 0.003), all other countries in Oceania decreased. In southern part of America, except for increases in Argentina and Suriname (ESCI = 0.048 and 0.006, respectively), all other countries in southern part of America decreased, Colombia and Brazil performed poorly (ESCI = −0.312 and −0.228, respectively). For sediment retention, except for decreases in Gambia and Benin (ESCI = −0.066 and −0.021, respectively), all other countries in Africa and Oceania increased. Except for decreases in Paraguay, Suriname, and Brazil (ESCI = −0.027, −0.003, and −0.002, respectively), the rest of the countries in southern part of America increased. Except for decreases in Antigua and Barbuda (ESCI = −0.070 and −0.051, respectively), the countries of northern part of America increased. Asia performed best for sediment retention, such as Qatar, Turkmenistan, Oman, Tajikistan, Yemen, Saudi Arabia, and Russia (ESCI = 1.857, 1.425, 0.622, 0.571, 0.396, 0.338, and 0.311, respectively). In Figure 7, we can see more intuitively the increase and decrease of three ecosystem services in each country between 2010 and 2100 under scenario B1, the countries in southwestern Asia had increased only in sediment retention, all three ecosystem services increased in America and Australia, China increased in sediment retention and carbon storage, decreased in water yield. It should be noted that there were two countries in which the ESCI of three ecosystem services were all less than 0 and 45 countries in which the ESCI of three ecosystem services were all greater than 0 (Figure 8). Regarding the ESSI, countries in Asia performed better than those of other continents, Turkmenistan and Lebanon had the highest increases (ESSI = 0.703 and 0.296, respectively), India and Saudi Arabia had the greatest decreases (ESSI = −0.168 and −0.087, respectively). Colombia and Brazil in southern part of America decreased most (ESSI = −0.056 and −0.053, respectively).

4. Discussion and Conclusions
As a very important factor affecting ecosystem services, land has always changed to meet the needs of human activity and the social economy. This paper demonstrates land use changes under four scenarios derived from IPCC SRES and their global impacts on three ecosystem services, resulting in an important reference for managers to understand how different development scenarios affect land use changes and how land use changes affect ecosystem services.

4.1. Land use Impacts on Ecosystem Service
Between 2010 and 2100 under B1 scenario, forest and grassland increased more than under other scenarios. The area of forest converted to grassland, farmland, and urban is lower than under other scenarios, with the
area of grassland and farmland converting to forest increased to a greater degree than under other scenarios. Although the impact of land use changes on the three selected ecosystem services varies from place to place, sediment retention and carbon storage under scenario B1 increase more than under other scenarios, with average global increases of 175.74 t/km² and 913.60 Mg/km², respectively, water yield increase only under scenario A2 between 2010 and 2100, with average global increase of 3.51 mm. On a global scale, forest is the largest producer of these ecosystem services and grassland is second, proving that forest and grassland are the main land types to provide these ecosystem services. Globally, the percentage of water yield provided by forest is far less than the percentage of sediment retention and carbon storage (Table 1), suggesting that forests’ capacity for providing water yield is weaker than the capacity for providing sediment retention and carbon storage. Although globally, the water yield rate of forest is higher than from other land types under the same scenario (Table 1), the water yield rate of forest is not always higher than that of other land types at the country scale, such as Finland, the water yield provided by forest in 2010 is 360.01 mm; however, the water yield provided by grassland, farmland, and urban are 390.98, 379.24, and 406.07 mm, respectively. One of the main reasons for this is that water yield is not only determined by land use type but is also affected by precipitation, temperature, slope, and soil conditions, with areas exhibiting abundant rainfall producing higher water yield (Farley et al., 2005).

Land use conversion has an important impact on these ecosystem services. The impacts of different land use conversions on specific ecosystem services vary. Examining the impacts of land use conversion on sediment retention and carbon storage between 2010 and 2100 under four scenarios, when other land uses are converted to forest, sediment retention, and carbon storage increase in all scenarios. This is because the capacity of sediment retention and carbon storage provided by forest is superior to other land use types. Previous studies have shown that increasing forest area can increase sediment retention and carbon storage (Panyawai et al., 2019). When other land uses except forest are converted to grassland, sediment retention increase in all scenarios, this is because grassland has a large ability to increase sediment retention. Hao et al. (2017) indicated that increasing grassland area can protect soil from soil erosion, while the impacts of land use conversion on water yield differ from those attributable to sediment retention and carbon storage, when forest is converted to grassland, farmland, and urban, water yield increase. The present paper shows that water yield increases when forest is converted to grassland, farmland, and urban because forest has greater transpiration, interception, and evaporation than grasses and crops, which can decrease water yield (Cao et al., 2009; Farley et al., 2005). Many papers refer to the fact that deforestation can increase water yield in some areas, including Andréassian (2004) who examined 137 watersheds around the world, Ice and Stednick (2004) for southern part of America, and Scott et al. (2004) on the tropics. Robinson et al. (2003) pointed out that the expansion of forest and afforestation in Europe will lead to decreases in water yield. When forest is converted to water, water yield decreases under all scenarios because of the high evaporation produced by uncovered water surfaces. Many papers find that there is synergy between sediment retention and carbon storage, and both of them demonstrate a trade-off relationship with water yield, when sediment retention and carbon storage increase, water yield will decrease (Dymond et al., 2012; Qin et al., 2015). However, we find that when forest, grassland, cropland, and urban are converted to barren, these ecosystem services all increase, there is synergy among them in this land use conversion. In 2010, barren land accounts about one third to the total global area, thus strengthening the utilization of barren land can increase ecosystem services greatly.

4.2. Analysis of Ecosystem Service States at the Country Scale

This paper uses the ESCI and ESSI to quantify increases or decreases in each individual ecosystem service and the cumulative change status of all considered ecosystem services. There was a mixture of increases and decreases in the ESCI among countries under all scenarios. The country-by-country cumulative ESSI and ESCI are often quite different. On the country scale, to examine the fact that under scenario B1 some countries possess ESCIs all less than 0 and some countries do not completely, this paper examines land changes in these countries between 2010 and 2100 under scenario B1 (Figure 8). We observe that in countries which the ESCIs for these ecosystem services were all less than 0, all experienced declines in forest and grassland area or increases in barren area. Conversely, in countries which the ESCIs for these ecosystem services were greater than 0, all experienced increases in forest and grassland or decreases in barren. For example, under B1 scenario, the ESCIs for three ecosystem services in Cyprus were all greater than 0, and the areas of forest and grassland in Cyprus all decreased while the area of barren decreased by 28.15%,
and urban and farmland increased by 30.16%. The same relationship between the ESCI and land use changes holds in Burkina Faso, Iraq, Lebanon, Mongolia, and Palestine. In countries with an ESSI greater than 0, there is the same land use changes in these countries, demonstrating that reductions in the area of barren help increase three ecosystem services, and thus, land use managers can increase the use of barren to enhance the ecosystem services.

This paper analyzed land use changes between 2010 and 2100 under four scenarios as described in the fourth assessment report of the IPCC and examined the impact on carbon storage, water yield, and sediment retention. The results showed that forest and grassland were the main land types providing three ecosystem services on a global scale. Different scenarios lead to different impacts on land use patterns, with resulting differences in their impacts on ecosystem services. Sediment retention and carbon storage under scenario B1 increased more than under other scenarios, with average global increases of 175.74 t/km² and 913.60 Mg/km², respectively, water yield increased only under scenario A2 between 2010 and 2100, with average global increase of 3.51 mm. On a global scale, increasing the area of forest and grassland contributed to increases in sediment retention and carbon storage, but when forest was converted to grassland, farmland, and urban, water yield decreased, so increasing forest area can increase sediment retention and carbon storage, but water yield will decrease when afforestation takes place in grassland, farmland, and urban. These ecosystem services have a synergy relationship when forest, grassland, cropland, and urban are converted to barren, which these ecosystem services all increase, so decreasing the area of barren can increase these ecosystem services. The results of this paper are of great significance for achieving the sustainable development of ecosystem services.

This paper considered only three ecosystem services (water yield, carbon storage, and sediment retention), it is insufficient for comprehensive ecosystem services. Another limitation was that we analyzed the change of land use through different development scenarios, and then led to the change of ecosystem services; however, ecosystem services have complex mechanisms; the linearity and simplification of analysis are uncomfortable for many ecosystem services researches. The last challenge for our paper was that we only chose China as the validation region to assess the accuracy of ecosystem services calculated by InVEST.

Data Availability Statement
The 2010 and 2100 global land use and land-cover (LUCC) map were obtained online (http://geosimulation.cn/GlobalLUCCProduct.html). Plant root depths, plant available water content, and soil depths were obtained online (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/). Precipitation, evapotranspiration, and solar radiation were obtained from TerraClimate data sets (https://doi.org/10.1038/sdata.2017.191). Monthly mean temperature was obtained from ERA5 Monthly aggregates (https://cds.climate.copernicus.eu/cdsapp#!/home). Global watersheds were obtained online (https://www.hydrosheds.org/). DEM was obtained from Hijmans et al. (2005). Soil erosion modulus data sets and runoff records were obtained from National Earth System Science Data Center and local hydrological stations (http://www.geodata.cn).

Conflict of Interest
The authors declare no conflicts of interest.

References
Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, 5(1), 170191. https://doi.org/10.1038/sdata.2017.191
Andréassian, V. (2004). Waters and forests: From historical controversy to scientific debate. *Journal of Hydrology*, 291(1–2), 1–27. https://doi.org/10.1016/j.jhydrol.2003.12.015
Bhagabati, N. K., Ricketts, T., Sulistyawan, T. B. S., Conte, M., Ennaanay, D., Hadian, O., et al. (2014). Ecosystem services reinforce Sumatran tiger conservation in land use plans. *Biological Conservation*, 169, 147–156. https://doi.org/10.1016/j.biocon.2013.11.010
Cao, S., Chen, L., & Yu, X. (2009). Impact of China’s Grain for Green Project on the landscape of vulnerable arid and semi-arid agricultural regions: A case study in northern Shaanxi Province. *Journal of Applied Ecology*, 46(3), 536–543. https://doi.org/10.1111/j.1365-2664.2008.01605.x
Copernicus Climate Change Service (CJS) (2017). ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS). https://cds.climate.copernicus.eu/cdsapp#!/home
Costanza, R., D’Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world’s ecosystem services and natural capital. *Ecological Economics*, 16(3), 253–260. https://doi.org/10.1029/2020EF001668
Daniel, D. W., Smith, L. M., Belden, J. B., McMurry, S. T., & Swain, S. (2015). Effects of land-use change and fungicide application on soil respiration in playas and adjacent uplands of the U.S. High Plains. *Science of the Total Environment*, 514, 290–297. https://doi.org/10.1016/j.scitotenv.2015.01.066

Dymond, J. R., Ausill, A. E., Ekanayake, J. C., & Kirschbaum, M. U. F. (2012). Tradeoffs between soil, water, and carbon—A national scale analysis from New Zealand. *Journal of Environmental Management*, 95(1), 124–131. https://doi.org/10.1016/j.jenvman.2011.09.019

Farley, K. A., Jobbagy, E. G., & Jackson, R. B. (2005). Effects of afforestation on water yield: A global synthesis with implications for policy. *Global Change Biology*, 11(10), 1565–1576. https://doi.org/10.1111/j.1365-2486.2005.01011.x

Feng-jin, X., & Hua, O. (2002). Ecosystem health and its evolution indicator and method. *Journal of Natural Resources*, 17(2), 203–209. https://doi.org/10.1111/1469-8355.00212

Gashaw, T., Tulu, T., Argaw, M., Worqplul, A. W., Tolessa, T., & Kindu, M. (2018). Estimating the impacts of land use/land cover changes on Ecosystem services: The case of the Andassa watershed in the Upper Blue Nile basin of Ethiopia. *Ecosystem Services*, 31, 219–228. https://doi.org/10.1016/j.ecoser.2018.05.001

Halpern, B. S., Selkoe, K. A., Micheli, F., & Kappel, C. V. (2007). Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. *Conservation Biology*, 21(3), 1301–1315. https://doi.org/10.1111/j.1523-1739.2007.00752.x

Hamel, P., Chaplin-Kramer, R., Sim, S., & Mueller, C. (2015). A new approach to modeling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. *Science of the Total Environment*, 524, 166–177. https://doi.org/10.1016/j.scitotenv.2015.04.027

Hao, R., Yu, D., Liu, Y., Liu, Y., Qiao, J., Wang, X., & Du, J. (2017). Impacts of changes in climate and landscape pattern on ecosystem services. *Science of the Total Environment*, 579, 718–728. https://doi.org/10.1016/j.scitotenv.2016.11.036

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25(15), 1965–1978. http://doi.org/10.1002/joc.1276

Ice, G. G., & Stednick, J. D. (2004). *Century of forest and wildland watershed lessons*. https://doi.org/10.1029/2002joc01201.00007-3

Lanza, R., Martinsen, T., Mohammad, A. K. W., Santos, M. M. O., Neelis, M., & Patel, M. K. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Vol. 3, pp. 3.57–3.91). Japan: Institute for Global Environmental Strategies.

Laurance, W. F., Dell, B., Turton, S. M., Lawes, M. J., Hutilus, L. B., McCallum, H., et al. (2011). The 10 Australian ecosystems most vulnerable to tipping points. *Biological Conservation*, 144(5), 1472–1480. https://doi.org/10.1016/j.biocon.2011.01.016

Let, M. D. K., Matlock, M. D., Cummings, E. C., & Nalley, L. L. (2013). Quantifying and mapping multiple ecosystem services change in coastal vegetative meadows at Tangkhen Bay, Phuket, Southern Thailand. *Ecological Research*, 28(3), 379–380. https://doi.org/10.1016/j.anurev.energy.2013.01.05.06

Li, X., Chen, G., Liu, X., Liang, X., Wang, S., Chen, Y., et al. (2017). A new global land-use and land-cover change product at a 1-km resolution for 2010 to 2100 based on human-environment interactions. *Annals of the American Association of Geographers*, 107, 1040–1059. http://doi.org/10.1080/24694452.2017.1303357

Lugato, E. I., Chen, C., & Wu, C. (2018). Evaluation of tropical coastal land cover and land use changes and their impacts on ecosystem service values. *Ecosystem Health and Sustainability*, 4(8), 188–204. https://doi.org/10.2906/20964129.2018.1512839

Liu, J., Ji, L., Gao, Y., Yang, M., Qin, K., & Yang, X. (2016). Ecosystem services insights into water resources management in China: A case of Xi’an city. *International Journal of Environmental Research*, 10(12), 1169. https://doi.org/10.3390/ijerph13211169

Liu, X., Li, X., Liang, X., Shi, H., & Ou, J. (2019). Simulating the change of terrestrial carbon storage in China based on the PLUS-InVEST model. *Tropical Geography*, 39(3), 379–409. https://doi.org/10.13264/cjnl.idd.003138

Liu, R., Mi, L., Zhang, J., Xu, M., & Li, J. (2019). Modeling the effects of urban expansion on regional carbon storage by coupling SLEUTH model and InVEST model. *Ecological Research*, 34(3), 380–393. https://doi.org/10.1111/1440-1703.1278

Mohawsh, Y., Taimeh, A., & Ziadat, F. (2015). Effects of land use changes and soil conservation intervention on soil properties as indicators for land degradation under a Mediterranean climate. *Solid Earth*, 6(3), 857–868. https://doi.org/10.5194/se-6-857-2015

Nowak, D. J., & Crane, D. E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution*, 116(3), 381–389. https://doi.org/10.1016/S0269-7491(01)00214-7

Panyawal, J., Tuntipprapas, P., & Prathep, A. (2018). High macrophyte canopy complexity enhances sediment retention and carbon storage in coastal vegetative meadows at Tagkhen Bang, Phuket, Southern Thailand. *Ecological Research*, 34(1), 201–212. https://doi.org/10.1111/1440-1703.1066

Qin, K., Li, J., & Yang, X. (2015). Trade-off and synergy among ecosystem services in the Guangzhou-Tianshui Economic Region of China. *International Journal of Environmental Research and Public Health*, 12(11), 14,094–14,113. https://doi.org/10.3390/ijerph121114094

Renard, K. G., Foster, G. R., Weesies, G. A., & Porter, J. P. (1991). RUSLE: Revised universal soil loss equation. *Journal of Soil and Water Conservation*, 46(1), 30–33. https://doi.org/10.2489/jswc.46.1.30

Robinson, M., Cognard-Plancq, A. L., Coumée, C., David, J., Durand, P., Führer, H. W., et al. (2003). Studies of the impact of forests on peak flows and baselines: A European perspective. *Forest Ecology and Management*, 186(1–3), 85–97. https://doi.org/10.1016/S0378-1127(03)00218-X

Scott, D. F., Bruijnzeel, L. A., & Mackensen, J. (2004). The hydrologic and soil impacts of forestation in the tropics. In M. Bonell, & L. A. Bruijnzeel (Eds.), *Forests, Water and People in the Humid Tropics* (pp. 622–651). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511556661.032

Seppelt, R., Dormann, C. F., Eppink, P. V., & Lautenbach, S. (2011). A quantitative review of ecosystem service study: Approaches, shortcomings and the road ahead. *Journal of Applied Ecology*, 48(3), 630–636. http://doi.org/10.1111/j.1365-2664.2010.01952.x

Sherrouse, B. C., Semmens, D. J., Ancona, Z. H., & Brunner, N. M. (2017). Analyzing land-use change scenarios for trade-offs among cultural ecosystem services in the Southern Rocky. *Ecosystem Services*, 26(Part B), 431–444. http://doi.org/10.1016/j.ecoser.2017.02.003

Sleeter, B. M., Sohl, T. L., Bouchard, M. A., Reker, R. R., Soulard, C. E., Acevedo, W., et al. (2012). Scenarios of land-use and land cover change in the conterminous United States: Utilizing the special report on emission scenarios at ecoregional scales. *Global Environmental Change*, 22(4), 896–914. http://doi.org/10.1016/j.gloenvcha.2012.03.008
Sohl, T. L., Sleeper, B. M., Sayler, K. L., Bouchard, M. A., Reker, R. R., Bennett, S. L., et al. (2012). Spatially explicit land-use and landcover scenarios for the Great Plains of the United States. *Agriculture, Ecosystems & Environment, 153*, 1–15. https://doi.org/10.1016/j.agee.2012.02.019

Sutton, P., & Costanza, R. (2002). Global estimates of market and non-market values derived from nighttime satellite imagery, land cover, and ecosystem service valuation. *Ecological Economics, 41*(3), 509–527. http://doi.org/10.1016/S0921-8009(02)00097-4

Tallis, H. T., Ricketts, T., Guarry, A. D., Wood, S. A., Sharp, R., Nelson, E., et al. (2011). InVEST 2.21 User’s Guide. *The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund*.

Wischmeier, W. H., & Smith, D. D. (1978). Predicting rainfall erosion losses—A guide to conservation planning. In USDA *Agriculture Handbook* (pp. 537–538), Washington, DC: US Govt. Printing Office.

Yang, X., Li, J., Qin, K., Li, T., & Liu, J. (2015). Trade-offs between ecosystem services in Guanzhong Tianshui Economic Region. *Acta Geographica Sinica, 70*(11), 1762–1773. http://doi.org/10.11821/dlxb201511006

Yin, G., Wang, X., Zhang, X., Fu, Y., & Hu, Q. (2020). InVEST model-based estimation of water yield in north China and its sensitivities to climate variables. *Water, 12*(6), 1692. http://doi.org/10.3390/w12061692

Yu, G., Yu, Q., Hu, L., Zhang, S., Fu, T., Zhou, X., et al. (2013). Ecosystem health assessment based on analysis of a land use database. *Applied Geography, 44*, 154–164. https://doi.org/10.1016/j.apgeog.2013.07.010

Yu, Y., Wei, W., Chen, L. D., & Jia, F. Y. (2015). Responses of vertical soil moisture to rainfall pulses and land uses in a typical loess hilly area, China. *Solid Earth, 6*(2), 595–608. https://doi.org/10.5194/se-6-595-2015

Zhang, L., Dawes, W. R., & Walker, G. R. (2001). Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research, 37*(3), 701–708. https://doi.org/10.1029/2000wr900325

Zhang, Q., Ye, H., Ding, Y., Cao, Q., Zhang, Y., & Huang, K. (2019). Carbon storage dynamics of subtropical forests estimated with multi-period forest inventories at a regional scale: The case of Jiangxi forests. *Journal of Forestry Research, 31*(4), 1247–1254. https://doi.org/10.1007/s11676-019-00891-3