Evaluating Ecosystem Services and Trade-Offs Based on Land-Use Simulation: A Case Study in the Farming–Pastoral Ecotone of Northern China

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Abstract: Evaluating the impacts of land-use change (LUC) on ecosystem services (ESs) is necessary for regional sustainable development, especially for the farming–pastoral ecotone of northern China (FPENC), an ecologically sensitive and fragile region. This study aimed to assess the impacts of LUC on the ESs and provide valuable information for regional planning and management in the FPENC. To accomplish this, we assessed LUC in the FPENC from 2010 to 2020 and simulated land-use patterns in 2030 under three plausible scenarios: the business as usual scenario (BAUS), economic development scenario (EDS), and ecological protection scenario (EPS). Then, we quantified five ESs (including crop production, water yield, soil retention, water purification, and carbon storage) for 2020–2030 and analyzed the trade-offs and synergies among ESs in all scenarios. The results show that FPENC experienced expanding farming land and built-up land throughout 2010–2020. Under the BAUS and EDS from 2000 to 2030, especially EDS, the increase in farming land and built-up land will continue. As a result, crop production and water yield will increase, while soil retention, water purification, and carbon storage will decrease. In contrast, EPS will increase soil retention, water purification, and carbon storage at the cost of a decline in crop production and water yield. These results can provide effective reference information for future regional planning and management in the farming–pastoral ecotone.

Keywords: land-use change; scenario analysis; ecosystem services; trade-off and synergy

1. Introduction

Ecosystem services (ESs) refer to the benefits people obtain directly or indirectly from nature, including provisioning services (e.g., food and water), regulating services (e.g., flood control), supporting services (e.g., nutrient cycling), and cultural services (e.g., spiritual benefits) [1,2]. Throughout human history, people’s well-being has depended on the functioning of the ecosystem around them [3]. Meanwhile, human’s impact on the ecosystem and the supply of their services is accelerating [3,4]. Humans have spent substantial effort modifying ecosystems to attain the ESs they need for production, such as food, raw material, and fuels [5,6]. However, relationships among ESs are complex and dynamic [7]. Increasing one ecosystem service may lead to an increase or decrease in other ESs [8,9]. The increasing of the Earth system to meet the demand for provisioning services will inevitably reduce the supply of other services [10]. The Millennium Ecosystem Assessment indicated that over 60% of the Earth’s ESs had experienced degradation, and this trend may continue to accelerate [2]. In this context, decision makers need to think about how to balance human development demands with ESs changes to ensure the sustainable provision of desired ESs.
As major anthropogenic changes [11], land-use changes (LUCs) closely connect human activities with ecological processes [12]. LUCs affect the physicochemical properties of the land surface and thus affect the supply process of ESs [13,14] and are considered one of the most important drivers affecting ESs [15,16]. To meet social development, humans often alter regional land-use patterns to obtain desired ESs [17,18]. However, this often leads to the degradation or unsustainable use of other ESs [19,20]. Studies have shown that rapid LUC might affect the direction of ESs trade-offs [21]. For instance, rapid urban expansion could lead to a decline in regulating services through changes in carbon sequestration [22,23], nutrient flow [24,25], and biodiversity [26,27]. Therefore, exploring the impacts of land-use change on ESs is essential for further understanding the relationship between humans and nature and achieving sustainable development.

In recent years, scenario analysis has become an important tool for evaluating the impact of LUCs on ESs. By setting up possible development scenarios based on different land-use demands and calculating variations in and trade-offs among ESs under different scenarios, this approach can provide helpful information for decision makers to develop the best land management strategies [28–31]. Sharma et al. analyzed the trade-off among ESs of oil palm plantations under different scenarios in West Kalimantan, Indonesia, and provided information for future oil palm plantation expansion [32]. Srichaichana et al. evaluated water yield and sediment retention in Klong U-Tapao under different land-use scenarios and found that the forest conservation and prevention scenario could optimize ESs [33]. Sun et al. examined the impacts of different land scenarios on ESs globally, finding that forests, etc., are major land types providing ESs, and enhancing the utilization of barren land could increase ESs [34]. Peng et al. explored the impacts of different Grain-for-Green Programme scenarios on ESs in the Dali Autonomous Prefecture, finding that Grain-for-Green Programme might intensify ESs trade-offs [35].

Studies on the impacts of LUC on ESs have been conducted in various landscapes, such as cities [36,37], watersheds [38,39], and protected areas [40]. Few studies have explored the impacts of land use on ESs with the goal of providing valuable insights for regional planning and management, which remains a challenge [18], especially for the farming–pastoral ecotone. The farming–pastoral ecotone is a transition zone from traditional farming regions to pastoral regions over space and time [41,42]. The farming–pastoral ecotone of northern China (FPENC) covers nine provinces, and it is the largest ecotone in China in terms of area and spatial scale [43]. Given its unique geographic location and arid climatic conditions, the ecological environment of FPENC is sensitive and fragile and prone to being changed and disturbed by human activities [44,45]. In such areas, land-use patterns generally experience more frequent changes [46]. Under massive agricultural reclamation, the region has suffered severe vegetation degradation, land desertification, and salinization [47,48]. Therefore, it is more urgent for FPENC to understand the impact of LUC on ESs to develop effective regional planning and management policies to achieve sustainable development.

In order to assess the impact of LUC on the ESs variation, we developed three scenarios to analyze the ESs changes and their trade-offs. This study aimed to provide reference information for future regional planning and management. To achieve it, we (1) analyzed LUC from 2010 to 2020 and designed three LUC scenarios; (2) quantified and mapped variations in key ESs (crop production, water yield, soil retention, water purification, and carbon storage) under three scenarios; (3) analyzed trade-offs among ESs under three scenarios; and (4) proposed suggestions for future regional planning and management.

2. Materials and Methods

2.1. Study Area

In recent years, agro-meteorological factors have been widely used to define the range of the farming–pastoral ecotone. The 400 mm rainfall contour as the centerline and the 300–450 mm rainfall contour as the range is the most fundamental division basis and is generally accepted by researchers [49]. This study defined FPENC using 300 mm and 450 mm rain-
fall contours, supplemented by county administrative divisions (Figure 1b). The FPENC (34°50′25″–48°36′27″ N, 102°35′58″–125°55′4″ E) is located in the arid and semi-arid regions of northern China and covers nine provinces (i.e., Inner Mongolia, Heilongjiang, Jilin, Liaoning, Hebei, Shanxi, Ningxia, Shaanxi, and Gansu), with an area of 681,095.10 km² and an elevation ranging from −83 to 4286 m (Figure 1a). With a typical semi-arid continental climate, the annual average temperature in the study area ranges from 2 °C to 8 °C, and the annual average precipitation ranges from 300 to 450 mm, mostly concentrated within June to August [50]. Due to the limitation of water resources, drought-resistant crops such as spring corn are the main food crop in this region [51].

Figure 1. Geographical location and elevation (a) and the definition (b) of the farming–pastoral ecotone of northern China.

2.2. Data Sources

In this study, the data used and their sources are as follows: (1) land-use data in 2010 and 2020 were obtained from the Globeland30 platform (http://globeland30.org/ (accessed on 4 October 2021)). They were divided into ten categories (i.e., farming land, forest, grassland, shrub, wetland, waterbody, built-up land, tundra, barren land and glaciers, and permanent snow). Based on the actual land use in the FPENC, land-use types were classified into seven categories: farming land, forest, grassland, wetland, waterbody, built-up land, and barren land in this study. (2) Climate data (i.e., precipitation, temperature, and potential evapotranspiration) were taken from the National Earth System Science Data Center (http://www.geodata.cn/data/ (accessed on 2 March 2022)). (3) Digital elevation model data (DEM), gross domestic product (GDP) [52], and population [53] data were provided by Resource and Environment Science and Data Center (https://www.resdc.cn/ (accessed on 19 March 2022)). (4) Road data were from Open Street Map (https://www.openstreetmap.org/ (accessed on 14 March 2022)). (5) Other socio-economic data were collected from the statistical yearbooks and national economic and social development bulletins of the counties and cities in the study area.

2.3. Framework

A process framework with three core steps was developed to evaluate the impact of LUC on ESs in the FPENC (Figure 2). First, the Future Land-Use Simulation (FLUS) model was used to simulate land use in 2030 under three alternative scenarios. Second,
we quantified and mapped five ecosystem services under the three scenarios. Finally, we analyzed trade-offs among the ESs.

Figure 2. Framework.

2.3.1. FLUS Model

The FLUS model is a model for LUC simulation that couples human and natural effects. The model integrates the top-down system dynamics model and bottom-up meta-cellular automata (CA) model [54]. Based on the traditional CA model, the FLUS model introduces the self-adaptive inertia mechanism and roulette mechanism, which makes it more advantageous for spatial simulation [55]. It has been successfully applied in regional and global LUC simulations [55–57]. The operation of the model is divided into two main parts: the first part generates a probability layer for each land-use type through an artificial network algorithm (ANN) based on the land use and its drivers; the second part mainly adopts self-adaptive inertia and a competition mechanism to predict the probability of all LUCs (Equation (1)) by considering probability surface, neighborhood effect, inertia coefficient, and conversion cost, and finally obtains land-use simulation results via roulette mechanism [58].

\[
TP_{p,k}^t = P_{p,k} \times \Omega_{p,k}^t \times \text{Inertia}_k^t \times (1 - sc_{c\to k})
\]  

where \(TP_{p,k}^t\) refers to the combined probability of pixel \(p\) to transform from the original land use type to the target type \(k\) at the iteration time \(t\); \(P_{p,k}\) represents the probability of occurrence of land use type \(k\) in pixel \(p\); \(\Omega_{p,k}^t\) is the neighborhood effect of land use type \(k\) on pixel \(p\) at time \(t\), and \(sc_{c\to k}\) is the conversion possibility from original land use type \(c\) to target type \(k\) (1 represents possible conversion and 0 represents impossible conversion).

In addition, to validate the simulation results, we introduced the Kappa coefficient, a commonly used coefficient reflecting the confidence of the prediction results. If it is greater than 0.75, it indicates that the simulation results are credible. We tried to adjust the neighborhood effect and conversion cost to obtain a higher kappa coefficient.

2.3.2. Scenarios Setting

Considering the geographical location, ecological characteristics, and strategic position of FPENC, we set three land-use scenarios for 2030.
Scenario 1: business as usual scenarios (BUS). In this scenario, the LUC follows the historical pattern and transition rules (2010–2020), and no constraints are set in land use allocation.

Scenario 2: economic development scenario (EDS). In this scenario, it is inevitable to expand the farming land and accelerate the urbanization process to meet the needs of economic development. Therefore, in line with previous studies [59,60] and with reference to land use conversion in 2010–2020, we set the probability of transferring forest, grassland, water, wetland, and barren land to farming land by an increase of 50% and the probability of transferring farming land, forest, and grassland to built-up land by an increase of 100% under the EDS.

Scenario 3: ecological protection scenario (EPS). In this scenario, the primary goal is to strengthen the protection of semi-natural land and maintain the stability of ecosystem functions. Therefore, in line with previous studies [59,60] and with reference to land use conversion in 2010–2020, we set the probability of conversion of forest, waterbody, and wetland to farming land to decrease by 100%; the probability of conversion of forest to built-up land to decrease by 100%; the probability of conversion of grassland and barren land to farming land to decrease by 50%; the probability of conversion of farming land to built-up land to decrease by 50%; and the probability of conversion of farming land to built-up land to decrease by 50%.

2.3.3. Quantification of Ecosystem Services (ESs)

Considering stakeholder concerns, social and service connections, and good data availability, we selected crop production, water yield, soil retention, water purification, and carbon storage to characterize the ecosystem status of the FPENC. First, based on the significant correlation between Net Primary Productivity (NPP) and crop yield [61], crop production was downscaled from county to grid levels. In addition, the Integrate Valuation of Ecosystem Services and Trade-offs (InVEST) model is a computer tool developed by the Natural Capital Project. The InVEST model aims to inform decisions about natural resource management [62], works on a grid map, and reports the results in biophysical and monetary terms [63], which is an effective tool to quantify and map the values of ESs. This study used water yield, sediment delivery ratio, and carbon modules in InVEST to assess the spatial distribution of water yield, soil retention, and carbon storage. The nutrient delivery radio module in InVEST was used to calculate nitrogen export, an indicator of water purification service. High nitrogen export level indicates a low water purification service supply [64]. Table 1 shows the method employed to quantify each ES.

Table 1. Methods for quantifying ecosystem services. (CP, crop production; WY, water yield; SR, soil retention; NE, nitrogen export; CS, carbon storage).

<table>
<thead>
<tr>
<th>Formulas</th>
<th>Description</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>CP [C_i = C_{sum} \times \frac{NPP_i}{NPP_{sum}}]</td>
<td>[C_{ij}] refers to the crop production in pixel (x(t)), (C_{sum}) refers to the total crop yield ((t)), (NPP_i) refers to the NPP of grid (i), and (NPP_{sum}) refers to the sum of the regional NPP.</td>
<td>[61]</td>
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<tr>
<td>WY [Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \cdot P(x)]</td>
<td>(Y(x)) refers to water yield for the landscape (x), (AET(x)) refers to the actual evapotranspiration for pixel (x), and (P(x)) refers to the actual precipitation on pixel (x).</td>
<td>[65]</td>
</tr>
<tr>
<td>SR [USLE = R \times K \times LS \times C \times P] [SR = RKLS - USLE]</td>
<td>USLE is the amount of soil loss; (R) is rainfall erosivity; (K) is soil erodibility; (LS) is a slope length–gradient factor; (C) is vegetation cover management factor; (P) is support practice factor; (SR) is the amount of soil retention.</td>
<td>[65]</td>
</tr>
<tr>
<td>NE [N_{export_i} = \text{load}_i \times NDR_i]</td>
<td>(N_{export_i}) refers to the nitrogen export on pixel (i), (\text{load}_i) refers to the modified nitrogen load on pixel (i), and (NDR_i) refers to nitrogen delivery ratio on pixel (i).</td>
<td>[65]</td>
</tr>
<tr>
<td>CS [C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead}]</td>
<td>(C_{total}), (C_{above}), (C_{below}), (C_{soil}), and (C_{dead}) refer to total carbon, aboveground biomass, belowground biomass, soil organic carbon, and dead matter, respectively.</td>
<td>[65]</td>
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</table>
2.3.4. Statistical Analysis

This paper used Pearson’s correlation test to examine the relationship among ESs. It can quickly identify and quantitatively compare relationships among ESs [66]. First, we randomly generated 300 points in the study area and extracted the corresponding values of all ESs to those points in all scenarios. Then, Origin software was used to examine the linear correlation of paired ESs. When the correlation coefficient of the paired ESs was negative and passed the significance test at the 0.01 level, it was considered that there was a trade-off. Conversely, if the correlation coefficient was positive and passed the significance test, there was a synergy [67]. Moreover, the value of the correlation coefficient can be used to determine the strength of trade-off/synergistic relationships between pairs of ecosystems [68]. The larger the absolute value of the correlation coefficient, the stronger the trade-off/synergistic relationship between ESs. Conversely, the smaller the absolute value, the weaker the trade-off/synergistic relationship. However, it is essential to emphasize that the significance tests in this research are just indicative because the dependence between the spatial variables tends to invalidate the independent hypothesis.

3. Results

3.1. Land-Use Change (LUC)

3.1.1. Land-Use Change (LUC) in the Past

Figures 3 and 4 show the spatial and temporal LUCs in the FPENC throughout 2010–2020. Grassland and farming land were the main land use types in the study area, occupying 48.58% and 37.75%, respectively, in 2010. Forests occupied 8.14% of the total area, and other land use types (i.e., built-up land, barren land, waterbody, and wetland) occupied less. From 2010 to 2020, FPENC experienced an increase in farming land and built-up land and a decrease in grassland. We used Chord Diagram to visualize the conversion direction between land use types (Figure 4). In 2020, the grassland area decreased to 45.18% of the total area, mainly converted to farming land, forest, and barren land. The forest and wetland area also decreased to 7.82% and 0.36% of the total area in 2020, respectively. Forest was mainly converted to grassland and farming land. Wetland was largely converted to farming land and grassland. The farming land, waterbody, built-up land, and barren land increased to 39.47%, 1.38%, 3.14%, and 2.65% of the total area, respectively. The increase in farming land and barren land largely came from grassland. The increase in built-up land mainly came from the conversion of farming land.

3.1.2. Land-Use Change (LUC) under the Scenarios

In 2010, the kappa coefficient and accuracy between simulated and actual land use were 0.8516 and 91.12%, respectively, indicating that FLUS has a good simulation effect in the study area. Figures 5 and 6 show the land-use patterns in 2030 under the three scenarios. The land-use pattern is still dominated by grassland and farming land for all scenarios. However, LUCs differ in the three scenarios. Under the BAUS, grassland, forest, and wetland further declined to 42.48%, 7.48%, and 0.35% of the total area, respectively. On the contrary, the farming land, built-up land, barren land, and waterbody showed an increasing trend. The farming land increased the most at 1.42% (9648.56 km$^2$), followed by built-up land with an increase of 1.07% (7311.56 km$^2$). Under the EDS shows a more significant increase in farming land and built-up land, with an increase of 3.26% (22,173.88 km$^2$) and 1.88% (12,779.06 km$^2$). Similarly, under the EDS from 2020 to 2030, grassland, forest land, and wetland declined more dramatically, by 5.14% (35,019.13 km$^2$), 0.45% (3078.25 km$^2$), and 0.02% (119.25 km$^2$). Unlike the BAUS, the barren land showed a decreasing trend (−0.05%) under the EDS. Compared to the other scenarios, the EPS had the smallest increase in built-up land, with an increase of 0.25% (1733.69 km$^2$). Under the EPS, the grassland, forest land, and wetland increased by 2.25% (15,323.63 km$^2$), 0.09% (624.50 km$^2$), and 0.03% (177.44 km$^2$), respectively. The farming land and barren land area decreased by 3.27% (22,268.25 km$^2$) and 0.09% (612.63 km$^2$), respectively. Overall, the farming land and built-up land area under the EDS were larger than those under the other scenarios. The
grassland area, forestland area, and wetland area under the EPS were larger than those under the other scenarios. The barren land area under the BAUS was the largest due to the low economic cost and ecological benefits.

Figure 3. Land-use change in the past: (a) 2010; (b) 2020.

Figure 4. Land use conversion direction from 2010 to 2020.

3.1.2. Land-Use Change (LUC) under the Scenarios

In 2010, the kappa coefficient and accuracy between simulated and actual land use were 0.8516 and 91.12%, respectively, indicating that FLUS has a good simulation effect in the study area. Figures 5 and 6 show the land-use patterns in 2030 under the three scenarios. The land-use pattern is still dominated by grassland and farming land for all scenarios. However, LUCs differ in the three scenarios. Under the BAUS, grassland, forest, and wetland further declined to 42.48%, 7.48%, and 0.35% of the total area, respectively. On the contrary, the farming land, built-up land, barren land, and waterbody showed an increasing trend. The farming land increased the most at 1.42% (9648.56 km²), followed by built-up land with an increase of 1.07% (7311.56 km²). The EDS shows a more significant increase in farming land and built-up land, with an increase of 3.26%.

3.2. Comparison of the Ecosystem Services (ESs) under the Future Scenarios

Figure 7 shows the spatial characteristics of crop production, water yield, soil retention, nitrogen export, and carbon storage in 2020 and the future scenarios. High-value areas for crop production are mainly distributed in the southwest, south-central, and southeastern areas of the study area, where the rainfall is abundant and suitable for agricultural production. In contrast, low-value areas are distributed in the northern arid zone. Likewise, influenced
by precipitation, the water yield is also characterized by a spatial distribution of high value in the southwest and northeast and low value in the north. High-value soil retention and carbon storage areas are located in the southern and northeastern regions with high terrain and dense vegetation. Low-value areas are concentrated in regions with flat terrain and sparse vegetation. The high nitrogen export values are found in the farming land and built-up land, which are the primary nitrogen sources. In comparison, the no-farmed areas with high terrain present low nitrogen export values.

Figure 5. Land-use patterns in 2030 under three scenarios: (a) BAUS; (b) EDS; (c) EPS; with (a1–c2) detailed simulation results.
Figure 6. Area percentage of land use in the farming–pastoral ecotone of northern China.

The total amount of each ecosystem service in 2020 and three scenarios is shown in Table 2. The BAUS shows an increasing trend in crop production and water yield while performing poorly in soil retention, water purification, and carbon storage. In Figure 8, we can see that, compared with 2020, crop production increases by 3.68% (244.57 × 10^4 t), and water yield increases by 1.05% (3.37 × 10^8 m^3) under the BAUS. These increases in provision services are the results of the expansion of farming land and built-up land. These expansions, in turn, directly lead to a decrease in water purification services. Compared with 2020, the amount of nitrogen export increased to 4.57% (325.13 × 10^4 kg) under the BAUS. Additionally, due to the reduction in forest and grassland in the BAUS, soil retention and carbon storage decreased by 0.16% (0.03 × 10^8 t) and 2.40% (0.52 × 10^8 t), respectively.

Table 2. Total amount of each ecosystem service in 2020 and under three scenarios in 2030.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Crop Production (10^4 ton)</th>
<th>Water Yield (10^8 m^3)</th>
<th>Soil Retention (10^8 ton)</th>
<th>Nitrogen Export (10^4 kg)</th>
<th>Carbon Storage (10^8 ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>6628.24</td>
<td>322.02</td>
<td>16.71</td>
<td>7112.37</td>
<td>21.65</td>
</tr>
<tr>
<td>BAUS</td>
<td>6872.81</td>
<td>325.39</td>
<td>16.68</td>
<td>7437.50</td>
<td>21.13</td>
</tr>
<tr>
<td>EDS</td>
<td>7148.08</td>
<td>330.49</td>
<td>16.60</td>
<td>7704.70</td>
<td>20.87</td>
</tr>
<tr>
<td>EPS</td>
<td>6959.66</td>
<td>315.15</td>
<td>16.74</td>
<td>6665.30</td>
<td>21.70</td>
</tr>
</tbody>
</table>

Under the EDS, further increases could be observed in crop production and water yield. Likewise, decreases in soil retention, water purification, and carbon storage are more significant. Compared with 2020, crop production increases by 7.84% (519.84 × 10^4 t), water yield increases by 2.60% (8.47 × 10^8 m^3), and nitrogen export increases by 7.96% (592.33 × 10^4 kg) under the EDS. On the contrary, compared with 2020, soil retention and carbon storage under the EDS decreased by 0.63% (0.11 × 10^8 t) and 3.60% (0.78 × 10^8 t), respectively.

Unlike the other scenarios, the EPS performs well in soil retention, water purification, and carbon storage while performing more weakly in crop production and carbon storage. Compared with 2020 under the EPS, crop production decreases by 8.03% (532.58 × 10^4 t), water yield decreases by 2.08% (6.87 × 10^8 m^3), and nitrogen export decreases by 5.80% (447.07 × 10^4 kg). Instead, soil retention increases by 0.19% (0.03 × 10^8 t) and carbon storage increases by 0.23% (0.05 × 10^8 t).
Figure 7. Ecosystem services in 2020 and the alternative future scenarios: (a) 2020; (b) BAUS; (c) EDS; (d) EPS.
3.3. Ecosystem Services (ESs) Trade-Offs

ESs are not independent; instead, they are interdependent [13]. Figure 9 reveals the correlation among five ESs in 2030 under three scenarios. It can be seen that, of the ten possible pairs of ESs, seven pairs are significantly correlated ($p < 0.01$) in all scenarios. Overall, the relationships among ecosystem service pairs are consistent under three scenarios. Crop production is positively correlated with water yield. Under the agricultural drought conditions in the FPENC, agricultural practices are influenced mainly by precipitation, which is the main primary of water yield. Crop production and water yield positively correlate with nitrogen export, indicating the trade-offs between them and water purification. Soil retention is not significantly correlated with crop production, water yield, and nitrogen export, while it is significantly and positively correlated with carbon storage. Soil retention is largely, in fact, dependent on vegetation regulation, and vegetation-rich areas accumulate abundant organic matter, which leads to higher carbon storage [64]. In addition, areas with high vegetation cover have lower agricultural production activities and higher evapotranspiration. Therefore, carbon storage is negatively correlated with crop production and water yield. Moreover, carbon storage is negatively correlated with nitrogen export, indicating a synergistic relationship between carbon storage and water purification.

Figure 8. Percentage difference of the ecosystem services under the alternative scenarios.

Figure 9. Trade-offs among ecosystem services under three scenarios in 2030: (a) BAUS; (b) EDS; (c) EPS. (CP, crop production; WY, water yield; SR, soil retention; NE, nitrogen export; CS, carbon storage).
4. Discussion

4.1. Land-Use Change (LUC) and Its Impacts on Ecosystem Services (ESs) in the FPENC

In the land use conversion from 2010 to 2020, it can be seen that the mutual conversion of farming land and grassland is the main feature of the FPENC. After balancing, the conversion of grassland to farming land still dominated in this region (Figure 4). On the one hand, due to the growth of population, the drive for economic interests, and the policy orientation of “stressing agriculture and restraining animal husbandry,” FPENC experienced large-scale agricultural reclamation [48]. On the other hand, the agricultural drought conditions cannot support intensive farming practices. Farmers here tend to adopt extensive cultivation to increase the farming land area and crop yield, resulting in soil fertility loss. Due to the low population density and the vast land resources, farmers are forced to abandon the fertility-depleted land and find new grassland to reclaim [69]. The extensive cultivation practices have accelerated soil desertification [70]. A total of 5409.75 km$^2$ of land was converted to barren land throughout 2010–2020. How would dramatic LUCs affect the ecosystem?

Our study found that the BAUS and the EDS raise water yield compared to the EPS. The increase in the farming land area will increase the regional crop production. The increase in farming land and built-up land can increase the water yield, consistent with previous studies’ results [71,72]. When grassland is replaced by farming land, water yield will increase due to lower evapotranspiration. Simultaneously, the increased built-up land area increases the area of impervious surfaces, which vastly increases the water yield. Studies have shown that moderate urbanization can help alleviate water scarcity in semi-arid regions [73]. However, the increase in farming land and built-up land led to increased nitrogen discharge, resulting in a decline in water purification. For instance, under the BAUS, farming land and built-up land are projected to be 9648.56 km$^2$ and 7311.56 km$^2$, respectively, resulting in an increase in nitrogen export by $3.25 \times 10^6$ t. Studies indicated that agricultural and urban expansion leads to water quality degradation [30,64]. On the other hand, both the BAUS and EDS decrease carbon storage and soil retention. Previous studies have shown that the loss of natural ecosystems (forest, grassland, and marsh) results in a decline in carbon storage [74]. Meanwhile, the reclamation of grassland and forest increases soil erosion [73]. In addition, due to agricultural drought conditions, dryland maize is the major crop in the FPENC, while the large distance between the maize rows also increases the risk of soil erosion [75,76].

4.2. Trade-Offs/Synergies under Different Scenarios

Previous studies have shown that trade-offs are generally found between provisioning services and regulating services, and synergies are generally found among regulating services [77]. According to the Millennium Ecosystem Assessment (MEA) framework, crop production and water yield were classified as provisioning services, and soil retention, water purification, and carbon storage were regulating services. Our findings supported previous conclusions that crop production and water yield were negatively correlated with carbon storage and water purification, while carbon storage was positively correlated with soil retention and water purification (Figure 9). Further, a synergistic relationship between provisioning services was found in this study. Our results showed that the synergistic relationship between provisioning services was highest in EPS, followed by BAUS, and the lowest in EDS. This indicated that the over-cultivation of farming land was not entirely beneficial to water yield in the arid region. Meanwhile, the trade-offs between provisioning services and carbon storage in the BAUS and EDS were higher than the EPS. The BAUS and EDS tend to obtain provisioning services at the expense of regulation services. In contrast, the EPS is a better scenario to maintain regulation services in the FPENC.

4.3. Suggestions for Future Regional Planning and Management

Integrating ESs trade-offs in regional and management remains a complex challenge due to the complexity of management [18,40]. Although the FPENC is regarded as a spe-
specific ecologically fragile area, it is an essential ecological barrier that prevents the invasion of the northwestern desert to the southeast, maintaining ecological security in northern China [48,78]. In recent decades, the FPENC has become a region facing vegetation degradation and land desertification due to the disturbance of human activities and frequent occurrence of severe climate, urgently requiring our attention. We developed three land-use scenarios to provide options for future planning in the FPENC. The BAUS continues the 2010–2020 land-use pattern; the EDS has the most significant economic benefits at the cost of loss of multiple regulating services, while the EPS has the most considerable ecological benefits at the cost of slower urban expansion and a significant loss of farming land. Notably, these trade-offs are issues facing FPENC planning. In this regard, we propose some recommendations for regional management and planning. The first and most important is strengthening ecological construction to improve the regional ecological environment. The Grain for Green Program has been implemented in this region. However, due to intense transpiration, large-scale tree planting can cause water shortages in arid and semi-arid zones [79]. In contrast, grasses and scrubs are better adapted to arid climatic conditions [79,80]. Therefore, in the future, local policy makers should adjust the implementation plan and intensity of ecological restoration projects concerning the geographical location and climatic conditions. Second, optimizing the structure of agricultural production is an inevitable choice for the sustainable development of FPENC. That is, to change the current crude agricultural production and management methods, advocate for conservation farming, reduce low-yielding farmland, and promote the development of grass-fed animal husbandry based on Grain-for-Green to achieve increased productivity and efficiency of animal husbandry. Meanwhile, the government can enhance the means of animal husbandry operation and create grassland ecological tourism to realize the unification of ecological and economic benefits. In addition, raising farmers’ and herders’ awareness of protecting grassland ecosystems is also necessary for the future sustainable development of FPENC.

4.4. Limitations and Future Research

The FLUS model showed good effects in regional-scale land-use simulations [81,82]. This model adopts self-adaptive inertia and a competition mechanism based on roulette selection, which can effectively cope with the complexity and uncertainty among the different land use types [54,83]. However, due to the unpredictability of human activities, the fragility of the FPENC, and the changing in policy orientations, the LUC in the study area has great uncertainty. Moreover, land-use distribution is spatially heterogeneous and influenced by different driving factors in different eco-geographic regions [84]. For large-area simulation, such as the FPNEC, we can try to perform it in sub-regions in the future, which might give better results.

This paper designed three alternative land-use scenarios to explore ESs in 2030. Three scenarios (i.e., BAUS, EDS, and EPS) presented the dilemma of the trade-off between economic development and ecological protection faced by FPENC. They provided information for future land use management. However, this study’s land use scenario settings were limited to future development in the FPENC. In future research, we can set more scenarios, such as farming land protection and eco-economic balance, to provide more possibilities for future land use management. Furthermore, climate change is another important driver of ecosystem service variation [85]. Climate change should be considered in future research frameworks to provide more practical information for policy decision makers.

5. Conclusions

In this study, we developed three alternative scenarios for 2030 to explore the impacts of LUCs on ESs and trade-offs among ESs in the FPENC. According to our estimates, farming land and built-up land area increased while grassland area significantly declined in 2010–2020 in the FPENC. This changing pattern is continued by BAUS and EDS. As a result, crop production and water yield increase, while soil retention, water purification,
and carbon storage decrease. Contrarily, EPS increases soil retention, water purification, and carbon storage at the expense of crop production and water yield. Furthermore, EPS has the lowest trade-off between crop production and carbon storage and the highest synergy between crop production and water yield. This study can increase the understanding of trade-offs between development and protection. Our findings can provide supporting information for future regional planning and management in the farming–pastoral ecotone.

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