remote sensing

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A New Regionalization Scheme for Effective Ecological Restoration on the Loess Plateau in China

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Abstract: To prevent potentially unsuitable activities during vegetation restoration, it is important to examine the impact of historical restoration activities on the target ecological system to inform future restoration policies. Taking the Loess Plateau of China as an example, a regionalization method and corresponding scheme were proposed to select suitable vegetation types (forested lands, woody grasslands/bushlands, grasslands, or xerophytic shrublands and semi-shrublands) for a given location using remote sensing technology in order to analyze the vegetation growth status before and after the largest ecological conservation project in the country: The Grain for Green Program (GTGP). To design the scheme, remote sensing data covering the periods before and after the implementation of the GTGP (the 1980s and 2001–2013) were collected, along with soil, meteorological, and topographic data. The net primary production (NPP) values for 2001–2013 were calculated using the Carnegie-Ames-Stanford Approach (CASA) model. Locations representing the native vegetation and the restored vegetation were first recognized using maps of vegetation cover. Then, for the restored vegetation area, the places suitable for planting the covered vegetation type were selected by comparing the NPP value of the corresponding vegetation type in the native vegetation area to the NPP value in the site under consideration. Third, half of these sites were uniformly selected based on their NPP value, and these areas and the native vegetation area were used as training regions. Based on weather, soil, and topographic data, a new regionalization scheme was designed using standardized Euclidean distances. Finally, data from the remainder of the Loess Plateau were used to validate the new regionalization scheme, which was also compared to an existing Chinese eco-geographical regionalization scheme. The results showed that the new regionalization scheme performed well, with an average potential classification accuracy of 81.81%. Compared with the eco-geographical regionalization scheme, the new scheme exhibited improved the consistency of vegetation dynamics, reflecting the potential to better guide vegetation restoration activities on the Loess Plateau.

Keywords: vegetation restoration; regionalization; remote sensing; Loess Plateau

1. Introduction

The Loess Plateau is located in the arid and semi-arid region of northwestern China, which was a critical area for ancient Chinese civilization. Due to the long-term impacts of the intensive human activities under the unique climatic and topographic conditions of the Loess Plateau, the ecosystem has suffered serious damage, including severe soil erosion [1,2], and it has been recognized as one of the most fragile ecological areas in China [3]. To reduce soil erosion and restore ecosystem health, many ecological restoration projects have been performed by the Chinese government over the past few decades, and China's Grain for Green Program (GTGP) is an outstanding example of these national ecological restoration programs. It started in 1999 and is the largest ecological restoration program in a developing country [4]. Within the Loess Plateau region, the major goal of this ecological project is to convert sloping farmland or barren land to forests and grasslands [5] and to increase the vegetation coverage in order to increase precipitation infiltration and reduce soil erosion. Since its inception, the project has made remarkable contributions to the recovery of vegetation on the Loess Plateau; many studies have reported a significant increase in net primary productivity (NPP) [3,4]. Since 2000, the year after the GTGP began, soil organic carbon has substantially increased [6], and soil erosion has decreased [7]. However, some problems also arose during the project because no clear guidelines or information exist to help local governments determine where to plant trees or grass or the appropriate planting density; thus, many re-vegetation activities have been inappropriate, such as planting species that use large amounts of water in areas with low precipitation [8] and planting trees too densely [5], which has led to unexpected ecological consequences. Some reports have stated that planting vegetation species with high water demands in areas with a low water supply cannot prevent soil erosion, but could in fact induce drought due to the increased loss of soil moisture through excessive evapotranspiration. Additionally, increasing drought and excessive soil erosion have been reported in many places on the Loess Plateau [5,9]. What happened on the Loess Plateau was not an isolated event. It also happened in other places around the world when vegetation restoration activities were conducted, especially in the East and South Asian regions [10]. Thus, strategies that help make decisions about whether to re-vegetate, and if so, how to do it and which species to use, are highly needed.

When considering how to select the vegetation type for restoration in a given location, the following studies are valuable. Based on future climate scenarios and the ecological characteristics of 46 shrubland species, Gelveiz-Gelvez et al. [11] selected six species suitable for restoration in a semi-arid region of central Mexico using ecological models. By matching the characteristics of different types of vegetation (trees, shrubs, and herbaceous plants) to the local environmental conditions (weather, soil, etc.), Kang et al. [12] divided the farming-pastoral region in northern China into different vegetation restoration zones. Using the characteristics of the natural vegetation distribution in northeast China, Liu et al. [13] established a regional model to simulate the geographical distribution of 16 natural vegetation types under current environmental conditions, representing the potential natural vegetation of northeast China. These studies identified vegetation restoration zones by theoretically matching plant characteristics to local climate and soil properties that existed before the vegetation restoration projects began. However, unlike the situation that existed when the ecological restoration projects had just started, numerous restoration projects have been conducted for many years, such as the aforementioned GTGP in China. If the actual growing status of vegetation during the restoration project can be investigated and used as a reference in developing a better plan for vegetation recovery, this should have considerable potential to lead to successful and efficient ecological restoration in the future.

Since mankind obtained the first image of the earth from a satellite in 1959, numerous earth observation data based on satellites have been acquired, especially in recent decades. In addition, remote sensing technology has been employed as an efficient tool to study the biophysical and biochemical characteristics of vegetation in a spatially and temporally explicit manner [14–17]. Therefore, remote sensing is a preferred technique for investigating the historical vegetation growth status.

According to above analysis, taking the Loess Plateau as an example, the specific objective of this study was to develop a regionalization method and use it to design a regionalization scheme to inform the proper selection of vegetation types for particular locations during ecological restoration using remote sensing technology to investigate the historical vegetation condition from before and after implementation of the restoration project.

2. Materials and Methods

2.1. Study Area

The Loess Plateau is located between 102° and 114° East longitude and 35° and 41° North latitude (Figure 1), and it covers an area of approximately 640,000 km^2 [9], which spans five provinces, consisting of Shanxi, Shaanxi, Gansu, Qinghai, and Henan, and two autonomous regions, Ningxia and Inner Mongolia. The Loess Plateau accounts for 6.67% of the total territory of China and supports 8.5% of the Chinese population [7]. The topography is high in the west and low in the east, with altitudes between 200 m and 3000 m [3]. The region experiences a temperate continental monsoon climate [3], and the annual mean temperature ranges from 8 to 14 °C, with annual precipitation generally increasing from 200 mm in the northwest to 700 mm in the southeast [9]. The soils contain larger amounts of clay in the southeast and are sandy in the northwest, and the vegetation land cover types include forests, bushlands, grasslands, xerophytic shrublands, and semi-shrublands.

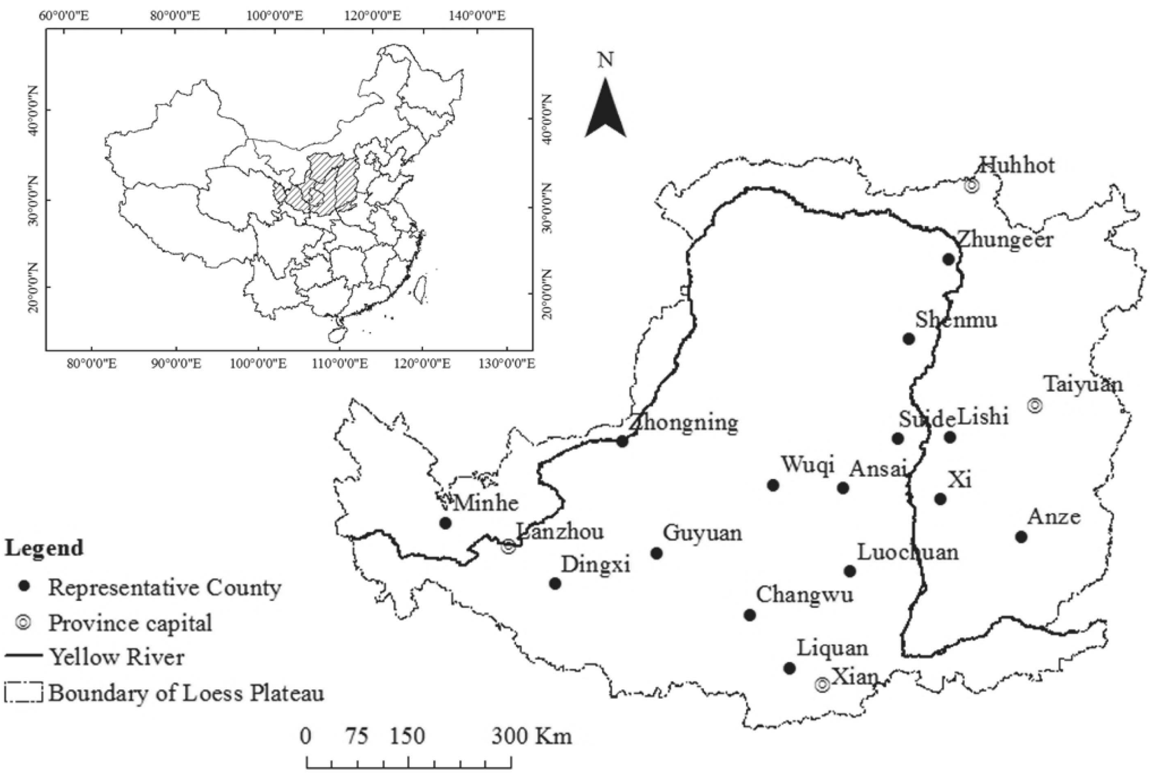

Figure 1. Location of the study area in China.

2.2. Data Acquisition

To investigate the vegetation growth status, the net primary productivity data were calculated using the Carnegie-Ames-Stanford Approach (CASA) model because it is the critical indicator of crop growth. Soil data, meteorological data, land cover data, and vegetation index data were collected and used as the input parameters in the CASA model. In addition, since the distributions of the vegetation types are mainly influenced by the weather, soil, and topographical conditions, the aspect data were also collected, as well as soil and meteorological data, in order to create the regionalization of ecological restoration.

2.2.1. Soil Data

The soil data include information on soil texture types and clay and sand contents, and they were derived from the Harmonized World Soil Database, version 1.1, which was developed by the Food and Agriculture Organization (FAO) of the United Nations and the Vienna International Institute of Applied Systems (IIASA). The soil data used in this study were provided by the Cold and Arid Regions Sciences Data Center in Lanzhou (http://westdc.westgis.ac.cn). The original dataset uses the WGS_1984_Albers projection with a spatial resolution of 1 km. The soil texture data are expressed as numbers ranging from 1 to 13, with larger numbers indicating coarser soil types.

2.2.2. Meteorological Data

The meteorological data, which included monthly radiation, precipitation, and temperature values, were derived from the China Meteorological Forcing Dataset (CMFD), which was provided by the Data Assimilation and Modeling Center for Tibetan Multi-spheres, Institute of Tibetan Plateau Research, Chinese Academy of Sciences. This dataset was developed by fusing observational data from weather stations in China with reanalyzed data from Princeton University, Global Land Data Assimilation System (GLDAS) data, the National Aeronautics and Space Administration's Global Energy and Water Cycle Experiment (NASA/GEWEX) surface radiation budget (SRB) data, and Tropical Rainfall Measuring Mission (TRMM) precipitation data [18]. This dataset has a temporal resolution of 3 h and a spatial resolution of 0.1°, and it employs the WGS 84 Geographic Coordinate system. A program written using Matlab R2011a was used to calculate the monthly temperature, precipitation, and radiation values from this dataset.

2.2.3. Land Cover Data

Time-series land cover data were collected for this study, and those for the 1980s were obtained from the Advanced Very High Resolution Radiometer (AVHRR) land cover product, since it is the only available product that covers the earlier part of our study period. The dataset was generated using the land cover classification system proposed by the Department of Geography of the University of Maryland (UMD) [19], which was downloaded from the UMD website (http://glcf.umd.edu/data/landcover); it has a 0.01° spatial resolution and uses the GCS_WGS_1984 projection. Land cover data for the years between 2001 and 2013 were taken from the Moderate Resolution Imaging Spectroradiometer (MODIS) MCD12Q1 land cover product, which includes annual land cover maps; these data have been widely used [20,21] and have a resolution of 0.5 km. This dataset offers five different classification schemes. To ensure correspondence with the land cover data from the 1980s, the UMD classification system was used in this study. This dataset, which was downloaded from the NASA website (http://reverb.echo.nasa.gov), is sinusoidally projected.

2.2.4. Vegetation Index Data

Monthly enhanced vegetation index (EVI) values that cover the period between 2001 and 2013 were extracted from the MODIS MOD13A3 product. The MOD13A3 data product was also downloaded from the NASA website (http://reverb.echo.nasa.gov). The original data have a temporal resolution of one month and a 1-km spatial resolution, and they use the sinusoidal projection.

2.2.5. Estimation of Net Primary Productivity

As mentioned above, the annual NPP values covering the years from 2001 to 2013 were calculated using the CASA model, which was proposed by Potter et al. [22] and has been widely used to estimate NPP [23–25]. This model can estimate NPP at a monthly time step and is a light use efficiency-based model, in which the NPP is estimated as the product of the amount of photosynthetically active radiation (PAR) absorbed by the vegetation (APAR, MJ m^{-2}) and the light use efficiency (ε, g C MJ^{-1})

with which the APAR is converted into plant biomass [17,22]. For a given geographic location x in month t, the NPP can be calculated from the following three basic equations:

$$\mathrm{NPP}(x,t) = \mathrm{APAR}(x,t) \times \varepsilon(x,t) \quad (1)$$

$$\mathrm{APAR}(x,t) = \mathrm{FPAR}(x,t) \times R_s(x,t) \times 0.5 \quad (2)$$

$$\varepsilon(x,t) = \varepsilon_{max}(x,t) \times T_1(x,t) \times T_2(x,t) \times W(x,t) \quad (3)$$

where R_s is the total solar radiation (MJ m^{-2}); $FPAR$ is the fraction of PAR absorbed by the vegetation; ε_{max} is the maximum possible light use efficiency, which has a value of 0.389 when AVHRR satellite data are used; T_1 and T_2 refer to the temperature stress coefficients; and W refers to the water stress coefficient. The coefficient 0.5 in Equation (2) accounts for the fact that approximately half of the incoming solar radiation is PAR in the 0.4–0.7 μm waveband. Additionally, since the original model was based on AVHRR satellite imagery, Potter et al. [26] used EVI instead of FPAR in Equation (2) and fixed $\varepsilon_{\max}$ at a constant value of 0.55 when MODIS satellite data were considered. More detailed information on how to calculate the elements of the above equations can be found in Potter et al. [22]. The above soil, meteorological, land cover, and vegetation index data were used in the CASA model. To place them into the same spatial resolution, projection system, and file type, the data were converted into the Krasovsky_1940_Albers projection system with a 1-km spatial resolution. During the resampling, the nearest neighbor sampling method was used. Additionally, the annual NPP was computed by summing the monthly NPP data for each year.

2.2.6. Aspect Data

A global 30 arc-second elevation dataset (GTOPO30) was downloaded from the website of the United States Geological Survey (USGS; http://earthexplorer.usgs.gov). This dataset uses the WGS 84 Geographic Coordinate system, and as with the above datasets, it was also converted into the Krasovsky_1940_Albers projection system with a 1-km spatial resolution. Data on topographical aspect were then calculated.

2.3. Data Analyses

2.3.1. Design of the Vegetation Restoration Regionalization Scheme

A regionalization method was designed to facilitate the selection of suitable vegetation types for planting in a given site under ecological restoration. Based on the vegetation conditions on the Loess Plateau, the regionalization scheme used the following five types of vegetation zones: forested lands, woody grasslands/bushlands, grasslands, xerophytic shrublands/semi-shrublands, and passive restoration lands. To propose the scheme, the following hypotheses were presented: (1) if the vegetation type in a given location did not change from the 1980s to 2013, the location can be assumed to be an area of native vegetation; (2) since the implementation of the GTGP in 1999, the restoration area for forest and grassland increased tremendously until 2005 [3], so if the vegetation type at a given location remained the same from 2006 to 2013 but was different from that in the 1980s, the site was considered to have undergone restoration. The main ideas underlying these hypotheses were to extract areas of native vegetation and some locations with restored vegetation that are suitable for planting the cover vegetation type and then to use them as a training area to classify the Loess Plateau into different vegetation restoration zones based on weather, soil, and topographic factors. The detailed steps for proposing the regionalization scheme are shown in Figure 2 and described as follows: (1) the collected land cover data were reclassified into forested lands, woody grasslands/bushlands, grasslands, xerophytic shrublands/semi-shrublands, and passive restoration lands, according to the vegetation type definitions in the UMD classification scheme (detailed information is presented in Table 1); (2) Native vegetation areas (N) and restored vegetation areas (R) were extracted according to the above hypotheses using land cover data from the 1980s and 2001–2013; (3) Since NPP is a good factor to indicate the vegetation growth status, it was used to judge whether a parcel of land was properly restored. During this procedure, the boundary values corresponding to the lower 5% NPP limit for each vegetation type were calculated within area N during 2006 to 2013 (A_{ij}; where i indicates the vegetation type, and j indicates the year). Next, these values were used to determine whether the vegetation cover type in a given place in area R was suitable for planting; (4) In area R, the NPP value of each pixel in each year was compared with the corresponding A_{ij}, selecting the pixel that always had a higher NPP than the A_{ij} value from 2006 to 2013; these pixels form region RS, which was considered to have experienced proper vegetation restoration; (5) To retain more independent data for validation, only half of the samples from region RS were selected and used for training in the next step. During this procedure, the pixels in region RS were arranged from minimum to maximum NPP values, and half of the pixels were uniformly selected and marked as region U; (6) Pixels in regions N and U were used as training samples, and the Loess Plateau was divided into different vegetation restoration zones using the standardized Euclidean distance (SED) method, which was proposed by Flury and Riedwyl [27] and is considered a good classification method [28]. Each pixel within the studied domain was classified according to the nearest vegetation type. During this procedure, parameters such as annual mean temperature (T), monthly mean temperature in July (T_{ju}), monthly mean temperature in January (T_{ja}), annual precipitation (P), and annual radiation (R) were calculated using weather data for the years from 2006 to 2013 and used for classification by incorporating aspect (A_{sp}) and soil texture (S_{tex}) data. Prior to conducting the classification, all the variables were scaled to a range of 0 to 1 to eliminate errors resulting from differences in the magnitude of the variables [29]. The formula for calculating SED is shown in Equation (4).

$$d_{ilm} = \sqrt{\sum_{k=1}^{u} \left(\frac{x_{lmk} - \overline{x}_{ik}}{s_{ik}}\right)^2} \tag{4}$$

where d_{ilm} is the SED between the value of the pixel in row l and column m and the value of vegetation type i; x_{lmk} is the value of the pixel in row l and column m for factor k; $\overline{x}_{ik}$ is the mean value of factor k corresponding to vegetation type i in the training dataset; s_{ik} is the standard deviation of factor k corresponding to vegetation type i in the training dataset; and u is the total number of factors.

Table 1. Definitions of the vegetation restoration zones used in the newly designed scheme.

Vegetation Type	Definition and corresponding vegetation type in the UTM classification system
Forested Lands	Areas dominated by trees with >60% canopy cover. Corresponds to evergreen needleleaf forests, evergreen broadleaf forests, deciduous needleleaf forests, deciduous broadleaf forest and mixed forests
Woody Grasslands/Bushlands	Areas with herbaceous or woody understories and tree canopy cover <60% and >10% or with closed bush cover. Corresponds to woodlands, wooded grasslands/shrublands, and closed bushlands/shrublands
Grasslands	Areas dominated by herbaceous cover and <10% trees or shrubs. Corresponds to grasslands
Xerophytic Shrublands/Semi-Shrublands	Areas dominated by xerophytic shrubs/semi-shrubs and canopy cover <40% and >10%. Corresponds to open shrublands
Passive Restoration Lands	Without irrigation, these areas never have more than 10% vegetation cover at any time of the year. Corresponds to barren lands.

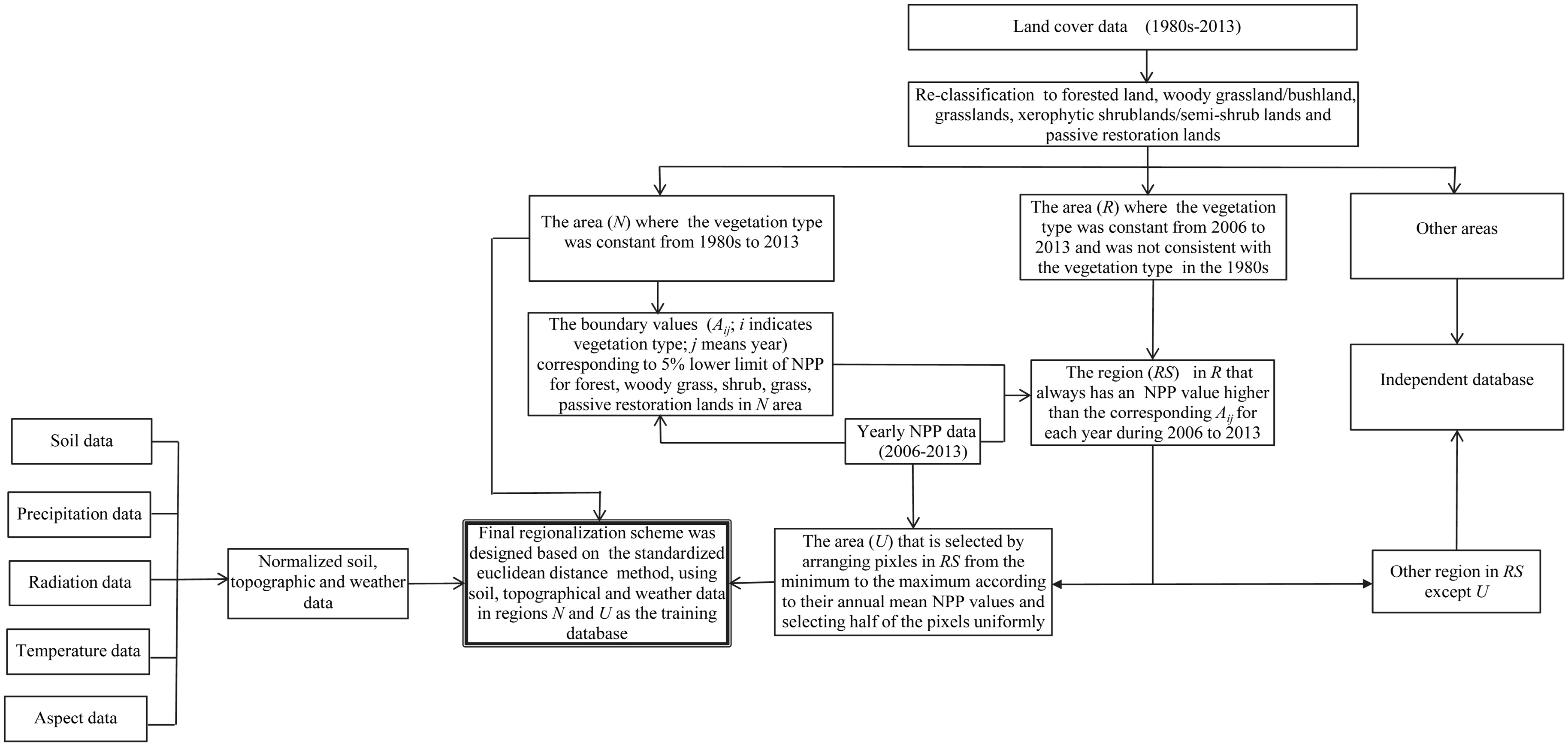

Figure 2. Flow chart illustrating the design of the vegetation restoration regionalization scheme.

2.3.2. Assessment of the Regionalization Scheme

The accuracy and usefulness of the new regionalized vegetation restoration scheme was validated using an independent dataset (Figure 2) and by comparing it with the Chinese eco-geographical regionalization [30]. In the Chinese eco-geographical regionalization dataset, the Chinese territory is divided into distinct natural areas based on heat conditions, moisture availability, vegetation type, topography, and other relevant factors. It is a commonly used scheme.

For validation using an independent dataset, the potential classification accuracy was used to assess the new regionalization scheme. It was proposed based on the following considerations: (1) According to the NPP values, the order was forested lands, woody grasslands/bushlands, grasslands, xerophytic shrublands and semi-shrublands, and passive restoration lands when arranging them from high to low; (2) in reference to the above section, the A_{ij} value can be used to judge whether a parcel of land was restored using a suitable vegetation type. The potential classification accuracy is defined as the probability that a pixel was not suggested to be restored into a vegetation type, indicating a lower NPP value than its vegetation cover type when its NPP is higher than A_{ij}, and was not suggested to be restored into a vegetation type the same as its covered vegetation type or a vegetation type, indicating a higher NPP value than its vegetation cover type when its NPP is lower than A_{ij}. For example, if a pixel is presently covered by grass and was correctly classified, it should not be classified into a xerophytic shrublands/semi-shrublands or a passive restoration lands zone when it has an NPP value higher than the A_{ij} value of grasslands, and it should not be classified into a forested lands, woody grasslands/bushlands, or grasslands zone when it has an NPP value lower than the A_{ij} value of grasslands. The average potential classification accuracy during 2006 to 2013 was calculated as:

$$R = \left(\left(\sum_{j\,=\,2006}^{2013} \left(\frac{\sum_{i=1}^{n} wr1_{ij+} \sum_{i=1}^{n} wr2_{ij}}{\sum_{i=1}^{n} T_{ij}}\right)\right)/t\right) \times 100\% \quad (5)$$

where R is the average potential classification accuracy; $wr1_{ij}$ is the number of pixels covered by vegetation type i that have higher NPP values than the corresponding A_{ij} value and are not assigned to vegetation types indicating lower NPP values than its covered vegetation type in year j; $wr2_{ij}$ is the number of pixels covered by vegetation type i that have lower NPP values than the corresponding A_{ij} value and are either not assigned to the same vegetation type as its covered vegetation type or not assigned to a vegetation type, indicating higher NPP values than its covered vegetation type in year j; T_{ij} is the total number of pixels for vegetation i in year j; n is the number of vegetation types; and t is the total number of years.

Comparing the new regionalization scheme with the Chinese eco-geographical regionalization scheme was challenging because the two regionalization schemes do not use the same classification system. Therefore, they were compared in terms of the following two aspects: (1) the usefulness of the classification system to assist in vegetation restoration; and (2) the dynamic consistency of the vegetation, which was evaluated using the method of Zhang et al. [31] for each regionalization scheme. According to Zhang's study, if the regionalization scheme has a good dynamic consistency of vegetation, the curves describing the NPP time series for each zone should not intersect, and the coefficient of variation (CV) of the NPP values should be low. The CV is calculated as:

$$CV_j = \frac{\sum_{i=1}^{n} CV_{jk} \times N_k}{\sum_{i=1}^{n} N_k} \quad (6)$$

where CV_j is the coefficient of variation for a given regionalization scheme in year j; CV_{jk} is the coefficient of variation for zone k in year j; N_k is the total number of calculated pixels in zone k; and n is the number of zones in the given regionalization scheme.

3. Results

3.1. General Vegetation Conditions on the Loess Plateau

The NPP values on the Loess Plateau generally decrease from the southeast to the northwest (data not shown). It is similar to the general pattern for rainfall, which also decreases from the southeast to the northwest. Since most of the region is located within arid and semi-arid areas, it is expected that the land cover types and their growth statuses were mainly influenced by moisture conditions. Between 2006 and 2013, the annual NPP values for forested lands, woody grasslands/bushlands, grasslands, xerophytic shrublands/semi-shrublands, and passive restoration lands were 333 g m^{-2} yr^{-1}, 257 g m^{-2} yr^{-1}, 158 g m^{-2} yr^{-1}, 107 g m^{-2} yr^{-1}, and 46 g m^{-2} yr^{-1}, respectively.

3.2. Vegetation Conditions in the Defined N and R Regions

The *N* and *R* areas were extracted based on land cover data for the 1980s and 2001–2013, respectively. For both the *N* and *R* regions, forested lands and woody grasslands/bushlands mainly occur on the southeastern part of the Loess Plateau; xerophytic shrublands/semi-shrublands and barren lands are located on the northwestern part of the Loess Plateau; and grasslands are distributed in the central part from northeast to southwest (data not shown). During the implementation of vegetation restoration on the Loess Plateau, trees and grass were the main types of vegetation planted, very often in unsuitable environments. Thus, in principle, forested lands, woody grasslands/bushlands, and grasslands in the *N* region should have higher NPP values than the corresponding values in the *R* region. During 2006–2013, the average annual NPP values for forested lands, woody grasslands/bushlands, and grasslands were 365 g m^{-2} yr^{-1}, 247 g m^{-2} yr^{-1}, and 175 g m^{-2} yr^{-1} in the *N* region and 338 g m^{-2} yr^{-1}, 241 g m^{-2} yr^{-1}, and 148 g m^{-2} yr^{-1} in the *R* region, respectively. Thus, the NPP values in the *N* region were all greater than the values in the *R* region. Annual variations in NPP for the vegetation types listed above in the *N* and *R* regions are shown in Figure 3. It can also be noted that the NPP values in the *N* region were always higher than the corresponding values in the *R* region for each vegetation type in each year, which verified the above conjecture. The results are consistent with Wang and Shao's findings [8]. They reported that during the implementation of vegetation restoration on the Loess Plateau, trees were planted in some areas that are suitable for shrubs and grasses, leading to limited vegetation growth. It should also be noted that the forested lands, woody grasslands/bushlands, and grasslands are found on different parts of the Loess Plateau, where seasonal and inter-annual climate variability are significantly different. Different climate regimes might also be a key factor driving different annual patterns of NPP for the three vegetation types.

3.3. A New Regionalized Vegetation Restoration Scheme

According to the method proposed in this study, the Loess Plateau can be divided into different vegetation restoration zones, as shown in Figure 4a. For reference, the land cover map for 2010 is shown in Figure 4b. In general, forested lands and woody grasslands/bushlands are suitable for re-vegetation in the humid and semi-humid area in the southeastern part of the Loess Plateau; grass is an appropriate re-vegetation type for the semi-arid areas on the central part and selected portions of the western segment of the Loess Plateau; and the arid region on the northwestern part of the Loess Plateau is only suitable for xerophytic shrublands/semi-shrublands or for being left as a passive restoration area.

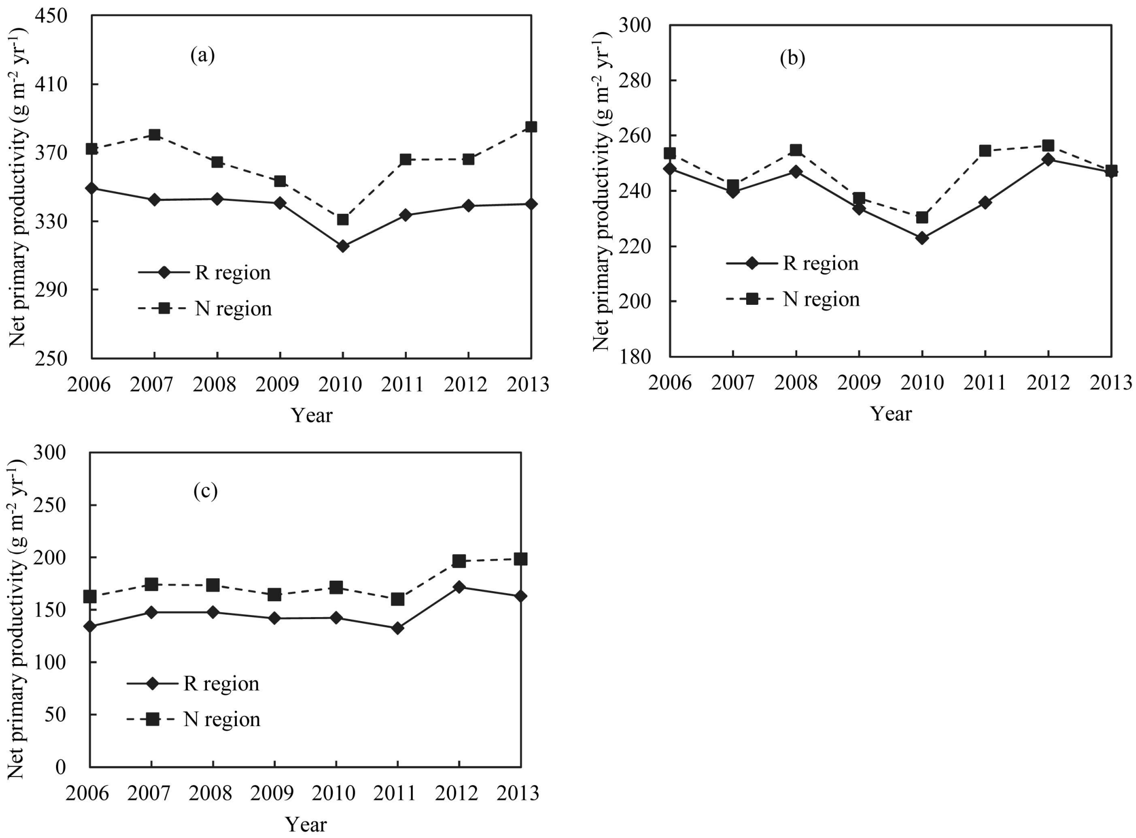

Figure 3. Net primary productivity of forested lands (**a**); woody grasslands/bushlands (**b**); and grasslands (**c**) in regions *N* and *R*.

3.3.1. Regions Suitable for Tree Restoration

The annual mean temperature and radiation and precipitation values for the region were 10.2 °C, 5046 MJ m^{-2}, and 602 mm, respectively. The areas suitable for tree planting mainly occur along the southeastern edge of the Loess Plateau and include the prefecture-level cities of Tianshui, Baoji, Xianyang, Xian, Sanmenxia, and Luoyang, as well as the southern part of Weinan (Figure 4a). These cities are located in north of the Qinba Mountains and receive sufficient precipitation to promote tree growth. In addition to the prefecture-level cities above, the southeastern part of Lüliang, as well as the eastern part of Qingyang, Xinzhou, and Yuncheng, the southern part of Yanan, and most of Jinzhong and Yangquan are also ideal for tree re-vegetation (Figure 4a).

3.3.2. Regions Suitable for Woody Grass/Bush Restoration

Compared with the forest zone, moisture conditions in the regions suitable for the restoration of woody grasslands/bushlands are slightly worse. These regions are only suitable for planting trees with less than 60% coverage, while the remaining areas can be planted with grass or bushes. The average annual mean temperature, radiation, and precipitation values for this zone were 11.7 °C, 5163 MJ m^{-2}, and 564 mm, respectively, and these areas are mainly found in the prefecture-level cities of Jincheng and Changzhi, as well as the northern part of Weinan, the western part of Yuncheng and Linfen, and the central part of Qingyang (Figure 4a).

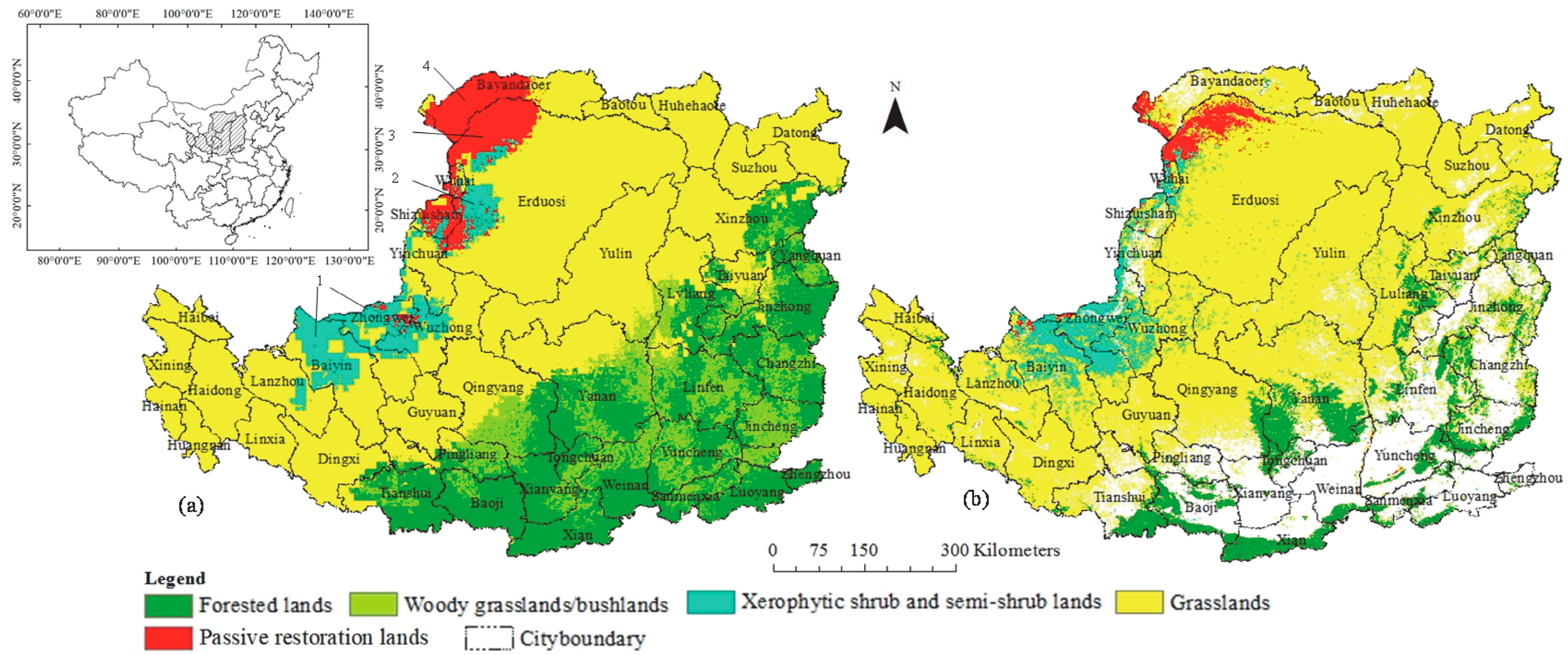

Figure 4. New regionalized vegetation restoration scheme (**a**) and land cover map (croplands, urban and built-up areas, and water bodies are not shown) for 2010 (**b**).

3.3.3. Regions Suitable for Grass Restoration

Grass is the most suitable re-vegetation type for most of the Loess Plateau, a zone that spans the central part of the plateau from the southwest to the northeast. The prefecture-level cities of Huhehaote, Yulin, Suzhou, Guyuan, Dingxi, Linxia, Haidong, Hainan, and Xining, as well as the central and eastern parts of Erduosi and the western part of Xinzhou, are all in this area (Figure 4a). The annual mean precipitation is 418 mm, which is less than that of the regions suitable for tree and woody grass/bush restoration; this zone is only suitable for planting grass.

3.3.4. Regions Suitable for Xerophytic Shrub/Semi-Shrub Restoration

In this zone, the annual mean precipitation is only 231 mm, and due to drought and overgrazing, the dominant plants within the transition zone between grasslands and desert are xerophytic shrubs and semi-shrubs [32,33]. Xerophytic shrublands and semi-shrublands are sparsely distributed within this area in regions such as the prefecture-level city of Zhongwei, as well as the northern part of Baiyin and the western portion of Wuzhong (corresponding to areas marked with the number 1 in Figure 4a). The areas marked with the number 2 in Figure 4a are located in the western part of the Mu Us Desert; xerophytic shrubs and semi-shrubs are also the dominant vegetation within this region. Grazing should be strictly forbidden in this zone, and in some suitable areas with sufficient precipitation, xerophytic shrubs and semi-shrubs can be planted to protect the land surface from wind erosion.

3.3.5. Regions Suitable Only for Passive Restoration without Irrigation

The regions that are only suitable for passive restoration without irrigation are indicated in red in Figure 4a. Within this zone, the annual mean temperature, radiation, and precipitation values are 9.1 °C, 5976 MJ m^{-2}, and 187 mm, respectively. Most of the area labeled with the number 3 in Figure 4a is located in the Hobq Desert, and the western part of the area marked with the number 4 is on the edge of Ulan Buh Desert. These areas are completely unsuitable for artificial planting, so passive vegetation restoration is the best method. The Yellow River passes through the area marked with the number 4. With regard to anthropogenic interaction, it must be noted that irrigated agriculture has been extensively developed in the central and eastern parts of this region. However, the irrigation needs of the vegetation that is planted in the area must not compete with the distribution of water by the government along the upper and lower reaches of the Yellow River.

3.4. Assessment of the New Regionalized Vegetation Restoration Scheme

3.4.1. Evaluation Using the Independent Dataset

When the new regionalization scheme was validated using the independent dataset, a good result was obtained, with an average potential classification accuracy value of 81.81%. This result indicates that the new regionalization can classify lands on the Loess Plateau efficiently.

3.4.2. Comparison of the New Regionalization Scheme with the Chinese Eco-Geographical Regionalization Scheme

As stated previously, the Chinese eco-geographical regionalization was proposed and has been used to encourage the rational use of natural resources and to study the effects of climate change on ecosystems; it also has the potential to be used for re-vegetation. Thus, we compared it with the new regionalization scheme described in this study. First, in terms of the classification system, although the Chinese eco-geographical regionalization has nine zones on the Loess Plateau, it only includes four vegetation types: forest, grass, forest with grass, and barren. Topographic factors were used to classify the four vegetation types into nine zones [30]. The regionalization scheme proposed in this study included five vegetation restoration zones: forested lands, woody grasslands/bushlands, grasslands, xerophytic shrublands/semi-shrublands, and passive restoration lands. The purpose of using these vegetation zones was to assist in re-vegetation in this area. Then, to compare the dynamic consistency of the vegetation, annual NPP data for each zone for each year were plotted for the two regionalization schemes in Figure 5. If the regionalization approach is good for vegetation restoration, the curves describing the NPP time series for each zone should not intersect. No points of intersection appear for the new vegetation regionalization scheme, but six points of intersection appear for the Chinese eco-geographical regionalization scheme. In addition, Figure 6 indicates that the Chinese eco-geographical regionalization consistently produced higher *CV* values for NPP than the new regionalization scheme for every year during the 2006–2013 periods, even though it has more zones. This result indicates that the new vegetation regionalization scheme has a better dynamic consistency for vegetation than the Chinese eco-geographical regionalization. Therefore, the new regionalization scheme is generally more suitable and accurate than the Chinese eco-geographical regionalization for use in re-vegetation projects on the Loess Plateau.

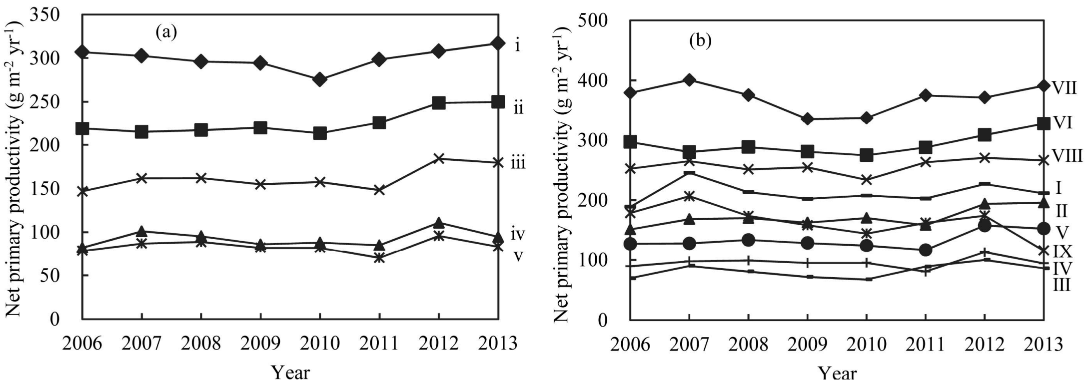

Figure 5. Yearly NPP data for the new regionalization scheme (**a**) and the Chinese eco-geographical regionalization scheme (**b**) in different years. i: Forested lands; ii: woody grasslands/bushlands; iii: grasslands; iv: xerophytic shrublands and semi-shrublands; v: passive restoration lands. I: Area of coniferous forest and grasslands in the basin east of the Qilian Mountains; II: steppe region in the north-central portion of the Loess Plateau; III: desert area in Alxa and the Hexi Corridor; IV: desert grassland area in Erdos and western Inner Mongolia; V: grassland area in eastern Inner Mongolia; VI: deciduous forest and farmland in the Fenwei basin; VII: area of evergreen broadleaf forest and mixed forest in the Qinba Mountains; VIII: area of deciduous broadleaf forest in the mountains of northern China; IX: area of farmland on the North China Plain.

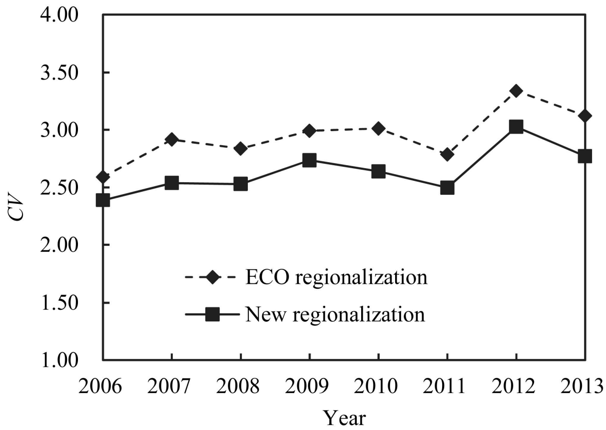

Figure 6. The coefficient of variation of net primary productivity values for the new regionalization scheme and the Chinese eco-geographical regionalization (ECO regionalization) scheme in different years.

4. Discussion

4.1. Potential applications of the scheme to vegetation restoration on the Loess Plateau

To discuss whether a regionalization scheme is effective, it is important to examine the accuracy in boundary areas. A series of studies about vegetation restoration in the border region of the scheme were collected. Yang et al. [34] analyzed the soil water deficit under different types of land cover in a hilly catchment located in Dingxi City, and the results showed that compared to restored forested land and bushland, grassland had no soil water deficit. Du et al. [35] studied the plant diversity under various land use patterns in Yanchi County in the northeast part of Wuzhong City and suggested "artificial fencing" as an effective measure for regenerating the degraded grassland vegetation compared with returning farmland to forest or woody grasslands/bushlands. Dai et al. [36] also compared the effect of the passive restoration of Artemisia ordosica and the artificial restoration of Caragana intermedia in the Hobq Sandy Land and suggested that passive restoration was more appropriate in this region. By comparing the different restoration vegetation types used in the Liudaogou catchment in the northern part of Yulin City, Li et al. [37] suggested that secondary natural grassland restoration through the establishment of artificial grassland might be best for ameliorating the soil structure. Changwu County, which is located in Xianyang City, is a typical area for returning farmland to forested land, and Wen et al. [38] documented that the restoration project has had a positive effect on the vegetation in this county. According to the regionalization scheme in this study, the suggested restoration vegetation types in the above locations were consistent with these studies. Overall, the above results indicate that the new regionalization has considerable potential for providing scientific assistance in vegetation restoration on the Loess Plateau.

In addition, existing studies about vegetation restoration regionalization identified vegetation zones by theoretically matching plant characteristics to local climate and soil properties using designed simulation models. In fact, when the vegetation is planted in a given location, the situation may be different from the simulation condition because of the error of the model or the special regional microclimate. This study created a regionalization scheme based on investigating the vegetation growth status during the vegetation restoration project. Science it is based on the actual vegetation restoration, it could be more accurate than the existing method. Furthermore, the GTGP is a long-term ecological project. When considering vegetation restoration on the Loess Plateau in the future, implementation of the new regionalization scheme is suggested, with a consideration of the economic benefits. Sustainable vegetation restoration can be obtained when the balance between ecological function and economic benefit is found.

4.2. Potential Applications of the Proposed Method to Other Regions

As stated previously, many restoration projects were launched to restore degraded ecosystems around the world. This study only took the Loess Plateau as an example to show the importance of formulating an effective restoration policy by analyzing historical data using remote sensing technology and other related tools. Thus, the method used to design the regionalization scheme in this study can also be used in analogous areas to examine whether the restoration project was conducted reasonably and to design a restoration regionalization scheme to inform the selection of the proper vegetation type for a given location.

5. Conclusions

Using remote sensing data to investigate the vegetation growth status in periods before and after the historical vegetation restoration activities, a method was proposed to help select the proper vegetation type for a better vegetation restoration in the future. Taking the Loess Plateau as an example, the method was used to suggest a regionalization scheme for vegetation restoration. Based on the new regionalization scheme, forested lands and woody grasslands/bushlands are only suitable in the humid and sub-humid areas of the southeastern part of the Loess Plateau, and grasslands represent the most appropriate vegetation type for the semi-arid region in the central area and part of the western plateau. In contrast, the northwestern part of the Loess Plateau is only suitable for planting xerophytic shrublands/semi-shrublands in places with sufficient water; otherwise, these areas should be left as passive restoration lands. Using independent data, the new regionalization scheme displayed good validation results, with an average potential classification accuracy value of 81.81%. Compared with the existing Chinese eco-geographical regionalization, the new regionalization scheme performed better in terms of its potential for guiding vegetation restoration activities. Additionally, the proposed regionalization method can be adopted in analogous areas worldwide to help make design effective vegetation restoration.

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