Monitoring rangeland degradation using a novel Local NPP Scaling based scheme on the "Three-Rivers Headwaters" region, the hinterland of the Qinghai-Tibetan Plateau

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Abstract—the "Three-River Headwaters" region (TRHR) rangeland ecosystem is extremely sensitive and fragile, and in recent years has undergone continuous degradation. The vast area and severe nature conditions inhibit data acquisition and field experiments, resulting in different understandings about the spatial characteristics and dynamics of rangeland degradation in the region. Therefore, reliable monitoring method of rangeland degradation is urgently needed for the rangeland protection and management. In this paper, a novel rangeland degradation monitoring scheme based on Local NPP Scaling (LNS) was suggested; A suitable partition program of rangeland productivity unit was set up by using Analytical Hierarchy Process (AHP); And the spatio-temporal pattern of degradation in 1990 and 2004 were revealed and validated by multiple data sets including field measured data, land use and land cover maps and the discoveries of other researches. This research provides basis in the avoidance of intensive field work and labor costs for visual interpretation of remote sensing image as used before. The results show that the percentage of rangeland degradation is 32.86% in 1990 and 36.7% in 2004, indicating increased 3.84% over 15 years. The eastern part of the study area, consisting of Banma, Gadê, Henan, Jigzhi, Tongde and Zêkog, had minimal deterioration. The most severely degraded area is Qumarlêb. The deteriorated rangeland accounted for 63.33% of the total area in 1990 and increased to 77.47% in 2004. The sum of degradation percentage at Madoi and Chindu is more than 40%. It is found that the results on the spatio-temporal distribution of the rangeland degradation at TRHR are reasonable through various verification,, and the approach we suggested is effective in rangeland degradation monitoring in inaccessible region with severe environment. According to the author, similar research reports are not accessible yet.

Keywords: Rangeland degradation; Remote Sensing Monitoring; Scheme based on LNS; Rangeland Productivity Unit; Multiple data sets verification; Qinghai-Tibetan Plateau; "Three-River Headwaters" Region (TRHR)

1. Introduction

Rangeland ecosystem, part of the terrestrial ecosystem, plays an important role in maintaining the ecological environment.

Rangeland degradation resulted in the decrease of productivity and economic potential, environmental deterioration and the decline of biodiversity and complexity. Moreover, this even leads to the weakening or loss of the restoration function of ecosystem (Chen and Jiang, 2003; Feng et al., 2006; Wang et al., 2004).

Usually, biological indicators and soil characteristics comprise the main indices that indicate rangeland degradation. However, it is difficult to obtain a soil characteristic index on a regional scale. Consequently, biological indicators are commonly used to evaluate rangeland degradation at national or large scales. Remote sensing (RS) records the spectral response of the degraded rangeland. There are multi-sources remote sensing data with time series characteristics, and we can derive the biophysical and ecological parameters of degraded rangeland from them. Remote sensing is widely used in rangeland degradation studies (Liu et al., 2008; Wang et al., 2004; Martínez and Gilabert, 2009; Jafari et al., 2008; Numata et al., 2007; Geerken and Ilaiwi, 2004; Gao et al. 2010). At present, some principal methods are as follows: (1) Extraction of rangeland degradation information based on remote sensing image classification; (2) Direct comparison. This method takes non-degraded rangeland as a reference through the comparison of characteristic parameters observed directly (such as biomass, vegetation coverage, edible forage, NDVI, NPP, soil physical and chemical properties indices) to analyze the degradation/restoration of rangeland (Numata et al., 2007; Liu and Zha, 2004; Röder et al., 2008); (3) Monitoring rangeland degradation based on time series analysis of remote sensing. In recent years, these methods have caught widespread attention, and mainly include rainfall use efficiency (RUE)(Wessels et al., 2006; Prince et al., 2004; Paruelo et al., 1999; Holm et al., 2003; Gao et al., 2005; Bai et al., 2008a) and residual trends (RESTREND)(Evans and Geerken, 2004; Wessels et al., 2007; Xu et al., 2010; Cao, 2006; Eckert et al., 2015); (4) Local NPP (the actual Net Primary Productivity) Scaling (Wessels et al., 2007; Wessels et al., 2008; Prince et al., 2009).

In order to detect degradation, reference value or baseline information is necessary for researchers and users to judge whether degradation occurs or not. Although remote sensing data can be used to monitor degradation, they are available only for three decades (for example, AVHRR is from 1981 to present). The processes of the degradation might begin before the existence of remote sensing data. Therefore, reference value of non-degraded rangeland is difficult to obtain. Local NPP Scaling (LNS) (Wessels et al., 2007; Wessels et al., 2008) takes spatial reference as the alternative of temporal reference and the 90th percentile of NPP in a productivity unit with the same productivity level is used as a non-degraded rangeland reference value. To establish this, the effects of difference in terrain types, soil types and climate fluctuation have to be considered. LNS can be used to detect the degradation occurred before the start satellite remote sensing data acquisition. Moreover, this method can effectively avoid the problems caused by inconformity of productivity level, such as misjudging the low-potential NPP area as a degradation area through the partition of the rangeland productivity unit. In this research, LNS will be adopted to monitor the rangeland degradation of the TRHR.

The TRHR is located in the hinterland of the Qinghai-Tibetan Plateau in the south of the Qinghai Province. A large number of observations and research results indicate that in recent decades, significant degradation phenomena, such as the decline of rangeland productivity, severe soil erosion, reduced water yield year by year and sharply shrinking biological diversity have occurred (Liu et al., 2008; Wang and Cheng, 2001; Zhang et al., 2006; Ma, 2006; Ren et al. 2013; Gao et al. 2010). The ecological system adjustment ability in this area is very weak on account of strong surface weathering, thin solum, coarse texture, cold climate, and short plant growth period (Zhang et al. 2015; Zheng et al., 2002).

Presently there are many definitions of rangeland degradation, with debates on the mechanism of rangeland degradation and its causes. For instance, rangeland degradation equilibrium and non-equilibrium viewpoints coexist (Vetter, 2005); and the mechanism of rangeland degradation formation remains to be clarified (Chen and Jiang, 2003; Harris, 2010; Veron et al., 2006). Research implemented in Northern Tibet of China found out that during 1981–2004, precipitation variability has benefited the recovery and protection of the grasslands, while temperature and solar radiation variability exacerbates grassland degradation in Northern Tibet (Gao et al., 2010). Research also showed that regional climate change has produced more negative than positive changes on alpine grasslands. The alpine grasslands significantly benefited under a moderate intensity of grazing activities. With the increased human activity, negative changes in NDVI are pervasive in Northern Tibet (Gao et al., 2013). The study at the Mt. Qomomagma National Nature Preserve in the southern Tibetan Plateau illustrated that climate changes have different effects on alpine grassland changes in different areas of the Tibetan Plateau (Gao et al., 2014). The research on the changes of aridity index and reference evapotranspiration over the central and eastern Tibetan Plateau in China during 1960-2012 had also found that these ecohydrological factors play an important role in the degradation of grassland (Wang et al., 2014).

Rangeland degradation monitoring problems have been identified at the region (Wang et al., 2004; Liu et al., 2008; Tu et al., 1999; Liu et al., 2010; Du and Zhang, 2006; Xu et al., 2011; Chen et al., 1998). Field investigation and visual interpretation are mainly used in the monitoring studies within local regions. The methods applied entails heavy workload, long cycle and strong subjectivity. Therefore, scientific and effective monitoring of rangeland degradation requires further study in the TRHR. This study aims to use remote sensing data and relevant auxiliary data to study rangeland degradation monitoring of the TRHR by using improved LNS scheme. Spatial distribution information of the rangeland degradation in 1990 and 2004 were extracted in the study area. And some analysis and remarks are given finally.

2. Data and study area

2.1.data

NOAA/AVHRR-NDVI and MODIS-NDVI datasets respectively acquired in 1990 and 2004 were combined with other datasets to estimate the NPP of the two periods in the study area. In order to verify, the relevant data was also collected about

August 2009. The AVHRR-NDVI was downloaded from the National Natural Science Foundation Committee, Environmental, and Ecological Science Data Center for West China (i.e. http://westdc.westgis.ac.cn). The datasets are 10-day maximum NDVI composites of the AVHRR sensor with a spatial resolution of 8km. The Terra/MODIS-NDVI datasets downloaded from NASA WIST (i.e. http://wist.echo.nasa.gov/api/) is a 16-day maximum NDVI composite with a spatial resolution of 250m. The following preprocessing was carried out on the images: projection transformations, monthly maximum NDVI synthesis and scale conversion. Furthermore, the correlation analysis of the overlapping period of the two kinds NDVI data in 2000 to 2001 was carried out, and the linear regression equation was established to amend the errors between the two different sensors.

Daily ground vapour pressure, surface temperature, percentage of sunshine, sunshine duration and precipitation were used. Vapour pressure and percentage of sunshine were spatially interpolated using the Kriging method. Due to the complexity of the terrain and the influence of altitude on surface temperature, a multiple-factor regression method was used to establish the regression model for the surface temperature rasterization.

Vector maps including the administrative boundaries, rangeland natural reserve, rangeland types, Digital Elevation Models (DEM) with 100 meter resolution, land use and land cover maps and field survey data on rangeland degradation in the TRHR were used. Data on soil type and texture were provided by the Institute of Soil Science of the Chinese Academy of Sciences and the Qinghai Environmental Monitoring Center.

Field investigation was conducted on August 6 to 19, 2009. At each site, a 50 centimeter multiply by 50 centimeter quadrat was set up. GPS was used to record the coordinates of the center of the quadrat, and the vegetation coverage, community constitution, dominant species and biomass were also recorded. The degree of rangeland degradation was recorded according to the experts' field experience, vegetation fractional cover and existing research results (Pan, 2007; Yu et al. 2012). These data were mainly used to validate the monitoring results, including 15 sample points of measured biomass obtained in Madoi, which were transformed as measured NPP to compare with the NPP estimated by CASA (the Carnegie-Ames-Stanford Approach） model on August 2009; Sites of 99 sample points of rangeland degradation degree measured in Madoi, Chindu, Yushu, the south of Qumarlêb and the northeast of Zhidoi are shown in Fig.1. For more details, please refer to 4.3.3.

Land use/cover maps in 1990 and 2005 used to verify degradation are downloaded from the Chinese Academy of Environmental Science data center (http://www.resdc.cn). Data set includes the late 1980s (1990), 1995, 2000, 2005 and 2010 five periods data. Data set was generated by visual interpretation using corresponding dates Landsat TM / ETM+ remote sensing images. Land use/cover is classified into six primary types (including cultivated land, woodland, grassland, water, residential areas and unused areas) and 25 secondary types.

2.2. Study area

The TRHR is the source of the Yangtze, the Yellow, and the Lantsang Rivers. It is located between latitudes 31°39'N and 36°12'N

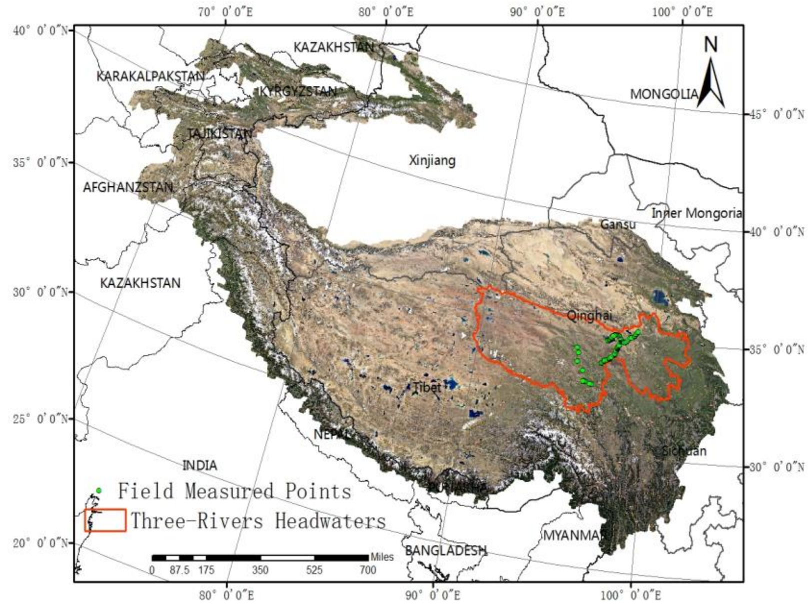


Fig.1. Geographical location of the "Three-River Headwaters" region and field investigation sites.

and longitudes 89°45'E and 102°23'E (Fig.1). It covers an area of approximately 363,000 km^2. The TRHR is called the "Chinese water tower" and it is the largest natural reserve in China. Its high altitude makes it an ecologically sensitive region with a wide variety of ecosystems and living organisms. The region accounts for 50.3% of the total land area of the Qinghai province (Fan et al., 2010); and its administrative areas include Gadê, Jigzhi, Banma, Chindu, Madoi, Darlag, Maqên, Zadoi, Zhidoi, Qumarlêb, Nangqên, Yushu, Xinghai, Zêkog, Tongde, Henan, Mongol Autonomous County and Tanggulashan town. The entire region is surrounded by massive mountain ranges. The elevation ranges from 2800 meter to 6564 meter with an average altitude over 4000 meter.

3. Methods

Vegetation net primary productivity (NPP) was first estimated and analyzed (Potter et al., 1993; Wang et al., 2009; Zhou et al., 2004), followed by partitioning the rangeland productivity units using PI (the productivity index) according to the terrain, climate and soil type (Lu and Yu, 2004). The reasonability of the results was analyzed. Finally, the LNS were derived using estimated NPP and productivity units, and the spatial distribution of degraded rangeland in the years 1990 and 2004 was obtained. The methodological flowchart is shown in Fig.2. The detailed description is as follows.

3.1. NPP estimation by CASA Model

NPP represents the organic compounds accumulated in a unit area in a unit time interval. It is the key link of carbon biogeochemical cycle and also is an important indicator of ecosystem function condition. It reflects the impacts of climate change

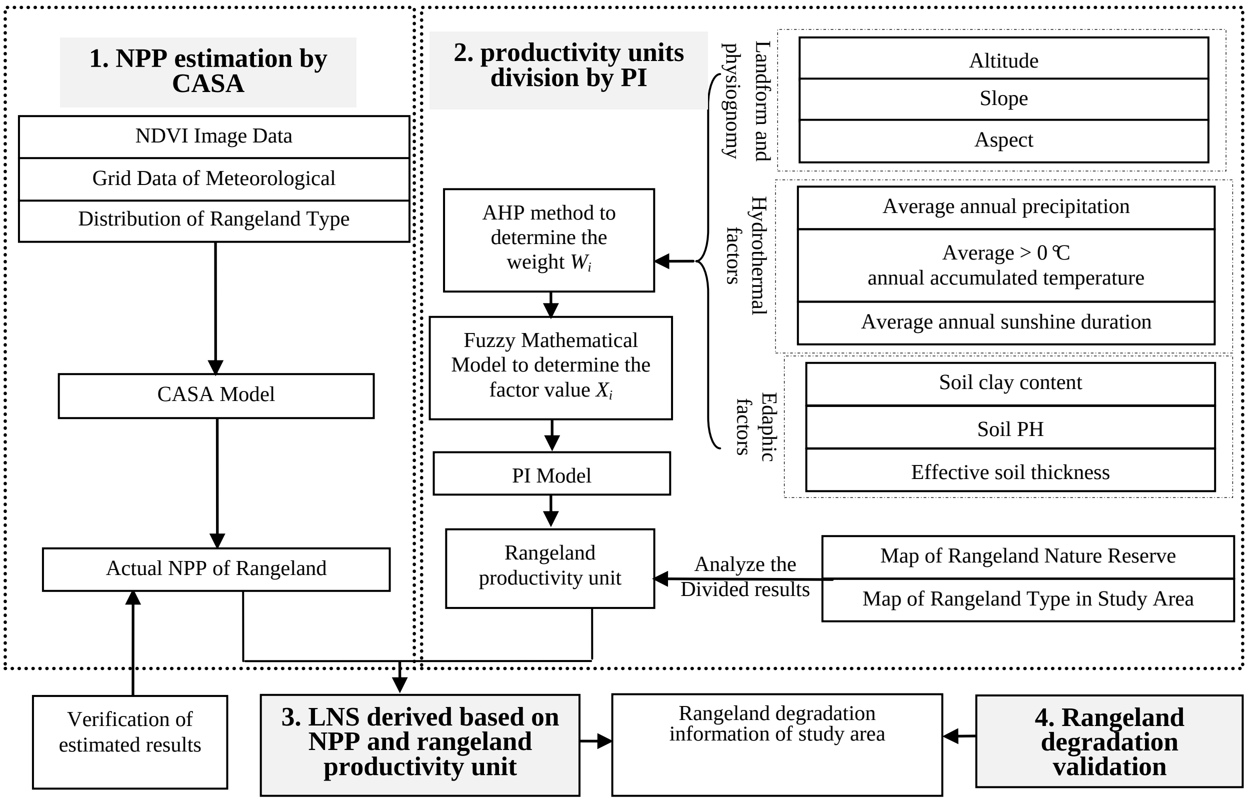


Fig.2. an novel rangeland degradation monitoring scheme based on Local NPP Scaling

and human activities on terrestrial vegetation. The CASA model (Potter et al., 1993) was used to simulate the rangeland NPP in the study area. The parameters used were adopted from previous relevant research reports (Potter et al., 1993; Zhu et al., 2005; Sellers et al., 1994; Shao et al., 2009; Cui, 2004; Lu and Yu, 2004; Gong et al., 1993; Chen et al., 2001; Yang and Qiu, 2002; Running et al., 2000). The monthly NPP of growing season (May to September) was estimated according to the maximum monthly NDVI, and then was accumulated to obtain NPP value of the year. In CASA, maximum light-use efficiency ε^* was set to 0.389 g C/MJ, while ε^* is set to 0.604 g C/MJ in the paper in light of the study by Running et al. (2000).

3.2. Partition of the rangeland productivity unit

Potential productivity of rangeland, which refers to the level of productive achieved under certain conditions, mainly reflects the natural production attributes of the rangeland. Studies showed that climate and other environmental factors are the key factors to determine the productivity of rangeland (Bai et al., 2008b; Yang et al., 2008).

Solar radiation, temperature and precipitation play a decisive role in the normal germination and growth of the grass plants (Qian et al., 2010). Vegetation growth is accompanied by photosynthesis, and the sun is the only source of energy for photosynthesis. The number of sunshine hours directly affects the yield of forage. When the temperature is stably greater than zero degrees Celsius, grass vegetation begins to grow. Greater than zero degree Celsius annual accumulated temperature is commonly used to study the effect of accumulated temperature on rangeland productivity. The TRHR is arid and semi arid region. The average annual rainfall in most areas is less than 500 mm. Coupled with a large part of the region is mountainous terrain, the groundwater is not rich. Therefore, precipitation is the most basic water resources in the area, and it is also the dominant factor affecting the yield of rangeland. Li et al. (2011) indicated that the precipitation and air temperature with similar influence on the vegetation growth in the TRHR. There are some differences in relationship between rangeland biomass and climate for different rangeland type. It is found that the precipitation conditions are better than the temperature conditions in the growth season; therefore, the influence of temperature on the alpine rangeland is relatively large. Nevertheless, biomass fluctuation of more arid desert steppe and typical steppe is closely related to precipitation and the high mountain vegetation was more inhibited by precipitation (Li et al. 2001, Chen et al. 2010, Ma et al., 2010). Otherwise, some researchers thought that temperature and solar radiation became dominant factors in driving NPP change in the Tibetan Plateau from 2000 to 2012 (Xu et al.,2016). It is also found that radiation is the climate factor with the greatest influence on NPP interannual variation from 1982 to 2012 and the factor that restricted NPP increase changed from temperature and radiation to precipitation (Zhang et al., 2016) . Due to the differences of spatial and temporal scales and the data used of researches mentioned above and the complexity of the problems, there are some differences in the understanding of the main climatic factors that affect the productivity of rangeland vegetation in this area. Based on the above analysis, many years of average annual precipitation, average greater than zero degrees Celsius annual accumulated temperature and the average growth season sunshine hours are used as dominant climate indicators for rangeland potential productivity assessment. In this way, the long-term relative stability of hydrothermal factor may be ensured, and the distribution of hydrothermal conditions of rangeland in the area may be more scientifically depicted.

The influence of topography and landform conditions on the productivity of rangeland is mainly reflected in three aspects, namely, elevation, slope and aspect. The distribution of alpine meadow is in the altitude range of 3500-4500 meter, and the alpine rangeland is in 4000-4500 meter in the TRHR. Micro topography plays an important role in the redistribution of hydrothermal, and it also influences the formation of soil and the production of rangeland. The altitude affects rangeland productivity level through controlling the distribution of precipitation and accumulated temperature. Slope mainly affects the redistribution of precipitation and water holding capacity, and with the increase of slope gradient, soil erosion is enhanced. Different light intensities in different slope aspect lead to receive different amount of solar radiation, so that there are differences of hydrothermal conditions and the surface temperature, and thereby affecting the soil evaporation and grass transpiration. All these have profound impact on the formation and distribution of mountain rangeland (Wang et al., 2013; Hou et al., 2013; Shao et al., 2008; Zhang et al., 2006).

The soil environment is the basic environment of rangeland ecosystem, which is closely related to the productivity of grassland. Soils with different structure and physical and chemical properties will affect the productivity of rangeland in different degrees. The thickness of soil layer determines the depth of the root activity of the vegetation. The soil texture mainly includes sandy loam and clay loam (represented by soil clay content). The support function of different soil texture to rangeland ecosystem is different.

If the soil is sandy loam, the gap of the soil in grass root layer is large, which is conducive to the infiltration of precipitation（Shi et al.,2015）.

Through the above analysis and the availability of data, this paper chooses hydrothermal factors (such as average annual precipitation, average greater than zero degree Celsius annual accumulated temperature and annual average sunshine duration), landform and physiognomy (such as altitude, slope and aspect), and edaphic factors (such as soil clay content, effective soil thickness and soil PH value) as the evaluation factors to assess the production potentiality of rangeland. This will provide a more effective means of extracting rangeland degradation information by evaluating the rangeland within the same production capacity unit. The introduction of the rangeland productivity unit effectively avoids misjudging the low potential productivity rangeland as a deteriorated rangeland.

For rangeland productivity evaluation research, the productivity index (PI) which reflects different levels of productivity was used. This was established based on the factor membership values and their weights in the PI evaluation model. The model is shown below:

$$PI = \sum_{i=1}^{n} (X_i \times W_i) \tag{1}$$

Where X_i (i=1, 2, 3,……n) is the productivity membership value of the evaluation factors, and W_i is weight ranges from 0 to 1 for each corresponding evaluation factor.

The suitability membership function values X_i of each factor were calculated using the fuzzy mathematics in terms of its contribution to NPP (Zhang et al., 2006; Shao et al., 2009; Cui, 2004). Take average annual precipitation（P）as an example, its membership function value calculation formulation is as follows:

$$X_i = \begin{cases} 1 & P > 500\text{mm} \\ \frac{P-200}{300} & 200\text{mm} \leqslant P \leqslant 500\text{mm} \\ 0 & P: < 200\text{mm} \end{cases} \tag{2}$$

The selection of evaluation methods for W_i is very important in the rangeland productivity evaluation process. The AHP was chosen for this research to compute weight W_i based on multiple evaluation indicators (Gong et al., 2010). It is widely used in geological studies (Lu and Yu, 2004). Take the alpine meadow as an example, the weights of each influence factor determined by AHP (Analytical Hierarchy Process) are shown in Table 1:

Table 1 The weights of multiple evaluation indicators for the *alpine meadow*

Influence factor	**Weight**
Altitude	0.020
Slope	0.036
Aspect	0.066
Average annual precipitation	0.349
Average>0 ℃ Annual Accumulated temperature	0.133
Annual Average Sunshine Duration	0.076
Soil Clay Content	0.172
Effective Soil Thickness	0.052
Soil PH	0.095

3.3. LNS derived based on NPP and rangeland productivity unit

The most difficult aspect of estimating the NPP for degradation monitoring is the uncertainty in choosing the reference value for the NPP. The prerequisite is that non-degraded rangeland exists in the habitat unit. The NPP of non-degraded rangeland, namely potential rangeland NPP, refers to the NPP of rangeland with good growth conditions without the influence of natural or man-made factors. According to National standard (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2004), the reference value for evaluating rangeland degradation should be based on the vegetation characteristics, the soil regime in non-degraded rangeland and the types of grass.

Wessels et al.(2007; 2008) and Prince et al.(2009) studied vegetation degradation using the NPP index for many years. They used the 90th percentile of the actual NPP as the potential NPP in the unit with the same productivity level. This is performed by extracting rangeland NPP values in all rangeland productivity units in each year and finding the 90th and 10th percentiles of the actual NPP in each unit, and then assigning 100 and 0 to them.

The LNS method has two aspects: (1) it is based on the unit with the same rangeland productivity level; and (2) non-degraded rangeland exists in the rangeland production capacity unit. In this paper, a vector map of the rangeland reserve (regarded them might include non-degraded rangeland area) was overlaid on the rangeland production capacity unit map to determine whether the reserve exists in each productivity unit. The NPP value of pixels in the same unit were compared with their potential NPP (namely, the 90th percentile of the actual NPP in the unit), respectively. If the NPP is lower than the potential NPP, the rangeland has degraded; and the closer the two values are, the better the grass growth is. The LNS method is described as following:

The distribution frequency of NPP value is computed firstly for each productivity unit, respectively. Then lets $q_{0.1}$ to represent the 10th percentile value of NPP for one productivity unit, $q_{0.9}$ to represent the 90th percentile value of NPP for the same productivity unit, q_i to represent the NPP value of one pixel in the productivity unit and it doesn't equal to the $q_{0.1}$ and $q_{0.9}$, and LNS_i to represent the NPP value after scaling.

If $q_i \le q_{0.1}$, then $LNS_i = 0$; and

If $q_i \ge q_{0.9}$ then $LNS_i = 100$.

Suppose $m = 100/(q_{0.9} - q_{0.1})$ and $c = -1 \times (m \times q_{0.1})$,

then $LNS_i = mq_i + c$

3.4 Validation of the rangeland degradation

Multiple data sets were employed to validate the result, including field investigation data, land use and land cover maps and discovery from other research. A total of 99 field observation data was used to verify the degree of rangeland degradation. Land use and land cover maps in 1990 and 2005 were employed for intercomparison of spatial patterns of LNS, degradation and the change of degradation for whole study region and typical area, such as Maduo County. Research achievement by Liu et al. (2008) was used for intercomparison of degradation area of each County.

The degree of rangeland degradation for field site was determined based on field measured vegetation fractional cover data, existing research results (Pan, 2007; Yu et al. 2012) and the experts' field experience. Vegetation fractional cover includes fraction of bare soil, edible grass and poisonous weeds. According to the research of Pan (2007) and Yu et al. (2012), the basis for the classification of rangeland degradation is shown in the Table 2.

Table 2 Degradation degree judgment index of alpine meadow rangeland

Degradation level	Edible forage ratio（%）	Poisonous weeds ratio（%）	Bare soil ratio（%）
Not degenerate	≥72	≤15	≤10
Mild degradation	55-72	15-35	10-25
Moderate egradation	35-55	35-50	25-50
Severe degradation	20-35	50-75	45-80
Extreme degradation	≤20	≥75	≥80

4. Results

4.1. Verification and analysis of NPP simulation results

The synchronous measurement of NPP provides the best data for verifying modeled estimated results. In this paper, 15 points of measured biomass data obtained in August 2009 in Madoi were transformed as measured NPP (Gao et al., 2007) and compared with the estimated NPP on August, 2009 (shown in Fig.3).

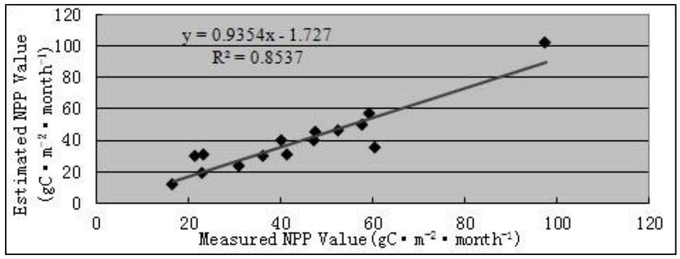


Fig.3. Comparison of the measured and estimated NPP on August, 2009.

From Fig. 3, the estimated value is slightly lower than the measured value. The correlation coefficient values revealed that the CASA model had a relatively high predictive accuracy, with r > 0.84 (P<0.05). The CASA model proved practical for simulating the rangeland NPP in the TRHR.

Fig.4 shows the spatial distribution of the rangeland NPP in 1990 and 2004. The 1990 rangeland NPP value is relatively low, ranging from 19.8 to 485.9gCm^{-2}yr^{-1}, with an average value of 139.4gCm^{-2}yr^{-1}. The 2004 rangeland NPP value is relatively high, ranging from 23.8 to 502.4gCm^{-2}yr^{-1}, with an average value of 159.7gCm^{-2}yr^{-1}. NPP is mainly influenced by temperature and precipitation, and the statistical analysis showed that the precipitation is higher in 2004 than that in 1990 according to measured data at 15 meteorological stations in the TRHR. The mean temperature of the growing season (i.e. April to September) in 2004 was also higher than that in 1990. The dual roles of precipitation and the increasing temperature in the growing season provides wet environment conducive for grass growth. This directly affected the performance of the increased rangeland NPP.

4.2. Analysis the results of rangeland productivity unit partition

The spatial distribution of the rangeland PI in the TRHR is shown in Fig.5. The PI indicates potential rangeland production capability determined by terrain, climate and soil characteristics which is different from the actual rangeland productivity expressed by NPP. The PI is relatively high in the eastern and southern areas and relatively low in the western and northern areas.

Based on the rangeland productivity level, the alpine meadow and alpine steppe rangelands were divided into 11 and 5 units, respectively, and the former was coded from 1 to 11，the latter was coded from 12 to 16. The sizes of *temperate desert steppe*, *warm steppe*, *temperate montane meadow* and *marsh* rangeland were relatively small and each one had the same productivity level constituted 4 independent productivity units, numbered from 17 to 20. The distribution of the rangeland productivity units is shown in Fig. 6.

Rangeland productivity units represent the same productivity level of geographical units. The rationality analysis of the unit division is as follows: (1) if different rangeland types in the same unit, they may have the same level of productivity ((Jiang et al., 2007)). Extracting the corresponding NPP value using the rangeland type vector map, and by contrast analysis it was found that different rangeland types in the same unit are of close 10th and 90th percentiles of the NPP value; As shown in Table 3, six kinds of different "grassland type " contained in unit 3 have similar NPP of the 90th and 10th Percentile values in 2004, and this may indicate that the grassland PI estimation and grassland productivity unit division based on it is reasonable.

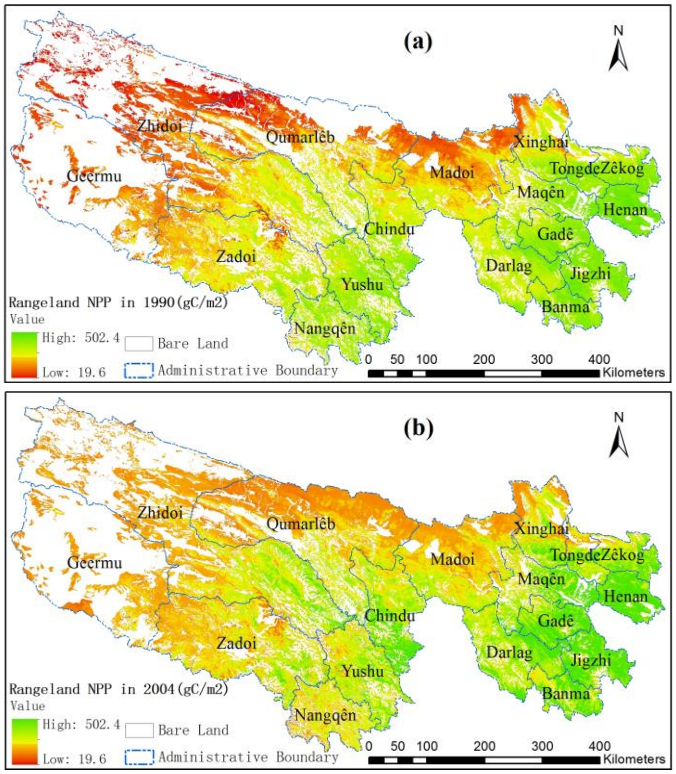


Fig.4. Annual rangeland NPP in the "Three-River Headwaters" Region. (a) Rangeland NPP in 1990 and (b) Rangeland NPP in 2004

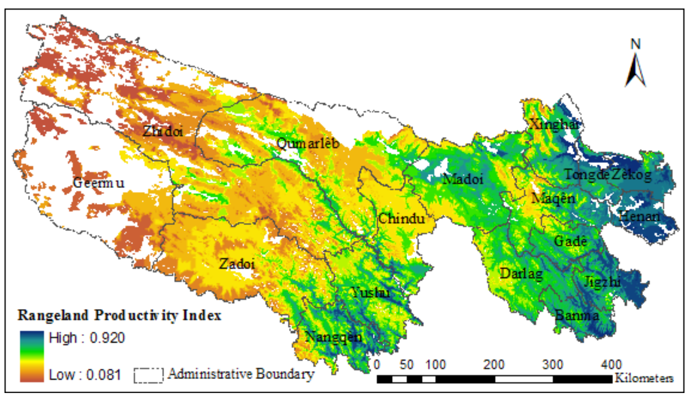


Fig.5. Rangeland Productivity Index (PI) distribution map.

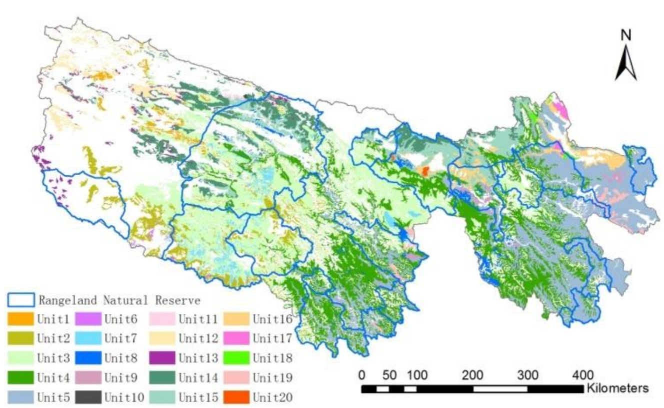


Fig.6. Rangeland productivity unit distribution in the study area.

Table 3 comparison of different "grassland type "productivity within the productivity unit 3 (NPP unit gC.m2.yr-1)

grassland type	90th Percentile of NPP	10th Percentile of NPP
Stipa purpurea	365.32	125.90
Stipa breviflora Griseb. + Stipa purpurea	370.55	135.13
Stipa purpurea + forbs	334.71	109.52
kobresia pygmaea + forbs	392.66	98.24
Kobresia tibetica	358.02	125.22
kobresia pygmaea	389.90	127.86

And (2) whether the same rangeland type is distributed in the same productivity unit or not. Based on criteria (2), *the stipa purpurea and kobresia capillifolia* rangeland types were overlaid on the rangeland productivity unit distribution map; and it is found that they are within the same productivity unit, respectively (Fig. 7).

Based on the above mentioned analysis, the results of the Rangeland Productivity Unit division is thought to be reasonable. Statistics of the NPP values in each rangeland productivity unit is shown in Table 4.

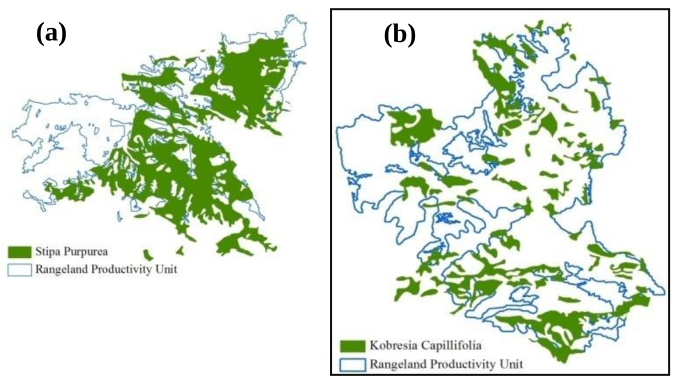


Fig.7. Comparison between rangeland type distribution and rangeland productivity unit. (a) Distribution of *stipa purpurea* type ; and (b) Distribution of *kobresia capillifolia* type

4.3. Monitoring and Analysis of Rangeland Degradation

4.3.1. LNS estimation

The rangeland LNS value distribution map is shown in Fig. 8. Statistical results of the 10th and 90th percentiles of the NPP values in each rangeland productivity unit are shown in Table 4. Comparing and analyzing the rangeland LNS value distribution map, it is found that the LNS value in eastern part in 2004 is lower than that in 1990. The results are particularly evident in the Henan, Jigzhi, Banma, Gadê and Tongde rangelands. The results indicate that the rangeland degradation is most significant in 2004. In the western part, the LNS in northern Qumarlêb, northwest Zhidoi and Tanggulashan town in 2004 shows an upward trend, which indicates a decline in the degradation.

4.3.2. Grade of rangeland degradation

In this paper, the LNS index was used as an evaluation index for the rangeland degradation within a range of 0 to 100. The lower the LNS index value is, the more serious the degradation is and vice-versa. Using national standards as a benchmark and the

Table 4 Statistics of the NPP value in each rangeland productivity unit

NO.	**rangeland type**	**Rangeland NPP in 1990**		**Rangeland NPP in 2004**	
		10^{th} Percentile	90^{th} Percentile	10^{th} Percentile	90^{th} Percentile
1	*subalpine meadow*	18.33	89.89	25.30	97.62
2	*subalpine meadow*	23.35	105.31	59.77	137.09
3	*subalpine meadow*	21.22	299.53	56.81	310.02
4	*subalpine meadow*	75.91	414.05	102.21	462.54
5	*subalpine meadow*	199.50	440.62	289.35	498.70
6	*swamp alpine meadow*	25.65	145.66	39.12	149.55
7	*swamp alpine meadow*	21.32	222.37	35.31	250.66
8	*swamp alpine meadow*	76.57	369.55	82.62	425.34
9	*swamp alpine meadow*	65.03	435.54	55.10	408.05
10	*salinized alpine meadow*	74.58	92.28	80.19	100.03
11	*salinized alpine meadow*	95.96	136.07	89.66	141.39
12	*alpine steppe*	20.15	43.72	31.02	60.43
13	*alpine steppe*	33.61	59.50	28.30	68.84
14	*alpine steppe*	29.77	97.67	41.40	108.06
15	*alpine steppe*	45.66	118.62	38.99	132.49
16	*alpine steppe*	83.47	208.57	61.47	214.05
17	*temperate desert steppe*	76.30	105.18	66.82	146.80
18	*warm steppe*	69.55	110.41	81.31	134.11
19	*temperate montane meadow*	230.65	428.47	214.22	432.48
20	*marsh*	188.70	398.47	171.14	370.05

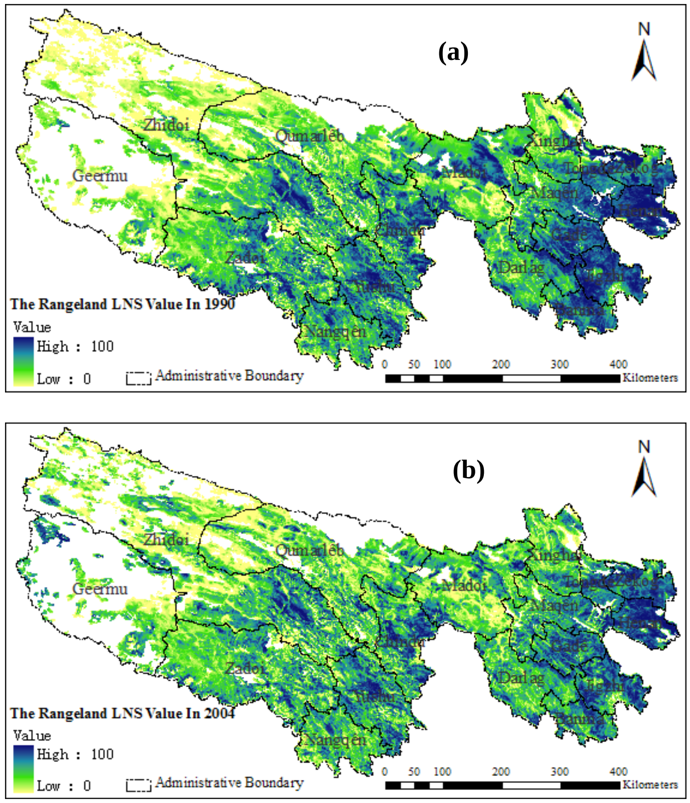
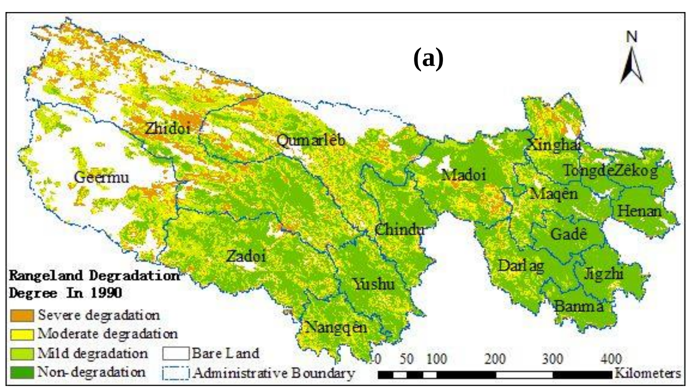


Fig.8. Rangeland LNS value distribution map in the TRHR: (a) LNS distribution map in 1990; and (b) LNS distribution map in 2004.

classification standards of rangeland degradation by Li (1997), Liu et al. (2008) and Jiang et al. (2007), the LNS value was divided into four groups (Fig.9): (1) ≥90, meaning non-degradation; (2) 70~90, meaning mild degradation; (3) 50~70, meaning moderate degradation; and (4) ≤50, meaning severe degradation. Validating the results with field measurements, it is found that the degree of degradation were in consistent with the observed results (See 4.3.3 section and Table 4).



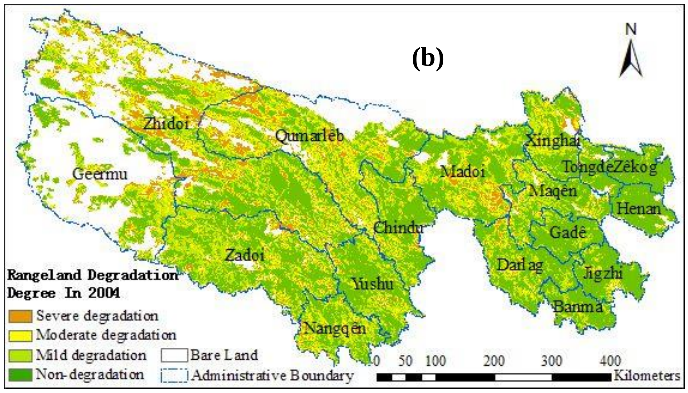


Fig.9. Distribution map of rangeland degradation in the "Three-River Headwaters" Region. (a)Degradation map in 1990; and (b) Degradation map in 2004.

4.3.3. Verification of rangeland degradation grade

Relatively serious degraded areas such as Madoi, Chindu, Yushu, the south of Qumarlêb and the northeast of Zhidoi, were validated by field observation. A total of 99 measured points were used (Fig.1). The measurements of the rangeland degradation samples are described as non-degradation, mild, moderate, severe, and black beach. Black beach refers to the large areas with secondary bare land caused by wind and water erosion from alpine meadow. It is termed "black beach" due to its bare black soil. It can be found between heights of 3600~4800m in the Qinghai-Tibet Plateau which has a hilly natural landscape caused by the degradation of native vegetation. According to definition, black beach represents severe degradation. Results of the LNS value in 2004 were corresponded to the measured points. The comparison between the two datasets was grouped as exact match, slight deviation, large deviation and fundamental misalignment. 85 points were in exact match, 3 were misaligned and 1 was largely deviated. The verification accuracy was 85.9%, and 25 points were selected randomly as shown in Table 5. The accuracy of the validation result is relatively high and indicates that the LNS method is suitable for monitoring rangeland degradation in the TRHR.

4.3.4. Statistical analysis of degradation

The statistical results of the deteriorated rangeland area in the TRHR in 1990 and 2004 are shown in Fig. 10. The degraded rangeland area accounts for 32.86% of the total area in 1990s, and among which the mild degradation area is 17.50%, moderate degradation area is 11.15% and severe degradation area is 4.10%. The total degraded rangeland area had a slight upward trend in 2004 compared with the early 1990s; from 32.86% in 1990s to 36.70% in 2004. The percentage ratios of mild, moderate and severe degradation were 21.1%, 12.5% and 3.09% respectively. The rangeland with mild degradation dominated followed by moderate degradation. The ratio of severe degradation is relatively small. From the analysis, it was found that the rangeland degradation situation is severe in the TRHR. Moderate and severe degradation exist in the entire area.

Table 5 Verification of part of research results in 2004

ID	Latitude	Longitude	Degradation degree by field	LNS value	Degradation degree by LNS	Verification results
1	34.51	95.55	Black beach	55.68	Moderate degradation	Slight deviation
2	34.37	95.68	Black beach	0.89	Severe degradation	Exact match
3	34.36	95.69	Black beach	28.84	Severe degradation	Exact match
4	33.77	95.80	Black beach	45.40	Severe degradation	Exact match
5	33.36	96.24	Black beach	36.84	Severe degradation	Exact match
6	33.35	96.24	Black beach	47.77	Severe degradation	Exact match
7	33.33	96.26	Black beach	14.14	Severe degradation	Exact match
8	33.31	96.30	Black beach	32.67	Severe degradation	Exact match
9	32.89	96.74	Black beach	35.53	Severe degradation	Exact match
10	32.90	96.63	Non-degradation	92.08	Non-degradation	Exact match
11	32.89	96.55	Black beach	77.50	Mild degradation	Large deviation
12	32.96	96.36	Non-degradation	99.98	Non-degradation	Exact match
13	32.96	96.31	Non-degradation	99.13	Non-degradation	Exact match
14	32.97	96.23	Non-degradation	99.42	Non-degradation	Exact match
15	32.96	96.19	Black beach	32.64	Severe degradation	Exact match
16	33.82	97.15	Mild degradation	73.53	Mild degradation	Exact match
17	33.85	97.19	Black beach	46.93	Severe degradation	Exact match
18	33.86	97.21	Black beach	51.12	Severe degradation	Exact match
19	33.98	97.39	Non-degradation	91.50	Non-degradation	Exact match
20	34.00	97.47	Non-degradation	92.04	Non-degradation	Exact match
21	34.01	97.48	Non-degradation	86.38	Mild degradation	Slight deviation
22	34.02	97.52	Non-degradation	90.84	Non-degradation	Exact match
23	34.04	97.56	Non-degradation	98.77	Non-degradation	Exact match
24	34.08	97.61	Non-degradation	31.32	Severe degradation	Fundamental misalignment
25	34.08	97.61	Non-degradation	94.08	Non-degradation	Exact match

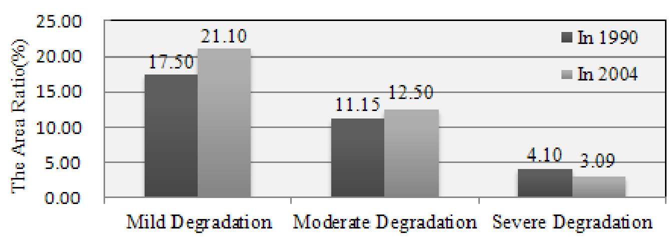


Fig.10. Area ratio of different degradation degrees in the “Three-River Headwaters” Region.

4.3.5. Analysis based on administrative region

The eastern part of the study area, consisting of Banma, Gadê, Henan, Jigzhi, Tongde and Zêkog, had minimal deterioration. The degradation degree is relatively mild and grass growth is healthier. The most severely degraded area is Qumarlêb. The deteriorated rangeland accounted for 63.33% of the total area in 1990 and increased to 77.47% in 2004. This depicts continuous degradation. The percentage degradation at Madoi and Chindu is more than 40% and about half of the grasses in these counties are degrading.

In the past 15 years, the deteriorated rangeland area is mostly increased in Banma, Maqên, Madoi and Qumarlêb. The percentage of degradation at Madoi from 1990 to 2004 is increased by 22.9%. At Qumarlêb it is increased by 14.14%. In contrast, the deterioration is decreased in Zhidoi, Zêkog, Xinghai, Tongde and Henan counties. The percentage of degradation is decreased by 9.74%, 6.72%, 4.8%, 3.7% and 0.16% from 1990 to 2004 at Zhidoi, Zêkog, Xinghai, Tongde and Henan, respectively. The ratio of deteriorated rangeland area of each administrative region in 1990 and 2004 is shown in Fig. 11.

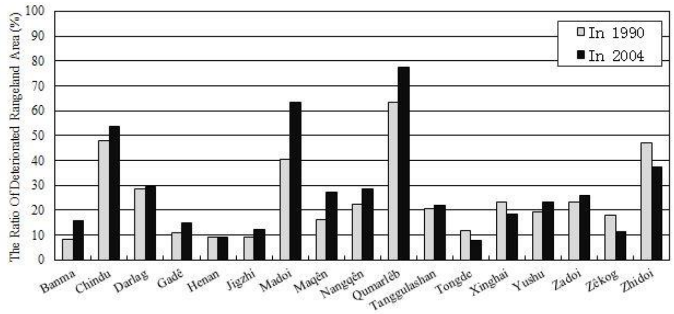


Fig.11. Comparison of deteriorated area ratio of each administrative region in 1990 and 2004

4.3.6. Statistics of change of rangeland degradation in two dates

In calculating the different value of the LNS distribution map for 1990 and 2004, there were ±10 deviations between the divided LNS and the corresponding degradation level. The range of -10 to 10 defines the unchanged area. The interval was reclassified as: (1) -100~ -10, meaning worsening rangeland; (2) -10~10, meaning unchanged rangeland; and (3) 10~100, meaning improving rangeland. Since the LNS distribution map represents the absolute degradation degree, it avoids the incomparability of degradation degree caused by interannual changes of natural conditions such as drought and precipitation enhancement. Based on the statistics, grass improvement accounted for 4.9% of the total rangeland area in the past 15 years. The most severely degraded area is concentrated around Madoi and accounts for 10.2% of the total deteriorated rangeland area. Improved rangeland area accounted for 1.7% of the total area and it is concentrated in Tanggulashan town in the western part of the northwest of Zhidoi, northwest of Qumarlêb and Xinghai. The distribution map of 15 years of change in degradation in the TRHR is shown in Fig. 12.

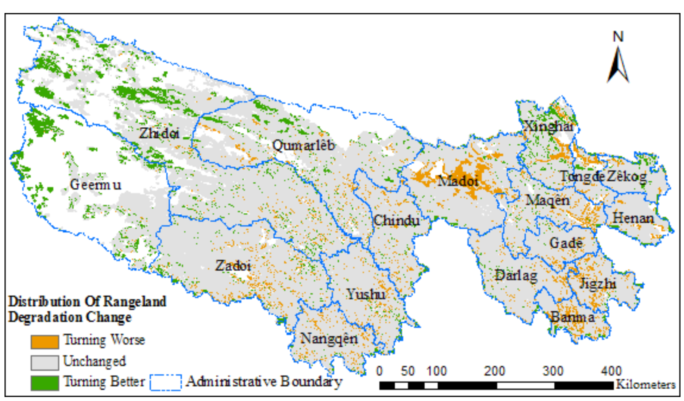


Fig.12. Map of the change of rangeland degradation between 1990 and 2004.

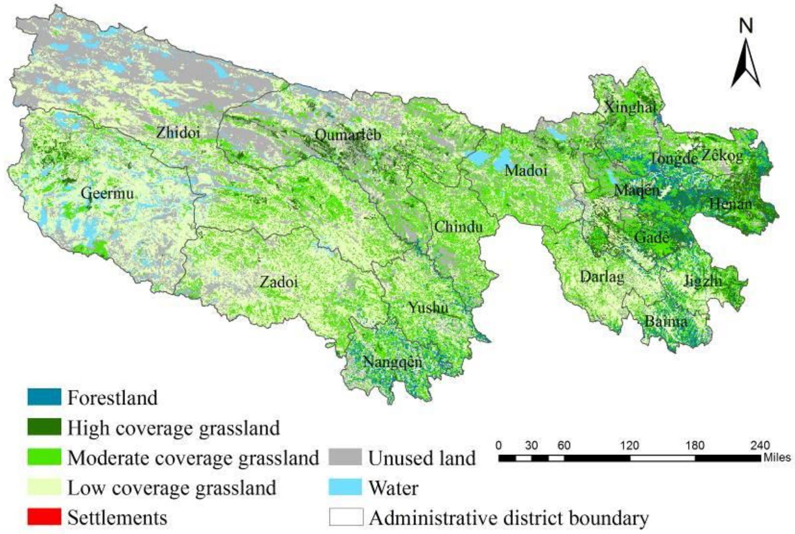
5. Discussion

5.1. Comprision of spatial tempral pattern of rangeland degradation with that of vegetation coverage degrees on land use/cover maps

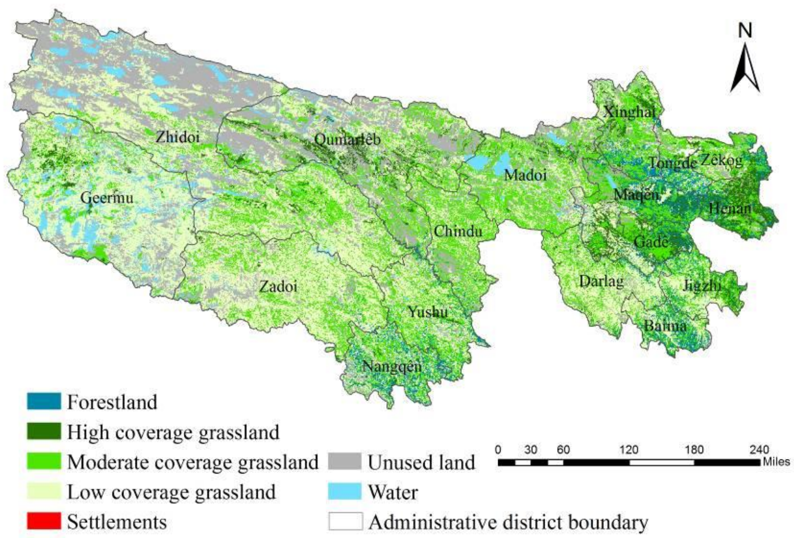
Due to regional differences in climate, water and heat conditions, topography and anthropogenic activities, rangeland degradation in the "Three-Rivers Headwaters" region varies significantly from area to area. According to our research, spatial distribution of degradation matched well with vegetation coverage degrees on land use/cover maps. In 2004, for example, by comparison of LNS value map (Fig.8) and rangeland degradation map (Fig.9) with the land use / cover map (Fig.13), it was found that part of seriously degraded rangeland regions could well correspond to those of low vegetation coverage areas or bare areas on the land use/ cover map in southeastern Madoi, north-central Xinhai, Maqên, Darlag, Qumalêb, Zhidoi, Chindu, Zadoi etc. Most of non-degraded areas in east-central part of Tongde, Zêkog, Henan, Gadê, Banma, Chindu, and Yushu could correspond to the same regions on the land use/cover maps with high or medium vegetation coverage. Moreover, in western and northern regions, such as the north-west of Zhidoi, Geermu and the northern part of the Qumarlêb, most area was unused land with relatively low vegetation coverage (5% -20%), which correspond to the severely degraded areas on the degradation map.

On temporal scale, no strong matching degree was found between change of degradation (Fig.12) and change of vegetation coverage from 1990 to 2005 (Fig.14). Fig.14 shows how land use/cover changed over the 15 years. From the map, increased rangeland vegetation coverage means that bare ground becomes meadow or grassland with coverage rising from low to moderate or high, and vice versa is the reduction. Increased or decreased vegetation coverage is distributed in the whole area without any obvious geographical distribution characteristics. Through comparing land use/cover change map (Fig.14) with Fig.12., spatial distribution similarity of rangeland turning better (such as in parts of Qumarlêb, Zhidoi and Geermu) or turning worse (such as in eastern Madoi) is weak. The main reason may be differences in both the concept connotation and the uncertainty induced from different data and methods.

The conclusions above could be verified more clearly through further analysis of the typical area of Madoi. From Table 6, an enlarged view of Madoi, it was obvious that LNS value in 1990 was bigger than that in 2004 in mid-eastern Madoi, reflecting severer degradation in 2004 than in 1990. From change of degradation, it was found that big changes had taken place in mid-Madoi, showing the similar degradation patterns as Sun (2015) discovered in Madoi by using NDVI time series analyze method. However, no similarity was found between changes of degradation and changes of land use/cover as mentioned in the last paragraph. To explain this, in addition to differences in concept connotation and uncertainty from different data and methods, one possible reason may be the different reference baseline in land use/land cover map and in LNS. Changes in the former maybe induced by interaction of anthropogenic activity and climate change. Meanwhile, in LNS, the impact of climate change is removed by taking potential NPP of each year as reference baseline respectively. In Sun’s (2015) research, the impact of climate fluctuation is also removed by using method similar to RUE (Rainfall Use Efficiency) to get a similar degradation spatial pattern.



(a)



(b)

Fig.13 Land use / cover maps :(a) in 1990; (b) in 2005.

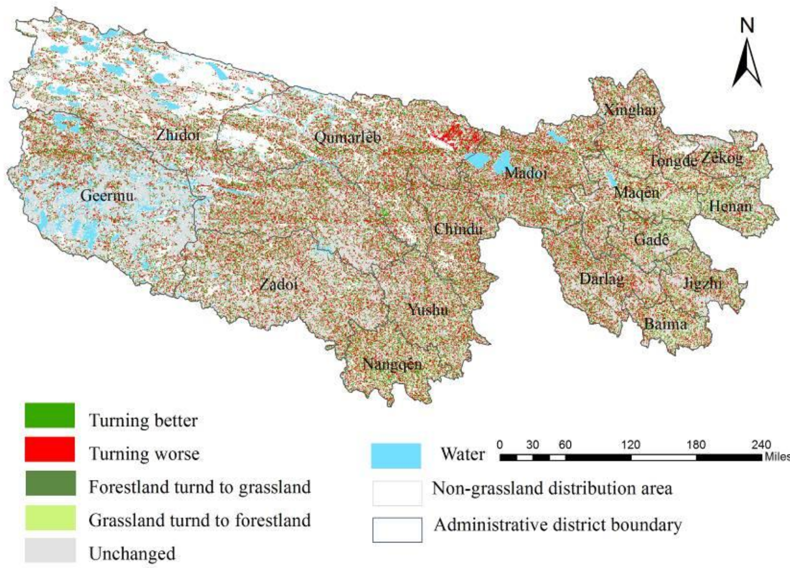
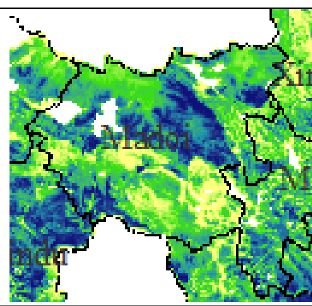
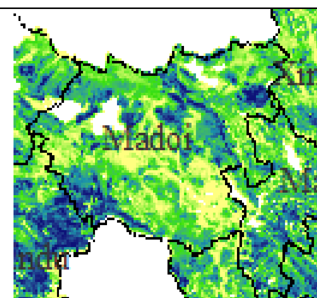
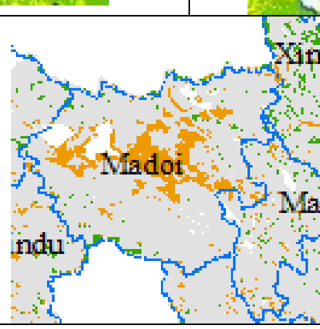
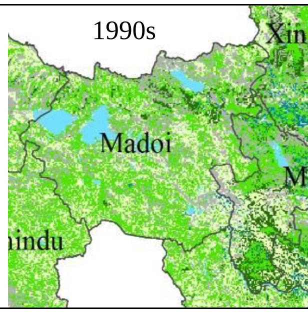
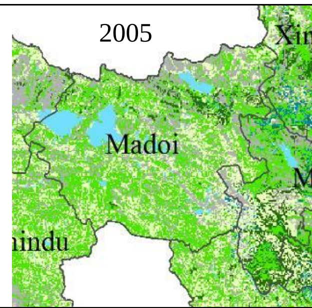
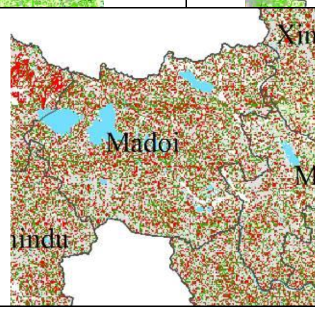


Fig.14 Land use / cover change map from 1990 to 2005.

Table 6 Madoi County Maps of LNS value, degradation and change, land use/cover and change in related year

	1990s	2004
LNS		
Degradation		
Change of degradation from 1990 to 2004		

Land use/cover		
Change of land use/cover from 1990 to 2005		

5.2. Statistical comparative analysis of proportion of degraded area for each county between Liu et al.(2008) and this work

Grassland degradation data collection for study area was completed by Liu et al. in 2008 through direct analysis and comparison of three date remote sensing images (the late 1970s MSS images, the early 1990s TM images, and 2004 TM / ETM+ image) by using visual interpretation. The spatial and temporal characteristics of rangeland degradation were analyzed since the late 1970s based on these data. Table 7 shows the proportion of degraded area for each county in Liu et al.'s (2008) research and this research. The correlation coefficient in the 1990s is 0.81, the average absolute error was 8.89%, and a relative error is 0.33. In 2004, the correlation coefficient was 0.92, with an average absolute error of 6.33% and a relative error of 0.26. These all indicate a high correlation between the two research results.

Table 7 Statistical comparative analysis of proportion of degraded area for each county

	Liu et al.(2008)		This paper	
	In 1990 (%)	In 2004 (%)	In 1990 (%)	In 2004 (%)
Banma	5.74	14.85	8.24	15.54
Chindu	63.33	63.58	47.99	53.51
Darlag	24.21	20.45	28.58	29.36
Gadê	15.76	19.97	11.02	15.03
Henan	17.22	6.85	9.30	9.14
Jigzhi	8.2	15.52	9.25	12.37
Madoi	46.69	55.42	40.63	63.53
Maqên	19.97	23.70	16.29	27.12
Nangqên	36.42	44.58	22.33	28.37
Qumarlêb	79.54	81.41	63.33	77.47
Geermu	10.94	13.88	20.80	21.78
Tongde	24.35	6.10	11.66	7.96
Xinghai	12.07	10.60	23.15	18.35
Yushu	27.61	27.22	19.26	23.41
Zadoi	23.02	27.14	23.16	25.83
Zêkog	21.78	7.02	18.06	11.34
Zhidoi	17.80	27.66	47.16	37.42

5.3 Analysis the uncertainty of parameters and processes in this work and results

(1) Uncertainty about the spatial interpolation of meteorological parameters used in model CASA

The meteorological parameters used in the improved CASA model were obtained through interpolation of the data from the meteorological stations. Because of the scarcity of meteorological stations in the study area (18 in the area, and 18 in the outer area) and the spatial distribution is uneven (mainly distributed in the middle and eastern regions and the west is relatively sparse), so there is uncertainty about the accuracy of the meteorological interpolation in the area. This study references Gao et al. (2013) method, and the CRU TS-3.1 (3.1 of the climate research unit high resolution Time-Series version, http://badc.nerc.ac.uk/view/Badc.nerc.ac.uk) meteorological data sets were used to generate site data to supplement the lack of the measured data of the site. The simulated and measured site data were applied to interpolate water vapor pressure and the sunshine percentage of each month by spatial statistical Kriging approach, and Leave-One-Out verification was made. The interpolation accuracy of vapor pressure is 85.5% and that of the percentage of sunshine is more than 90%. The macro factor regression method was selected for space interpolation of land surface temperature. The regression factors include altitude, longitude and latitude, and the Holdout Cross Validation accuracy reaches more than 90%. In addition, the interpolation accuracy of greater than zero Celsius degree annual accumulated temperature is 85% that of accumulated rainfall of growth season is 89% and the average sunshine duration of growth season is 94%, respectively. These spatial interpolation results should meet the requirements of the CASA model and PI evaluation.

(2) Uncertainty about the division of the rangeland productivity units

Due to limited information on degraded areal vector maps, the rangeland natural reserve (supposing some non-degenerated areas might exist) was used in the division of the rangeland productivity units. Compared with other regions, rangeland natural reserve is more likely to contain non degraded grassland, but it does not necessarily guarantee that there must be a non degraded grass area among it. Therefore, this may has an effect on accuracy of the results.

(3) Uncertainty of validation of grassland degradation monitoring results

The field observation data, multi periods land use / cover data and other research results on grassland degradation monitoring have been used to verify the results of this study in a variety of ways of comparative analysis, and shows that the results of the study have better credibility. Because of the bad natural conditions in the study area, and it is difficult to obtain a large number of site measured data and long-term positioning observation time series data, verification of grassland degradation monitoring results is still of uncertainty in some degree.

Community component information was considered in the field determination of degradation, and there was a certain difference between field determination of degradation and that defined in this paper, which may lead to the increased error of the verification of degradation.

6. Conclusions

The spatial and temporal pattern of rangeland degradation of the TRHR in 1990 and 2004 was obtained based on the LNS method. The dynamic characteristics of rangeland degradation were also revealed through a comparison of the rangeland degradation condition during the two periods.

With the combination of AHP and a fuzzy membership function, the rangeland was divided into 20 rangeland productivity units based on landform and physiognomy, hydrothermal factors and edaphic factors. Employing the technique of rangeland productivity units, the rangeland NPP change was used as an evaluation index for rangeland degradation. Through the verification of the rangeland degradation results, the verification accuracy was 85.9%. This demonstrates the applicability of the LNS in the study area. Otherwise, land use/cover maps and other research discoveries in the same periods also used to validate the spatial and temporal pattern of degradation, and all these illustrate the monitoring result of degradation by LNS is reasonable.

Due to the limitation imposed by data availability, the distribution of degradation was derived for only two years. More research work will be needed in the future. Also, application of NPP is only one aspect of determining the deterioration of the rangeland ecosystem. Future efforts should be made to assess the change in plant species in the rangeland ecosystem by using hyperspectral remote sensing data (Mansour et al., 2012).

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