remote sensing

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Research on Service Value and Adaptability Zoning of Grassland Ecosystem in Ethiopia

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Abstract: The evaluation of the ecosystem service value (ESV) and its regionalization toward coordinating ecological protection and socioeconomic development is of great significance. In this study, we developed a classification method based on the Random Forest algorithm and a feature optimization method to identify grassland types. Then, we proposed an approach to quantitatively evaluate the ESV of the grassland ecosystem in Ethiopia, in which net primary production derived from remote sensing was used to evaluate organic matter production value (ESV1), promoting nutrient circulation value (ESV2), and gas regulation value (ESV3), the RUSLE model was used to evaluate soil conservation value (ESV4), and cumulative rainfall was used to calculate water conservation value (ESV5). By integrating the mean ESV under various influencing factors, the zoning map of grassland ecosystem service value was obtained. Our study found that more fine grassland types can be well classified with the overall accuracy of 86.52%. And the classification results are the basis of the ESV analysis. The total ESV of grassland ecosystems was found to be USD 105,221.72 million, of which ESV4 was the highest, accounting for 44.09% of the total ESV. The spatial analysis of ESV showed that the differences were due to the impacts of grassland types, elevation, slope, and rainfall. It was found that the grassland is suitable to grow in the elevation zone between approximately 1000 and 2000 m, and the larger the slope and rainfall are, the greater the mean ESV is. The zoning map was used to conclude that the areas from approximately the fourth to sixth level (only 34.78% of the total grassland area, but 65.94% of the total ESV) have better growth status and development potential. The results provide references and bases to support the local coordination and planning of various grassland resources and form reasonable resource utilization and protection measures.

Keywords: ecosystem service value; grassland ecosystem; remote sensing; Ethiopia

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1. Introduction

Ecosystems consist of plant, animal, and microorganism communities and a non-living environment, which interact as a functional unit [1,2]. Grassland ecosystems are an essential component of ecosystems covering the Earth's surface and have notable ecological service functions such as product supply, climate regulation, soil conservation, water conservation, and cultural services, which are closely related to human well-being [3–5]. They provide a wide range of direct and indirect services, which are vital for human well-being, health, livelihood, and survival [6–9].

Ecosystem services have received extensive attention since the United Nations Millennium Ecosystem Assessment (MEA). Policy communities and research have increased interest in this field [10,11]. The widespread recognition of ecosystem services reframes the relationship between humans and the rest of nature and has led humanity to emphasize that natural assets are a key component of inclusive wealth, well-being, and sustainability [12]. Enhancing human well-being and sustainable development requires a balance of individuals, societies, economies, and ecosystems. Therefore, estimating ecosystem service value (ESV) is a basic and important step.

Understanding the multiple benefits of ecosystems is necessary via realistic valuation methods [13]. Measuring ESVs is an important approach for raising awareness, developing knowledge, improving decision making, and formulating policies [14–18]. This measure is also an important means to attract social attention to protect the environment [19]. The evaluation of ecosystem services in economic terms began with the ecosystem service valuation model established by Costanza et al. (1997) and the MEA (2005) [6,20]. In this model, the ecosystem service value coefficients of 16 biomes were established to determine the ESV based on land use/cover categories. This evaluation model has also been applied in many studies [21–23] and was criticized because of its uncertainties and regional applicability [24–28]. Although it has been revised several times on the basis of a benefit transfer method or expert knowledge of the study landscape conditions and other studies [29–32], its estimates remain criticized because they do not represent a particular region. However, researchers working in regions where data are scarce continue to use them to explore ecosystem service valuation [8,21,33]; as a result, the assessment is either overestimated or underestimated because of regional differences.

Ecosystem services directly depend on the type of ecosystem and their status in a given area [34,35]. Remote sensing is an effective tool for recurrently acquiring large-area observed data [36,37]. This tool allows for the status of ecosystems to be monitored to quickly obtain valuable information, and it has been widely used in ecological research [24,38]. Many remote sensing parameter estimation models and shared products increase the convenience of quantitatively evaluating ESV [39,40].

Ethiopia is an African country that also has insufficient data on ecosystem services [8]. Most studies about Ethiopia have used land use data and value coefficients to evaluate ESV or annual change and its impact [41]. Although the value coefficient may be localized, it cannot reflect the actual situation. For example, the same ecosystem may have different service values due to differences in biomass and vegetation coverage, but the method using the value coefficient cannot reflect such changes. In addition, previous studies focused on the optimization of land use structure to promote the sustainable development of human society, and few people paid attention to the regionalization of grassland ecosystems to promote their sustainable development [42]. To promote the sustainable development of grassland ecosystems in Ethiopia, the aims of this study were to (1) finely classify grassland ecosystems in Ethiopia; (2) make full use of remote sensing models and remote sensing products to accurately evaluate the ESV of grassland ecosystems in Ethiopia to reflect its internal differences; (3) analyze the spatial pattern of grassland ecosystem ESV and the influence of terrain and rainfall; (4) explore the regionalization of grassland ecosystem ESV to provide data support for the local coordination and planning of various grassland resources and the formulation of more reasonable resource utilization and protection support.

2. Materials and Methods

2.1. Study Area

Ethiopia is on the East African plateau in northeast Africa and is southwest of the Red Sea (Figure 1). It borders Djibouti and Somalia in the East, Sudan and South Sudan in the west, Eritrea in the north, and Kenya in the south.

Ethiopia is dominated by mountainous plateaus, most of which are part of the Ethiopian Plateau. The central and western regions are the main part of the plateau, accounting for two thirds of the entire territory. The East African Rift Valley runs throughout the territory, with an average altitude of nearly 3000 m. The terrain around the plateau gradually declines. The Darol depression in the north decreases to 113 m below sea level, the lowest point in the country. The Red Sea coast is a narrow strip plain. The desert and semi-desert areas in the north, south, and northeast account for approximately 25% of the national area. The elevation of the Dashan peak in the Ximen Mountains is 4623 m, the highest peak in Ethiopia. There are many rivers and lakes in the territory.

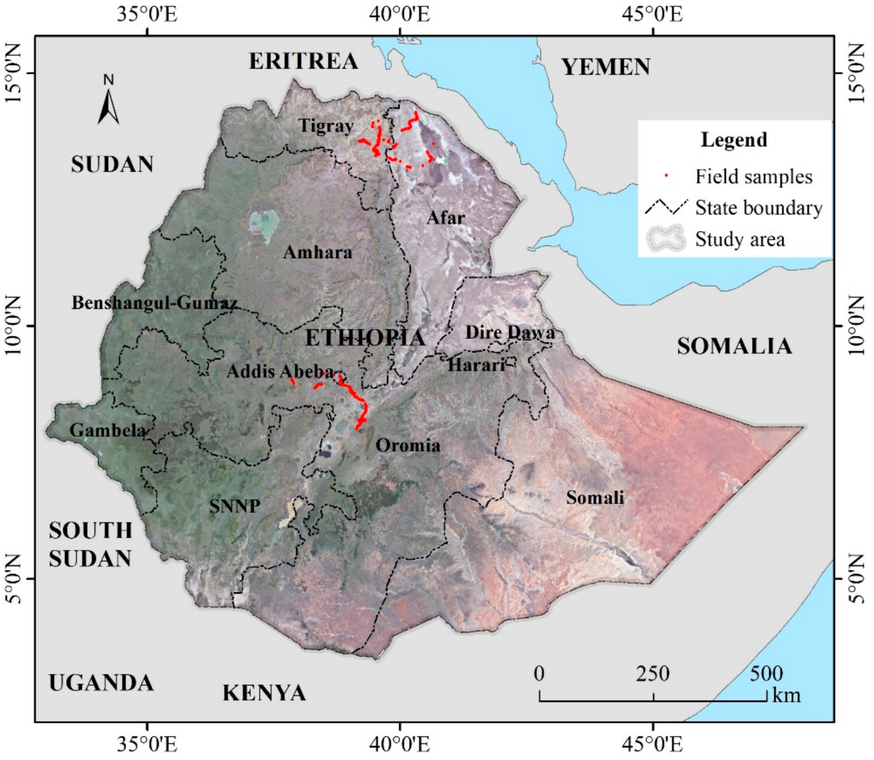


Figure 1. Ethiopia is in northeast Africa, and red points are the field samples obtained in 2019.

Ethiopia is in the tropics, but the temperature is uneven due to the large difference between the latitude span and altitude. The rainy season lasts from June to September, the dry season lasts from October to January, and the small rainy season lasts from February to May. Due to uneven rainfall in different seasons and regions, local drought can occur. The temperature range is 9.7 °C–25.5 °C. The annual average temperature is 16 °C.

2.2. Datasets

2.2.1. Sample Points of Grassland

In 2019, a grassland field survey was conducted in Ethiopia using the GVG (GPS-Video-Geographic Information Systems) mobile app [43]. A total of 747 ground survey sample points (red dots) were obtained through field survey for Ethiopia, which are shown in Figure 1. Taking these observation points as a priori knowledge, 3173 classification sample points were created based on high-resolution Google Earth images in 2020, referring to the land cover type product (MCD12Q1).

2.2.2. Remote Sensing and Related Products

MODIS time series data were used to extract the grassland types because of the size of Ethiopia. MOD13Q1 with a 250 m spatial resolution has 12 bands, such as vegetation index and spectral reflectance. The data for 2020 were downloaded from the NASA Earthdata website [44]. The normalized difference vegetation index (NDVI) is the best indicator of vegetation dynamics and spatial distribution, with a linear correlation with vegetation distribution density [45,46]. The NDVI and spectral reflectance were combined to classify the feature types.

MCD12Q1 is a MODIS land cover type product containing multiple classification schemes [47]. It describes land cover properties derived from observations spanning one year's input of Terra and Aqua data. The primary land cover includes 17 land cover classes defined by the International Geosphere Biosphere Programme, which includes 11 natural vegetation classes, 3 developed and mosaicked land classes, and 3 non-vegetated land classes. This product of 2020 was used as reference data assisting ground survey samples to create classification samples.

MOD17A3HGF is a MODIS net primary production (NPP) gap-filled product, providing annual NPP at a 500 m pixel resolution. Annual NPP is derived from the sum of all 8-day net photosynthesis (PSN) products (MOD17A2H) from the given year. Hence, the gap-filled MOD17A3HGF is the improved MOD17, which cleans poor-quality inputs from the 8-day leaf area index and the fraction of photosynthetically active radiation (LAI/FPAR) based on the quality control label for every pixel. The NPP in 2020 was used to evaluate the grassland ecosystem services value.

2.2.3. Others

The Harmonized World Soil Database is published by the FAO [48]. It is a 30 arc-second raster database with over 15,000 different soil mapping units that combines existing regional and national updates of soil information worldwide. This achievement is from a collaboration between the FAO and several scientific research institutions. The resulting raster database is linked to harmonized soil property data containing commonly used soil parameters. It was used to calculate the amount of soil conservation.

The digital elevation model (DEM) was used to determine the slope and slope length factors for soil erosion assessment. The NASA Shuttle Radar Topographic Mission (SRTM) was used and is free of charge for over 80% of globe. These data are distributed by the United States Geological Service and are available for download from the National Map Seamless Data Distribution System, the former’s ftp site. The SRTM data are available as 3 arc-second (approx. 90 m resolution) DEMs and were used to calculate the topographic factors of the soil erosion model and conduct topographic impact analysis.

Precipitation data were obtained from the Global Precipitation Measurement (GPM) and downloaded from the website [49]. This is an international satellite mission that provides global observations of rain and snow every three hours. Building on the success of the Tropical Rainfall Measuring Mission, the GPM core satellite was launched by NASA and the Japan Aerospace Agency on 27 February 2014. It carries an advanced radar/radiometer system to measure precipitation from space and serves as a reference standard to unify precipitation measurements from a constellation of research and operational satellites. These data were used to calculate rainfall erosivity factors of soil erosion models and ecosystem adaptability zoning analysis.

2.3. Methodology

Based on the literature [6–10], a quantitative estimation of grassland ESV was conducted by using the market value method, energy substitution method, and virtual engineering method. The five main ecological service functions were studied: organic matter production, nutrient circulation promotion, soil conservation, gas regulation, and water regulation. The technical route of this study is illustrated in Figure 2.

2.3.1. Extraction of Grass Coverage

A multilevel African grassland classification system was proposed based on the land cover classification system of the Food and Agriculture Organization of the United Nations via the investigation and analysis of the existing mainstream African land cover classification system and its characteristics (Table 1). The first three levels are shrubland, sparse grassland, and grassland. At the second level, shrubland is subdivided into closed shrubland and open shrubland, and sparse grassland is subdivided into woody savanna and savanna. Strict assumptions are usually applied to traditional classification algorithms, especially parametric ones. It is assumed that high-dimensional data have normality or some type of distribution is neither feasible nor logical. Non-parametric classification algorithms may be preferable for the classification of high-dimensional data because they require fewer assumptions and are more flexible [50].

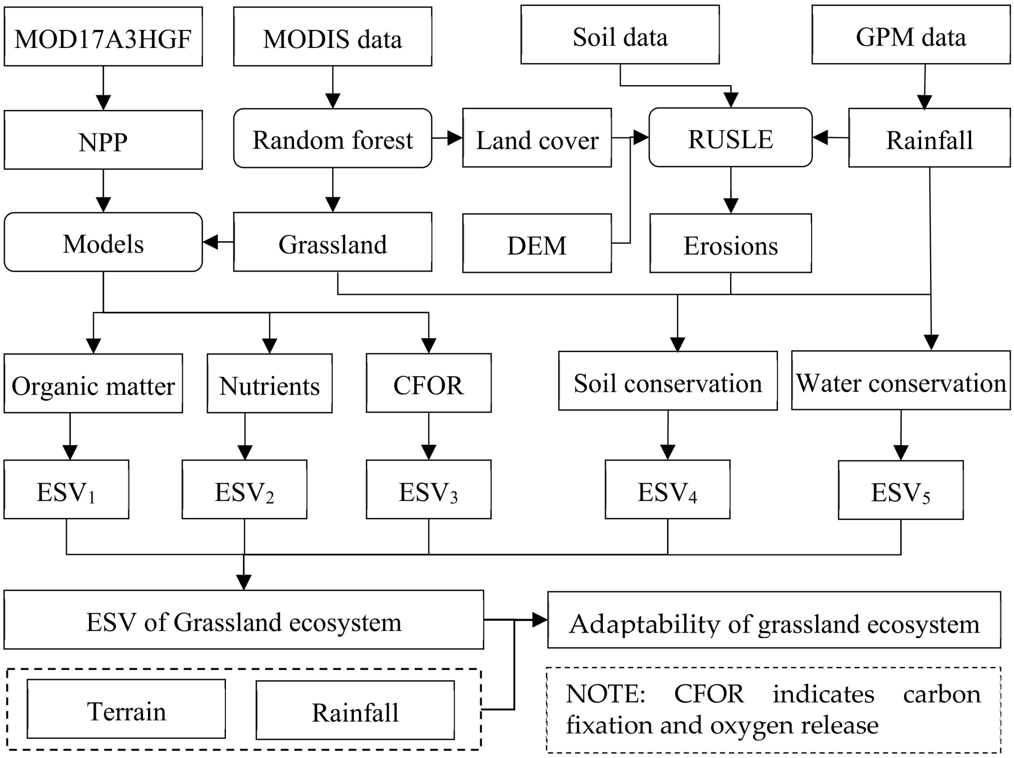


Figure 2. Flow chart of this paper's grassland ecosystem service value evaluation. ESV1: organic matter production value, ESV2: promoting nutrient circulation value, ESV3: gas regulation value, ESV4: soil conservation value, ESV5: water conservation value. NPP: net primary production. DEM: digital elevation model. RUSLE: revised universal soil loss equation. GPM: Global Precipitation Measurement.

Table 1. African grassland classification system.

First Level	Second Level	Description
Shrubland	Closed shrubland (CS)	(Shrub canopy cover over 60%, tree height less than 2 m)
	Open shrubland (OS)	(Shrub canopy cover 10–60%, tree height less than 2 m)
Sparse grassland	Woody savanna (WS)	(Woody canopy cover 30–60%, tree height over 2 m)
	Savanna (SA)	(Woody canopy cover 10–30%, tree height over 2 m)
Grassland	Grassland (GL)	Grassland (less than 10% shrub canopy cover, herbaceous cover > 5%)

Random forest is a classifier containing multiple decision trees in machine learning. It is a popular choice based on the concept of the ensemble building of decision trees [51]. As a non-parametric, interpretable, and efficient classification technique, it provides high classification accuracy for various applications [52]. By using the bagging technique, the unique ensemble of a decision tree and the procedure of random sampling enables improved application and increased use by decreasing the variance.

MODIS 250 m data were used to extract grass coverage information because of the size of Ethiopia. The high-dimensional data of the time series made the RF algorithm more suitable for classification in this research.

2.3.2. ESV Calculation of Grassland

Based on the classical method [6], five main ecosystem service functions of grassland ecosystems, i.e., organic matter production, promoting nutrient circulation, gas regulation, soil conservation, and water conservation, were selected to construct the evaluation system (Table 2) according to the availability of data and contribution to the total ESV.

Table 2. Ecosystem service value assessment system of grassland in this study.

Ecosystem Service Functions	Basic Data	Evaluation Method
Organic matter production	Net primary production	Energy substitution method
Promoting nutrient circulation	Net primary production	Market value method
Gas regulation	Net primary production	Virtual engineering and carbon tax method
Soil conservation (reducing soil loss, protecting soil fertility, and reducing river siltation)	Soil conservation amount	Market value and virtual engineering method
Water conservation	Annual rainfall amount	Alternative engineering method

(1) Organic matter production

Organic matter production is one of the main functions of ecosystem services. The NPP of natural vegetation is the result of interactions between biological plant characteristics and external environmental factors [53]. This index is important for evaluating the structural and functional characteristics of ecosystems and the carrying capacity of the biosphere. On the basis of the NPP, the energy substitution method was used to evaluate the ESV of grassland ecosystems. Specifically, the carbon fixed by grassland was converted into equal-energy standard coal, and its value was determined by the price of standard coal. The calculation formula is shown in Equation (1).

$$ESV1 = \frac{Ca}{Co} \times \sum NPP(x) \times P \tag{1}$$

where $ESV1$ is the organic matter production value of the grassland ecosystem, Ca is the calorific value of carbon, 0.036 MJ/g; Co is the calorific value of standard coal, 0.02927 MJ/g; $NPP(x)$ is the NPP of pixel x; and P is the price of standard coal, USD 50.5714 [54].

(2) Promoting nutrient circulation

All organisms in grassland ecosystems contain nutrient elements and exchange them with the external environment via nutrient circulation. The ESV of the ecosystem nutrient cycle was quantitatively evaluated using the market value method on the basis of its NPP. The calculation method of its value is shown in Equation (2).

$$ESV2 = \sum NPP(x) \times R_i \times P_i \tag{2}$$

where $ESV2$ is the value of promoting nutrient circulation in the grassland ecosystem; $NPP(x)$ is the same as the aforementioned; R_i is the content of the ith nutrient element in the grassland ecosystem, which mainly refers to nitrogen (R_1: 0.025426), phosphorus (R_2: 0.002), and potassium (R_3: 0.01012) [55]; and P_i is the price of the value of the ith fertilizer (P_1: USD 0.3/kg, P_2: USD 0.3714/kg, and P_3: USD 0.5429/kg) [56].

(3) Gas regulation

The grassland ecosystem releases 1.2 kg of oxygen and fixes 1.62 kg of carbon dioxide when it produces each 1 kg of dry matter [57], based on the equation of photosynthesis and the respiration of vegetation. Therefore, the amount of oxygen released and carbon dioxide fixed by the ecosystem can be obtained from the NPP. By using the method of virtual engineering, the value of the same amount of oxygen produced by the industry was calculated, and the value of carbon dioxide was calculated using the carbon tax rate conversion method. The value of maintaining the carbon–oxygen balance was calculated as shown in Equation (3).

$$ESV3 = NPP(x) \times \sum(1.2 \times P_{O2} + 1.62 \times R_C \times P_{CO2}) \tag{3}$$

where $ESV3$ is the value of the gas regulation of the grassland ecosystem; $NPP(x)$ is the same as the aforementioned; P_{o2} is the price of industrial oxygen production in the market, USD 0.05714/kg; P_{co2} is the price of carbon dioxide based on the carbon tax rate conversion method, USD 0.048/kgC; and R_c is the conversion coefficient of carbon and carbon dioxide, 0.2727 [54].

(4) Soil conservation

The potential soil erosion modulus and actual soil erosion modulus were calculated using the revised universal soil loss equation (RUSLE). Here, potential soil erosion means soil erosion without any vegetation cover and soil and water conservation measures. The difference between potential soil erosion and actual soil erosion is the amount of soil conservation (A_c), and the calculation method is shown in Equation (4). The calculation of soil erosion parameters mainly refers to local relevant research [58,59].

$$A_c = R \times K \times L \times S \times (1 - C \times P) \tag{4}$$

where R is the rainfall erosivity factor; K is the soil erodibility factor; L and S are the slope length factor and slope gradient factor, respectively; C is the vegetation cover factor; and P is the soil protection measures and factors.

The value of soil conservation mainly includes reducing soil loss (V_1), protecting soil fertility (V_2), and reducing river siltation (V_3). The calculation method is shown in Equation (5).

$$\begin{cases} ESV4 = V_1 + V_2 + V_3 \\ V_1 = \sum A_C(x) \times P_g \div D_s \div H_s \\ V_2 = \sum A_C(x) \times C_i \times P_i \\ V_3 = \sum A_C(x) \times A_w \times P_w \div D_s \end{cases} \tag{5}$$

where $ESV4$ is the value of soil conservation of grassland ecosystem; P_g is the grassland planting income per unit area (USD 35.0714/ha) [60,61]; D_s is the soil bulk density (from soil properties); H_s is the average soil thickness (from soil properties); C_i is the percentage content of nitrogen (C_1: 0.00177), phosphorus (C_1: 0.0008), and potassium (C_1: 0.01) in the soil [62]; P_i is the fertilizer price; A_w is the proportion of soil erosion deposition in the reservoir (0.24); and P_w is the cost per unit storage capacity (USD 0.09571/m^3) [63].

(5) Water regulation

The value of water conservation was calculated using an alternative engineering method. That is, the cost of reservoir construction was used to replace the water conservation value of the grassland ecosystem. The calculation method is shown in Equation (6).

$$ESV5 = PR_w(x) \times K_w \times R_w \times P_w \tag{6}$$

where $ESV5$ is the value of water conservation in the grassland ecosystem; $PR_w(x)$ is the annual rainfall at pixel x; K_w represents the ratio of runoff yield rainfall to total rainfall, 0.4 [64]; R_w is the runoff reduction benefit coefficient of grassland ecosystem (CS: 0.24, OS: 0.2, WS: 0.35, SA: 0.3, and GL: 0.15) [65]; and P_w is the cost per unit storage capacity.

(6) Total ESV of grassland ecosystem

The total ESV of the grassland ecosystem is the sum of these five service values. The calculation method is shown in Equation (7).

$$ESV = ESV1 + ESV2 + ESV3 + ESV4 + ESV5 \tag{7}$$

where ESV is the total ESV of the grassland ecosystem, and the other parameters are the same as the aforementioned.

2.3.3. Regionalization of Grassland Ecosystem

(1) Analysis of ESV distribution characteristics

To understand the spatial distribution pattern of grassland ecosystems' service value in Ethiopia, the contribution of different grassland types and the differences between ESV among states were analyzed based on the calculated ESV. Then, the terrain was divided into different zones, and the relationship between ESV and terrain (elevation, slope, and aspect) and rainfall was analyzed to study its impacts on the service value of grassland ecosystems. The results can provide scientific support for the sustainable development of grassland ecosystems.

(2) Adaptability zoning of grassland ecosystem

The zone ESV is the total amount of grassland ESV in the zone, which reflects the stock of grassland. Meanwhile, the mean ESV reflects the growth state of the grassland ecosystem and its adaptability under this condition. Therefore, the mean ESV was selected for the regionalization of grassland ecosystem ESV.

Elevation, slope, and rainfall have obvious effects on the mean ESV. The zones were sorted and reassigned according to their mean ESV. Then, the three types of reassigned zones were processed pixel by pixel using an addition function. As a result, the pixel values ranged from 1 to 18. Finally, the zoning map could be constructed by reclassifying the pixel values into 6 categories by means of equal interval. Afterward, the value was assigned according to the mean ESV in different zones, and the grassland zoning was comprehensively defined according to the value assignment of different types of zones.

3. Results and Analysis

3.1. Grass Coverage of Ethiopia

Based on the RF algorithm, spectral reflectance, time series NDVI, kurtosis, and skewness derived from MODIS 250 m data were used for classification. Half the classification samples were used for training and the other half for verification. Several combinations were tested to obtain the best recognition accuracy. The combination of time series NDVI and spectral reflectance yielded the highest classification accuracy; overall accuracy was 86.52%, and the Kappa coefficient was 0.8434. The extraction results of grassland coverage are shown in Figure 3.

Figure 3 indicates that CS and OS dominate southeast Ethiopia, WS and SA are mainly distributed in the west, and GL is mainly distributed in the northeast. Using statistical analysis, the areas and proportions of grassland types were obtained (Table 3).

Table 3. Area and proportion of grassland types in Ethiopia.

Grass Types	Area/10^4 km^2	Percentage/%
Closed shrubland (CS)	12.96	21.82%
Open shrubland (OS)	18.44	31.05%
Woody savanna (WS)	4.30	7.24%
Savanna (SA)	11.22	18.88%
Grassland (GL)	12.48	21.02%
Total	59.40	100.00%

The total area of grassland is 594,000 km^2. OS has the largest area (184,400 km^2), accounting for 31.05% of the total grassland area. The areas of CS and GL are similar, at 129,600 km^2 and 124,800 km^2, respectively, accounting for 21.82% and 21.02% of the total grassland area, respectively. The area of WS is the smallest (43,000 km^2, 7.24%).

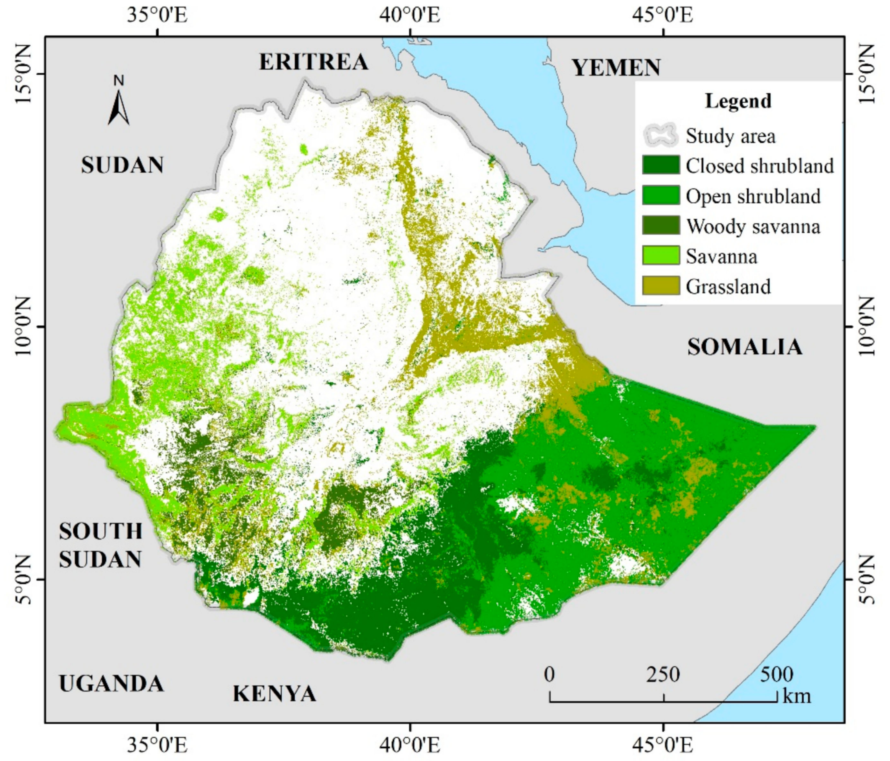


Figure 3. Grassland cover distribution extracted from remote sensing images in Ethiopia.

3.2. *ESV of Grassland Ecosystem*

Based on the aforementioned methods, different ecosystem services value can be obtained (Figure 4). The results show that the total ESV1 is USD 19,190.93 million (Figure 4a), the total ESV2 is USD 4679.08 million (Figure 4b), the total ESV3 is USD 30,298.68 million (Figure 4c), the total ESV4 is USD 46,388.59 million (Figure 4d), and the total ESV5 is USD 4664.44 million (Figure 4e) for the grassland ecosystem in Ethiopia.

After ESV1–ESV5 were calculated, the total ESV could be obtained using Equation (7). The calculation results are shown in Figure 4f. Based on the assessed ESV data, the total ESV of grassland in Ethiopia is USD 105,221.72 million.

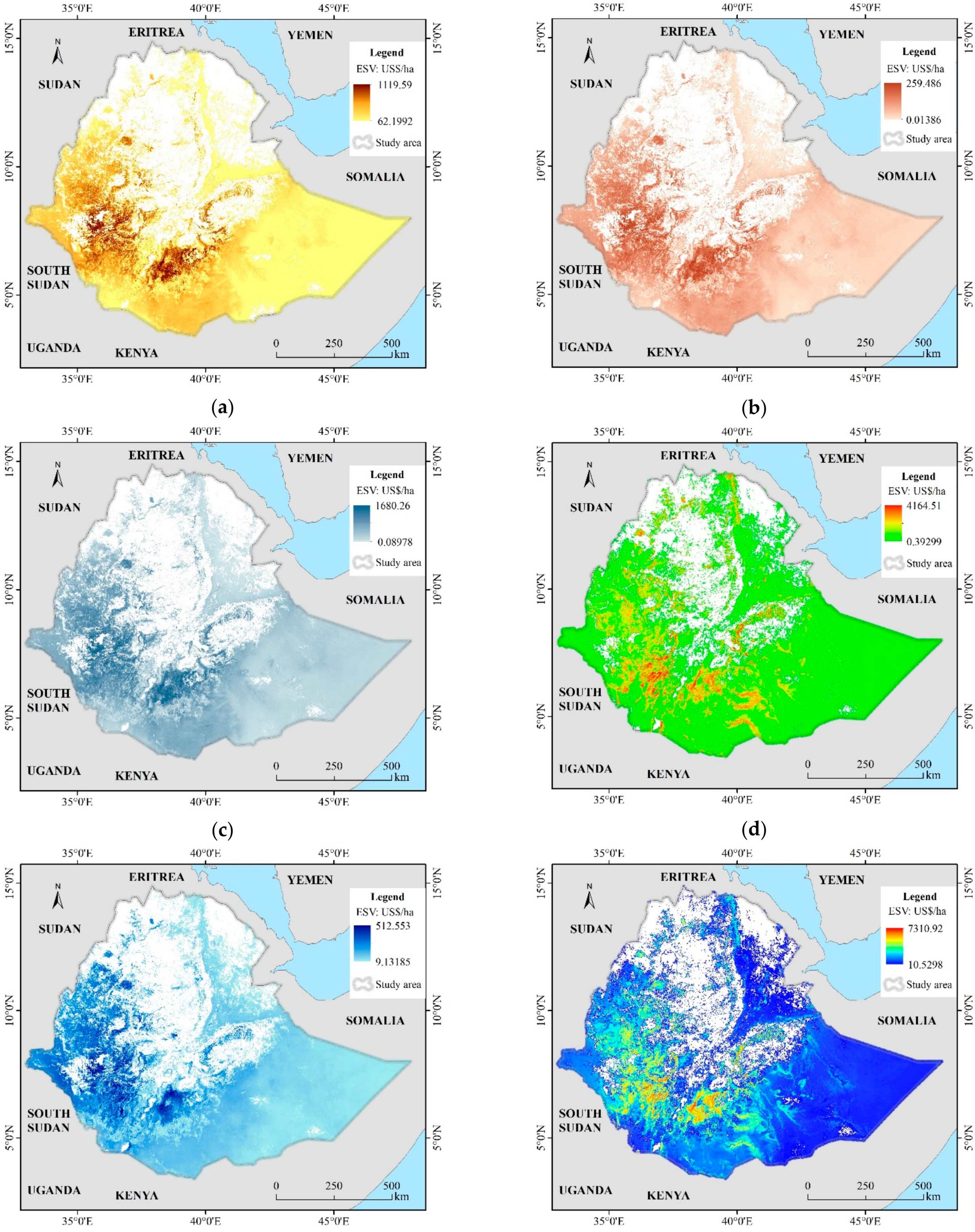
3.2.1. Differences in Grassland Types and Ecosystem Service Functions

The statistical data of ESV are presented in Table 4. The contribution of different grassland types to the total ESV is shown in Figure 5a. The amount of ESV differs by the ecosystem service function (Figure 5b).

Table 4. Statistics of ecosystem service value of grassland types for different functions.

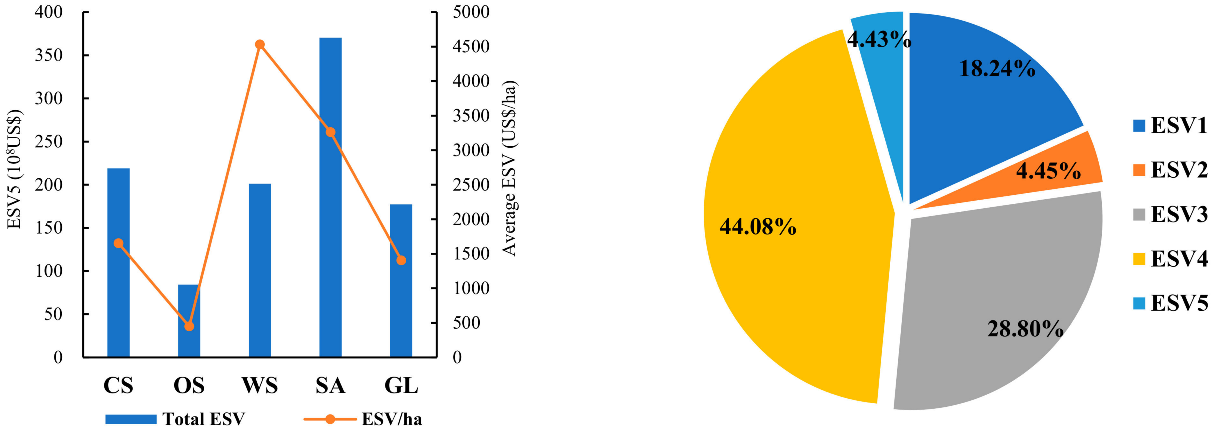
Grassland Types	CS	OS	WS	SA	GL	SUM
ESV1/106 USD	4256.41	1802.73	3628.73	6597.37	2905.69	19,190.93
ESV2/106 USD	1036.64	526.26	841.09	1546.71	728.38	4679.08
ESV3/106 USD	6712.61	3407.74	5446.36	10,015.47	4716.50	30,298.68
ESV4/106 USD	9059.68	2191.48	9285.05	17,039.40	8812.98	46,388.59
ESV5/106 USD	838.27	504.94	916.55	1836.61	568.07	4664.44
TOTAL ESV/106 USD	21,903.61	8433.15	20,117.78	37,035.56	17,731.62	105,221.72

Note: CS = closed shrubland, OS = open shrubland, WS = woody savanna, SA = savanna, GL = grassland, ESV1 = organic matter production value, ESV2 = promoting nutrient circulation value, ESV3 = gas regulation value, ESV4 = soil conservation value, ESV5 = water conservation value.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 4. Different service values of grassland ecosystem in Ethiopia. (**a**) ESV1: organic matter production value; (**b**) ESV2: promoting nutrient circulation value; (**c**) ESV3: gas regulation value; (**d**) ESV4: soil conservation value; (**e**) ESV5: water conservation value; (**f**) Total ESV.



(**a**) (**b**)

Figure 5. Statistical chart of total ESV of grassland ecosystem in Ethiopia. (**a**) the ESV of different types of grassland. (**b**) the proportion of each ecosystem service function in the total ESV. ESV1: organic matter production value, ESV2: promoting nutrient circulation value, ESV3: gas regulation value, ESV4: soil conservation value, ESV5: water conservation value.

Among the five types of grassland, the ESV of SA is the highest, reaching USD 37,035.56 million, accounting for 35.20% of the total ESV. This is followed by CS, reaching USD 21,903.61 million and accounting for 20.82% of the total ESV. The smallest is OS, reaching USD 8433.15 million and accounting for 8.01% of the total ESV. In terms of ESV per unit area, WS is the highest, reaching USD 4531.95/ha. The second is SA, reaching USD 3261.52/ha. The lowest is still OS, reaching USD 450.43/ha.

Soil conservation value (ESV4), gas regulation value (ESV3), and organic matter production value (ESV1) account for the majority of grassland ecosystem service values: USD 95,878.20 million (91.12% of the total ESV). Among the ESVs, the total ESV4 is the largest, accounting for 44.08% of the total ESV. Promoting nutrient circulation value (ESV2) and water conservation value (ESV5) are not significantly different (4.45% and 4.43%, respectively).

3.2.2. Distribution of Grassland ESV in Various States

The ESV of each state can be obtained by superposition analysis of its administrative boundary and the total ESV (Table 5). From Figure 1 and Table 5, it can be seen that areas with large ESVs are mainly distributed in the south, especially in the southwest. The ESV of Oromia reaches USD 44,578.62 million, accounting for 42.37% of the total ESV in Ethiopia. SNNP and Somali have ESVs of USD 23,487.11 million and USD 19,306.98 million, 22.32% and 18.35% of the total ESV, respectively. The other five states have small ESVs.

ESV per unit area represents the service capacity of grassland ecosystem and reflects its growth and development state in this area. By calculating the grassland ESV per unit area for each state, it was found that the overall average value is USD 898.42/ha. Among them, SNNP is the largest, reaching USD 2059.56/ha, followed by Oromia, Benshangul-Gumaz, Gambela, Somali, Amhara, Tigray, and Afar.

The per capita grassland ESV reflects the service potential of grassland that can be enjoyed by human beings in this area. The results show that the overall average value is USD 1398.46/ha, and the performance of western states is outstanding. Among them, Gambela is largest, reaching USD 14,007.31 per person. Additionally, Benshangul-Gumaz also reaches USD 9038.46 per person. The per capita ESV of Somali in the east is also relatively high, reaching USD 4048 per person. The minimum value appears in Amhara, which is USD 257.69 per person.

Table 5. Statistics of ecosystem service value of grassland types for different states.

State Name	ESV (10^6USD)	Percentage (%)	ESV/State Area (USD/ha)	ESV/State Population (USD Per Person)
SNNP	23,487.11	22.32%	2059.56	1576.11
Gambela	3459.81	3.29%	1066.88	14,007.31
Oromia	44,578.62	42.37%	1327.50	1491.12
Somali	19,306.98	18.35%	595.53	4084.40
Benshangul-Gumaz	5649.04	5.37%	1093.26	9038.46
Amhara	4926.99	4.68%	306.60	257.69
Afar	2329.10	2.21%	237.55	1676.81
Tigray	1484.07	1.41%	274.00	342.35
The whole country	105,221.72	100.00%	898.42	1398.46

Note: In the statistics, Addis Abeba and Harari were counted in Oromia, and Dire Dawa was counted in Somali. SNNP: Southern Nations, Nationalities and Peoples.

3.2.3. Influence of Topography on ESV

According to the DEM used in the study, the elevation ranges from 0 to 4486 m. The areas were divided into six zones in 500 m intervals. The slope gradient was also divided into six zones with the limits of 5, 8, 15, 25 and 35. By analyzing the ESV status of each zone, the influence of elevation and slope on ESV could be revealed in the space, which is very useful for maintaining grassland ecosystem services. For the elevation and slope zones, the analyzed results overlaid with the total ESV data are shown in Figure 6.

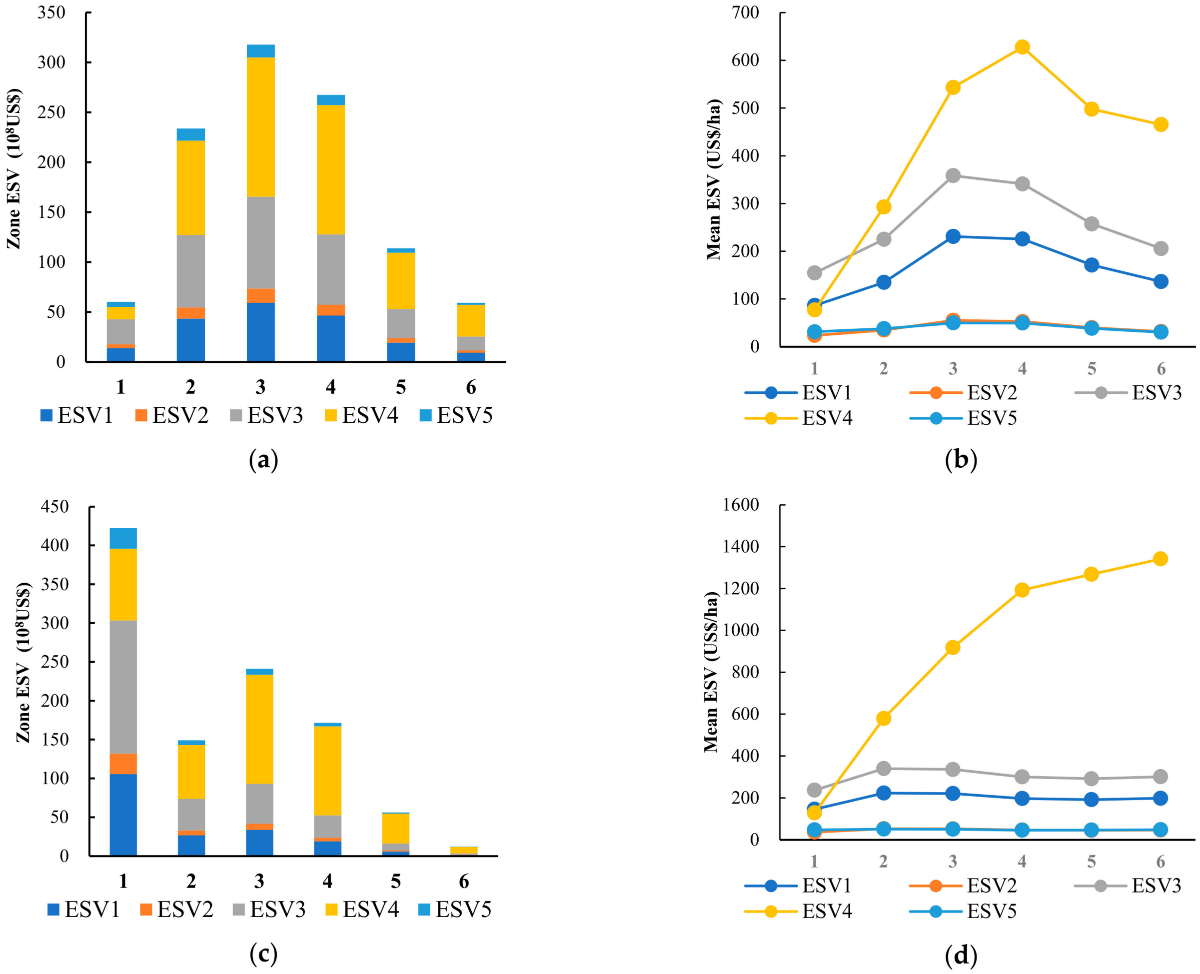
On the whole, the ESV of the third elevation zone is the highest and gradually decreases to both sides in Figure 6a. Among them, the 1000−1500 m elevation zone has the ESV of USD 31,765.61 million and occupies 30.19% of the total ESV in Ethiopia. The second highest ESV area is the 1500−2000 m elevation zone, which occupies 25.50%. The third highest ESV area is the 500−1000 m elevation zone, which occupies 22.15%. For the mean ESV of the zone, the fourth elevation zone is the highest and gradually decreases to both sides in Figure 6b.

The relationship between each ecosystem service value and elevation zone was also analyzed (Figure 6a). It can be seen that the proportion of ESV3 is the highest, reaching 41.41% in the elevation zone of 0–500 m. In the other elevation zones, the proportion of ESV4 is the highest, reaching about 45%. On the whole, ESV1, ESV3, and ESV4 contribute significantly to the ESV of each elevation zone. The variation in the mean ESV with elevation is shown in Figure 6b. The change in the mean ESV4 is the most obvious, which increases first and then decreases, and reaches the maximum in the elevation zone of 1500–2000 m. The changes in ESV2 and ESV5 are not significant.

For the six slope zones, their zone ESVs decrease with the increase in slope, except for the second slope zone. The first slope zone with 0−5° has an ESV of USD 41,590.50 million and occupies 39.53% of the total ESV in Ethiopia. The second slope zone with 0−5° has an ESV of USD 14,932.96 million and occupies 14.19%. The sixth slope has a minimum ESV, USD 1236.81 million, only occupying 1.18%. On the contrary, the mean ESV of the zone continuously increases with the increase in slope. These phenomena show that the growth state of the grassland ecosystem is good in the area with large slopes, while the stock is large in the area with small slopes.

The proportion of different ecosystem service values in the slope zone is shown in Figure 6c. For each ecosystem service in the slope zone, ESV1, ESV3, and ESV4 contribute significantly, similar to the elevation zone. Especially for the slope zone of 0−5°, the contributions of ESV1, ESV3, and ESV4 reach 24.97%, 40.55%, and 21.88%, respectively. For the mean ESV (Figure 6d), the mean ESV4 increases with the increase in slope, while there is little change in the other ecosystem service values (ESV1, ESV2, ESV3, and ESV5).

The aspect generated from DEM represents a direction in azimuth measured clockwise from north, and the value of 361 indicates no slope (flat ground). The study area was divided into eight zones by a 45° interval based on the aspect data. The ESV statistics of each aspect zone are shown in Table 6.



(**a**) (**b**) (**c**) (**d**)

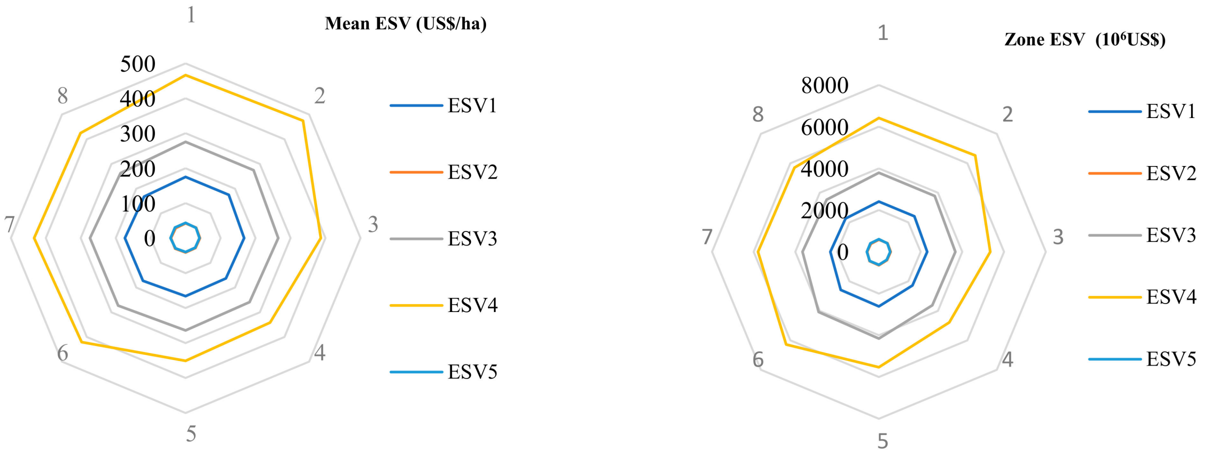
Figure 6. ESV of grassland ecosystem in the different elevation and slope zones. (**a**) the five ESVs in each elevation zone (the elevation range of zone 1~6: ≤500 m, 500~1000 m, 1000~1500 m, 1500~2000 m, 2000~2500 m, and ≥2500 m). (**b**) the variation in mean ESV with elevation. (**c**) the ESV in each slope zones (the slope range of zone 1~6: ≤5°, 5°~8°, 8°~15°, 15°~25°, 25°~35°, and ≥35°). (**d**) the variation in mean ESV with slope.

Table 6. Statistics of ecosystem service value of grassland types for the aspect zones.

Aspect Zones	Mean ESV (USD/ha)	Zone ESV (10^6USD)	Percentage (%)
Aspect < 45°	969.05	13,842.19	13.16%
45° ≤ Aspect < 90°	974.15	13,915.02	13.22%
90° ≤ Aspect < 135°	865.42	12,407.49	11.79%
135° ≤ Aspect < 180°	809.66	11,756.49	11.17%
180° ≤ Aspect < 225°	827.16	13,525.59	12.85%
225° ≤ Aspect < 270°	914.32	14,176.52	13.47%
270° ≤ Aspect ≤ 315°	932.46	12,950.56	12.31%
Aspect ≥ 315°	906.87	12,647.85	12.02%
Total	898.42	105,221.72	100.00%

It was found that there is a small difference for both zone ESV and mean ESV among the aspect zones. For the zone ESV, the aspect zones with 0–90° and 180–270° have relatively large values, while the other zones are small. For the mean ESV, the aspect zones with 0–90° and 225–315° have relatively large values, while the other zones are small. The small difference shows that the aspect has little effect on grassland ESV in the study area.

In order to visually show the performance of various ecosystem service values on the aspect zones, Figure 7 is displayed. It can be seen that ESV4 changes more with aspect than the other ecosystem service values.



(**a**) (**b**)

Figure 7. Five ESVs of grassland ecosystem in the different aspect zones. (**a**) the variation of five mean ESVs in different aspect zones. (**b**) the variation of five zone ESVs in different aspect zones. The aspect range of zone 1~8: <45°, 45°~90°, 90°~135°, 135°~180°, 180°~225°, 225°~270°, 270°~315°, and ≥315°.

3.2.4. Relationship between ESV and Rainfall

Rainfall is one of the important factors affecting vegetation growth. According to the annual rainfall, the study area was divided into six zones (Figure 8a). Combined with the total ESV data, the ESV of each zone was counted, as shown in Figure 8b.

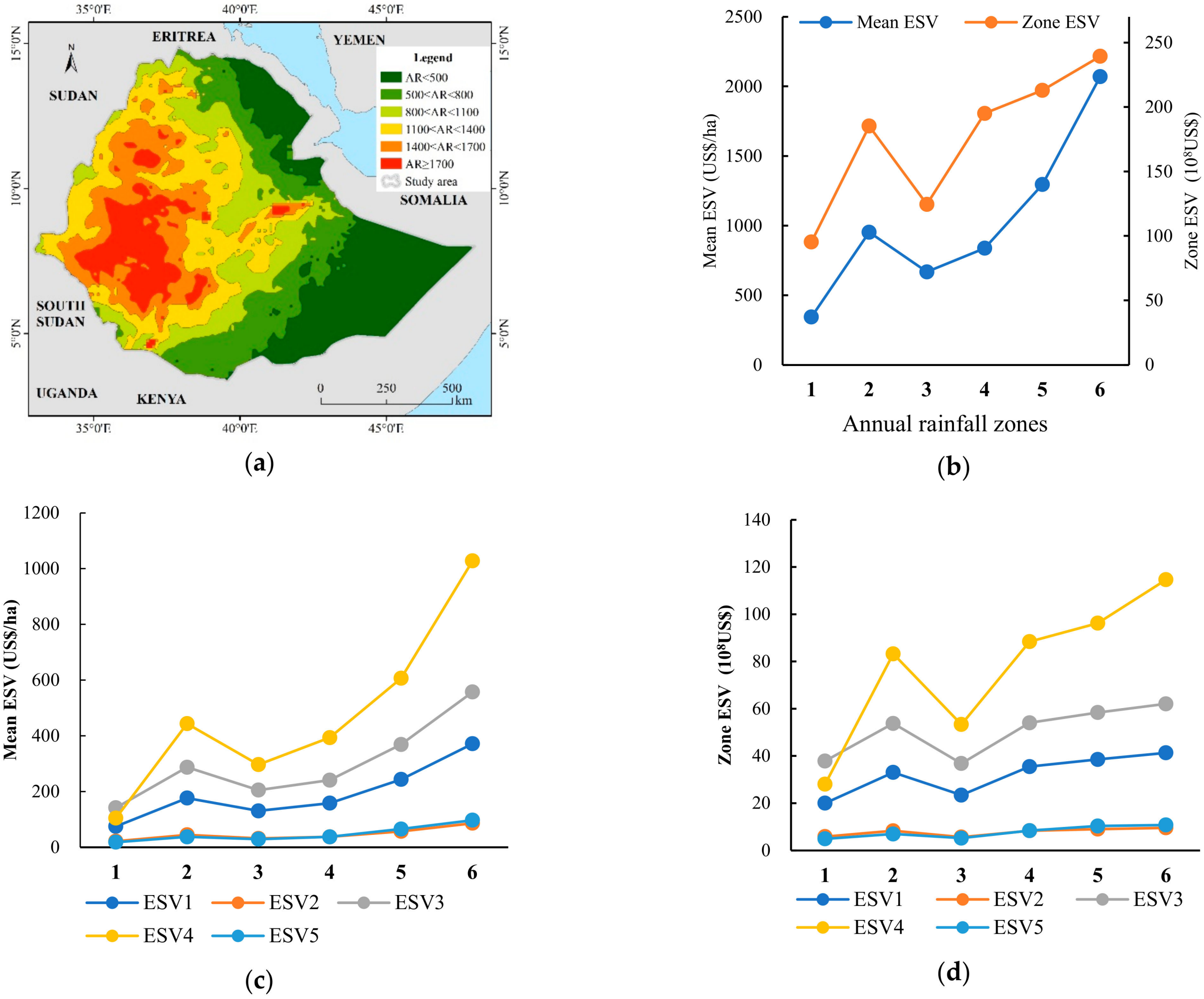
On the whole, the annual rainfall in the west is higher than that in the east in the study area. The maximum occurs in the southwest. From Figure 8b, it can be seen that both the zone ESV and mean ESV increase with the increase in annual rainfall, except for in the second zone with 500−800 mm annual rainfall. In the zone with the largest annual rainfall, the zone ESV (USD 23,927.51 million, 22.74% of the total ESV) and mean ESV are also the largest (USD 2070.13/ha). In the first zone, the annual rainfall is the smallest, and accordingly, the zone ESV (USD 9532.84 million, 90.6%) and mean ESV (USD 343.36/ha) are also the smallest.

Furthermore, the variation in each ecosystem service value with rainfall zones is shown in Figure 8c,d. They all increase with the increase in annual rainfall. Among them, the changes in ESV4, ESV3 and ESV1, are obvious.

3.3. Adaptability Zoning of Grassland Ecosystem

In the process of the rapid development of Ethiopia, the increasing demand for agriculture, industry, and urban area will lead to changes in land use/land cover, reducing the ability of the ecosystem to support human beings [66,67]. In order to maintain the harmonious development of grassland ecosystems and human social development, grassland ecosystems should be protected in a planned way.

According to the aforementioned analysis, the most suitable area for the growth of grassland ecosystems in Ethiopia is between 1000 and 2000 m. The adaptability of other areas decreases gradually with the change in elevation. Although the stock of grassland ecosystems in areas with small slopes is large, its mean ESV is the lowest, and these areas are easy to be reclaimed into cultivated land. With the increase in slope, the human disturbance decreases and the mean ESV increases, indicating that the growth state of grassland ecosystems gradually improves. However, the total stock of grassland ecosystems decreases in areas with large slopes, indicating the small area. Another finding is that the both mean ESV and zone ESV of grassland increase with the increase in annual rainfall, indicating that grassland tends to grow in areas with abundant rainfall.



(**a**)

(**b**)

(**c**)

(**d**)

Figure 8. The annual rainfall zones and their ESV of grassland ecosystem. (**a**) the divided zones according to the annual rainfall. AR: annual rainfall. (**b**) the variation of ESV in different AR zones. (**c**) the variation of five mean ESVs in different AR zones. (**d**) the variation of five zone ESVs in different AR zones. The AR range of zone 1~6: <500 mm, 500~800 mm, 800~1100 mm, 1100~1400 mm, 1400~1700 mm, and ≥1700 mm.

Using the method, in Section 2.3.3, the adaptability zoning map is obtained (Figure 9). It can be seen that the areas with high adaptability are mainly distributed in the southwest. These areas have high slopes and rainfall and are not easily disturbed by human activities. Low adaptability occurs mainly in the southeast, with small slopes and rainfall. The areas from the fourth to sixth level only account for 34.78% of the total grassland area but can maintain 65.94% of the total ESV, indicating high adaptability.

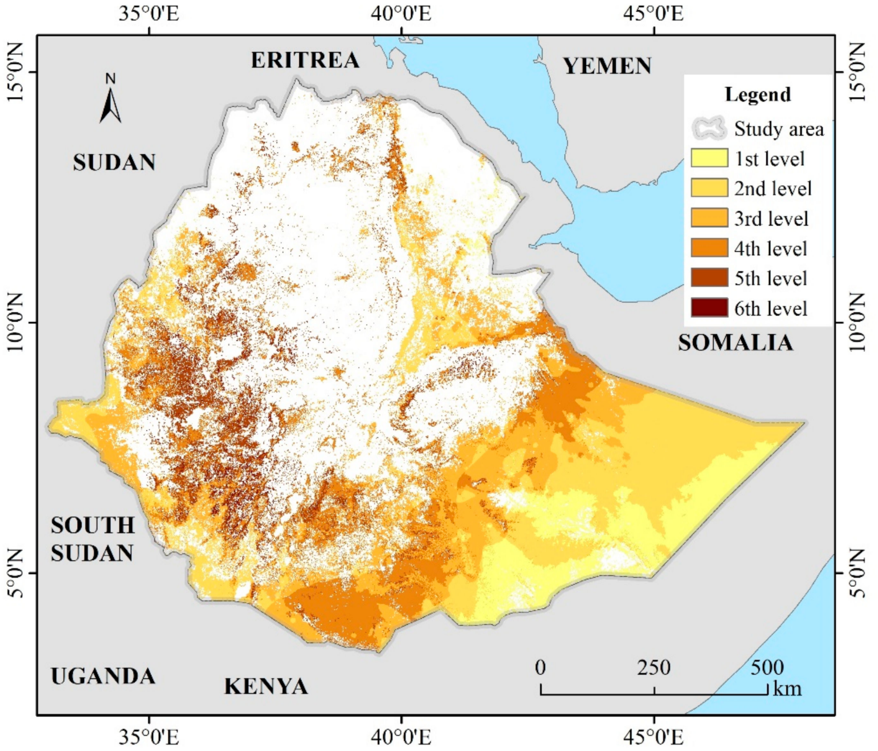


Figure 9. The adaptability zoning map of grassland ecosystem in Ethiopia.

4. Discussion

4.1. Datasets and Classification Methods

MODIS also has land cover products (MCD12Q1), but the production does not focus on a particular country. In our field investigation, we found many misclassifications, and farmland was misclassified as grassland. As a result, the accuracy of this product is not high when it is specific to a country. Therefore, we reclassified it based on the field data.

Datasets derived from remote sensing images are commonly used to estimate ecosystem service values [7–9]. Obtaining optical remote sensing data covering all of Ethiopia is difficult because of the influence of weather conditions, such as cloud cover, due to its location in a tropical region [68]. Therefore, synthetic data have become an option in related research. There is an opportunity to acquire cloudless synthetic images of a very high frequency, even in a period that is frequently cloud-covered. In this study, the MOD13Q1 product, 16-day synthetic data with a 250 m spatial resolution, was used.

The data used for classification were high-dimensional data, including the vegetation index, spectral reflectance data, and morphological parameters. A random forest classifier was used. It runs efficiently for large databases, manages thousands of input variables without variable deletion, and is unexcelled in accuracy among the machine learning algorithms. The final results also demonstrate the advantages of RF, with an overall accuracy of 86.52% and a Kappa coefficient of 0.8434.

4.2. Research on ESV

Many studies on ecosystem services value in Africa are based on value coefficients or modified value coefficients [8,23,41,42]. In other words, land use or land cover data were extracted from remote sensing images, and then a coefficient was added to different land use types to calculate the total ESV according to its areas. However, this method has disadvantages. First, the global value coefficient is not region-specific, and its evaluation must lead to an error with the actual value due to differences among regions. Even in a slightly larger country, the status of the same vegetation in different regions varies significantly. Therefore, the corrected value coefficient cannot reflect the actual regional details. Second, the size of ESV is closely related to the area of land use types but has nothing to do with its status. This treatment is unreasonable because this method causes the ESV to remain the same as long as the area remains unchanged regardless of whether its status changes. Notably, the production capacity of the same vegetation in different dimensions differs. This phenomenon leads to different ESVs in the case of the same area and vegetation type. Third, ESV is relatively complex, and its value is affected by terrain, climate, and other conditions. For example, the soil conservation capacity of grasslands differs by the slope.

In this study, the NPP was used to reflect the production capacity, calculate the promoting nutrient cycle value in combination with the element proportion of a grassland ecosystem, and evaluate the gas regulation value in combination with the photosynthesis and respiration formula of vegetation. The amount of soil conservation was calculated by the difference between potential soil erosion and actual soil erosion, reflecting the ability of grassland ecosystems to maintain soil, to evaluate its service value. The value of water conservation was calculated based on actual water retention by using an alternative engineering method. Therefore, each item reflected the actual situation of the grassland ecosystem in the study area. In our research, the value of the natural environment was the main concern, and social environmental values, such as culture, entertainment, and other values, were not considered.

In studies of the applied value coefficient [8–12], the service value of grassland ecosystems has usually been defined as USD 293.25/ha. In this study, the average ecosystem service value was higher than this value coefficient. The main reasons may be that (1) the value coefficient is usually studied globally, and its value is closer to the global average. However, Ethiopia is in a tropical region, characterized by strong vegetation production capacity and higher biomass; therefore, its service value should be greater than that of other regions. (2) In this paper, the definition of grassland was broader than what is commonly used, by including shrubs and savannas. Therefore, the overall grassland ecosystem service value was higher than USD 293.25/ha.

4.3. Guiding Significance of ESV

The most intuitive value of grassland ecosystem is forage production for livestock. Therefore, the organic matter production value (ESV1) is of great significance for animal husbandry. Of course, the service value of grassland ecosystem is the synthesis of all values. Through comprehensive evaluation, ESV can provide a clear understanding of the ecosystem service value by using a measurement standard that considers actual feelings. It can increase the awareness of the importance of various ecosystem functions and promote the formulation and implementation of local resource protection policies. In this paper, the total ESV of grassland ecosystem services was approximately USD 105,221.72 million in Ethiopia, similar to Ethiopia's Gross Domestic Product in 2020. The gigantic service value of grassland ecosystems can promote the local protection.

As shown in Figures 4–7, ESV is closely related to plant type, growth state, terrain, rainfall, and other factors. The ESV of the same vegetation type was also significantly different due to differences in biomass. The value coefficient method does not consider the differences within the same ecosystem, and there are problems in evaluating the ESV between regions. The vegetation in steep terrain will have a greater service function for soil conservation; thus, the ESV of grassland in the same state is greater than that in the plain. In areas with more rainfall, vegetation can accumulate more water; thus, its water conservation value is greater than other areas. Therefore, ESV is the result of the joint action of many factors.

Figure 9 shows the adaptability of grassland ecosystems in Ethiopia. The areas from approximately the first to the third level with low adaptability have gentle slopes. Therefore, these areas are suitable to be developed into cultivated land or artificial pastures to meet the needs of social development but have little impact on the total ESV of the grassland ecosystem. The detailed ESV data and analysis results will have important guiding significance in decision making on management.

5. Conclusions

In this study, time series remote sensing data were used to identify grassland types, biomass was used to reflect the growth status of vegetation, the RUSLE model was used to extract soil conservation, and cumulative rainfall was used to calculate water conservation. Based on the NPP and the amount of soil conservation and water conservation, several methods have been used to evaluate ESV, such as the energy substitution method, market value method, virtual engineering method, and alternative engineering method. Compared with the value coefficient method, the ESV evaluated in this manner is more accurate and can adequately describe the differences within the same ecosystem. The evaluation results show that the ESV of the grassland ecosystem in Ethiopia is close to the Gross Domestic Product in 2020. For ecological service functions, the value of soil conservation is the highest, accounting for 44.09% of the total ESV, followed by gas regulation (28.80%), organic matter production (18.24%), the promotion of nutrient circulation (4.45%), and water conservation (4.43%). For grassland types, SA has the largest ESV, accounting for 35.20% of the total ESV. Although the OS area is the largest, its ESV is the smallest (8.01% of the total ESV). Therefore, the area does not have an absolute leading role.

On the whole, the areas with large ESV are mainly distributed in the south, especially in the southwest. The ESV of Oromia state reaches USD 44,578.62 million, accounting for 42.37% of the total ESV in Ethiopia. ESV per unit area of SNNP state is the largest, reaching USD 2059.56/ha. Additionally, the per capita ESV of Gambela state is largest, reaching USD 14,007.31 per person.

Through the analysis of influencing factors, it was found that the grassland is suitable to be grown in the elevation zone between 1000 and 2000 m. With the increase in slope, the zone ESV decreases and the mean ESV continuously increases. Both the zone ESV and mean ESV increase with the increase in annual rainfall. Additionally, the aspect has little effect on ESV. By integrating various influencing factors, the adaptability of the grassland ecosystem was evaluated. The areas from the approximately fourth to the sixth levels possess the best adaptability; they only account for 34.78% of the total grassland area, but can maintain 65.94% of the total ESV.

ESV assessment can improve the awareness of biodiversity protection and the understanding of natural resource value, so as to promote paying attention to biodiversity protection and sustainable utilization to maintain a balance between economic development and ecosystem health. This research provides an ESV evaluation result under the comprehensive action of many factors to more objectively reflect the spatial distribution of ESV in grassland ecosystems. Therefore, it provides references and bases to support the local coordination and planning of various grassland resources and form more reasonable resource utilization and protection measures. Further, it can improve policy decisions for intervention strategies in the sustainable use and management of land resources to gain the maximum benefits from ecosystem services.

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Data Availability Statement: MODIS NDVI, NPP, HWSD soil, DEM, and GPM data are openly available. Land cover data can be extracted locally based on remote sensing data.

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