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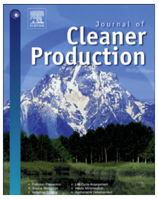

Assessing the effects of vegetation cover changes on resource utilization and conservation from a systematic analysis aspect

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ABSTRACT

How to improve the utilization efficiency of natural resources and control environmental impacts is one of the key steps to achieve the United Nations' Sustainable Development Goals (SDGs). A multi-dimensional approach integrating landscape and systematic analysis might be a good way to address this issue. In this study, three main ecosystems and six vegetation cover changes on the Loess Plateau (LP) from 2000 to 2015 were selected to clarify their impacts on resource utilization and conservation in three environmental regions based on landscape-level remote sensing data and an emergy-based thermodynamic system processing model. The evapotranspiration empower was regarded as the system emergy utilization, with the structure and function of the ecosystem being divided into resource utilization efficiency and environmental impacts. Results showed that (1) Forest could reinforce production by improving the water and soil conservation in water erosion region, although it had a lower water utilization efficiency than other ecosystems. (2) Grassland was more suitable than forest in the water-limited wind and wind-water erosion regions, with a higher water utilization efficiency and higher resource conservation. These results suggested that maximum resource acquisition is not always the optimal strategy for the development of ecosystems, especially in a resource-limited environment. The maximum empower principle could be a general principle to drive ecosystem development at a regional scale. Expanding cultivated land in the wind-water erosion region might be a choice for the sustainable increase of grain production in the LP. By incorporating the main characteristics of the major issues concerned in the studied area into the ecosystem processes and landscape integration model, the new multi-dimensional method has a good application potential in guiding land use planning and decision making in ecological fragile areas, like but not limited to the LP.

1. Introduction

Rational utilization and conservation of natural resources are thought to be beneficial to the United Nations' Sustainable Development Goals (SDGs) (Islam and Managi, 2019); vice versa, wasted/lost natural resources can become the driver of natural disasters such as flood and soil erosion. How to improve the utilization efficiency of renewable natural resources, especially the limited water resource in dry regions, adjust the severe local environment and reduce the loss of local nonrenewable resources (e.g., soil loss caused by runoff), are difficult, long-term issues. This could affect the sustainable development of the region and its downstream areas (Cassman and Grassini, 2020). Many efforts have attempted to solve the problem with large-scale satellite remote sensing (Tscharntke et al., 2005) or small watershed mechanism study (Li et al., 2018) in the last two decades. Multiscale studies integrating landscape and systematic scale are essential but lacking for practical strategy making, to clarify the performance of different ecosystems in different environments, and the underlying system processing mechanisms.

In general, natural ecosystems are the products of a continuous and never completed process of self-organizing systems, driven and constrained by the resource availability (Ulgiati et al., 2007). Energy is the driving force for all biological processes, and energy transformation appears in all kinds of metabolic behaviors (Li et al., 2013). As a systematic analysis method, emergy analysis could convert different kinds of resource/energy into the same unit of

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Solar Emergy Joules (sej) and thus can integrate different elements into a single system for analysis (Ghisellini et al., 2014). Emergy was defined as the available energy (generally based on solar energy) used directly or indirectly to sustain a process or to generate a service or a product (Odum, 1996). Emergy system diagram model can clarify the emergy flow, utilization and transformation in one system and therefore help to understand the structure and function of the system from a thermodynamic aspect (Odum, 1996). The resource utilization efficiency and environmental impacts of different vegetation ecosystems (e.g., forest, grassland and cultivated land) could be better understood at a landscape scale, through the emergy system network analysis.

Like all the general principles that drive the ecosystem from an ecological aspect, e.g., habitat filtering, competitive exclusion and so forth (Lohbeck et al., 2014), is there also a general thermodynamic principle that controls the self-organizing behavior of the ecosystem? As a basic principle of emergy analysis, the maximum empower principle (MePP) claims that all self-organizing systems (ecosystems) develop and prevail that maximize empower flow and utilization, and emergy utilization could in turn reinforce the production and efficiency of the system (Odum, 1996). Empower indicates emergy inputs per unit time. The MePP, therefore, can be regarded as one of the fundamental principles for determining whether the changes in a system are in a competitive direction (Ulgiati et al., 2007). By analyzing the resource utilization and environmental impact of regional vegetation change with the MePP, it is easy to determine whether the changes are sustainable. However, like other groundbreaking theories, the MePP still encounters some doubts owing to the lack of sufficient empirical evidence (Ulgiati et al., 2007).

As one of the typical representatives of arid and semi-arid regions in the world, the Loess Plateau (LP) of China has been suffered from the most severe soil and water loss and became one of the main ecological fragile areas in the world (Liu et al., 2017). Soil erosion has seriously depleted natural resources and degraded the eco-environment, thus directly affecting regional sustainable development and the security of the lower reaches (Tsunekawa et al., 2014). Meanwhile, due to the arid and semi-aired climate and unreasonable land use, the LP is also facing severe water shortage for a long time. How to improve the natural resource utilization efficiency (especially the water resources), and decrease environment risk is one of the main problems for the government. With the launch of a suite of vegetation restoration projects (e.g., the Grain for Green Project) since 1999, the vegetation cover of the LP has changed significantly (Fig. 1; Table A1, A2). As a result, the sediment yields decreased in this region (Zuo et al., 2016). It was reported, however, that the vegetation restoration in some areas were not reasonable due to the lack of scientific guidance, e.g., the “small-aged tree” was caused by planting trees (which consumed large quantity of soil and ground water) on water-limited areas (Chen et al., 2010). Many studies have evaluated the effects of vegetation restoration in the LP of China (Li et al., 2016), and in other areas of the world, e.g., the Mediterranean (Cortina et al., 2011), the Africa (Fill et al., 2017) and the global scale study (Wu et al., 2020). However, the interactions among ecosystem services and the underlying systematic processing mechanisms are still not clear. This increased the uncertainty of land use planning and decision making from both natural resource utilization and environmental impacts control aspects in ecological fragile regions. In which the natural resources are uneven distributed and scarce, like but not limited to LP. A comprehensive evaluation integrating the natural resource utilization, water and soil conservation, and other environment impacts is needed to fill this gap.

Understanding the effect of vegetation changes on natural resource utilization and environmental impacts and the behind mechanisms are valuable in accessing the potential impact of human activities on land use. This is also one of the important pathways to guide the land use planning and decision making in future. By constructing a landscape data based emergy system diagram model for different ecosystems (Fig. 2), this study provides a new multi-dimensional method that combines landscape and systematic scale analysis, which also integrates the resource utilization structure and environmental impacts. Due to the relatively simple constraints of natural resources, high environmental risks, and the massive vegetation cover changes over the last 20 years, the LP provides a good platform for the application and promotion of the new multi-dimensional method and the applicability verification of the MePP. In this study, the spatial distributions of the solar radiation empower, wind empower, and rain empower were first assessed. Because they are the main renewable resource/energy (RRE) inputs to the ecosystems on the LP (Liu et al., 2019). To assess the performance of different vegetation covers (ecosystems) on RRE utilization efficiency and environmental impact aspects, three main vegetation covers (i.e., forest, grassland, cultivated land) and six main vegetation cover changes from 2000 to 2015 (Fig. 1) were selected (tblA2). The aims of this study were to (i) evaluate the effects of vegetation cover (ecosystem) changes on RRE utilization efficiency and environmental impacts from a systematic aspect, and (ii) verify the applicability of MePP in resource-limited environments on a regional scale.

2. Materials and methods

2.1. Study area

Located in central China, the LP is one of the largest and deepest loess deposits in the world, covering approximately 640,000 km^2. The LP belongs to a temperate continental monsoon climatic zone of eastern Eurasia. The annual precipitation is commonly less than 500 mm, increasing from less than 300 mm in the northwest to 700 mm in the southeast (Fu et al., 2017). While in most area of this region, the annual potential evapotranspiration is greater than 1000 mm and the annual mean maximum temperature is larger than 13.0 °C, making this region a dry and semiarid climate (Feng et al., 2016).

Long-term human activities, intense summer rainstorms, and steep topography make most of the ecosystems of the LP much more fragile than other regions in China. Meanwhile, the low water utilization efficiency of most areas favors the rainfall runoff over infiltration, resulting in serious soil erosion. The highly erodible loess soil thus makes 60% of the LP subject to soil erosion with an average erosion rate of 5000–10,000 t km^{-2} year^{-1} (Ren, 2015). According to the erosion driving factors (i.e., wind and precipitation gradient), the LP can be divided into three regions (Fig. 1a): (1) the wind erosion region is mainly distributed in the northwest and accounts for 25.23% of the area of the LP, in which wind is another main factor, besides water, driving the soil erosion. The annual precipitation is below 300 mm, and the main ecosystem is grassland (accounting for 50.45% of this region) (Fig A1); (2) as the principal sediment source of the Yellow River, the water erosion region accounts for 46.60% of the LP, and rain is the main factor driving soil erosion. The annual precipitation is 400–700 mm and the main ecosystems are forest (35.01%) (including coniferous forest (13.24%), broad-leaved forest (4.23%) and shrubland (17.53%)) and cultivated land (35.34%) (Fig A1); and (3) the wind-water erosion region is distributed in the transition zone between the water and wind erosion regions, accounting for 28.17% of the LP, and has an annual precipitation of 250–400 mm. The main ecosystems of this region are grassland (51.28%) and cultivated land (28.39%) (Fig A1). Water erosion mainly occurs in summer and

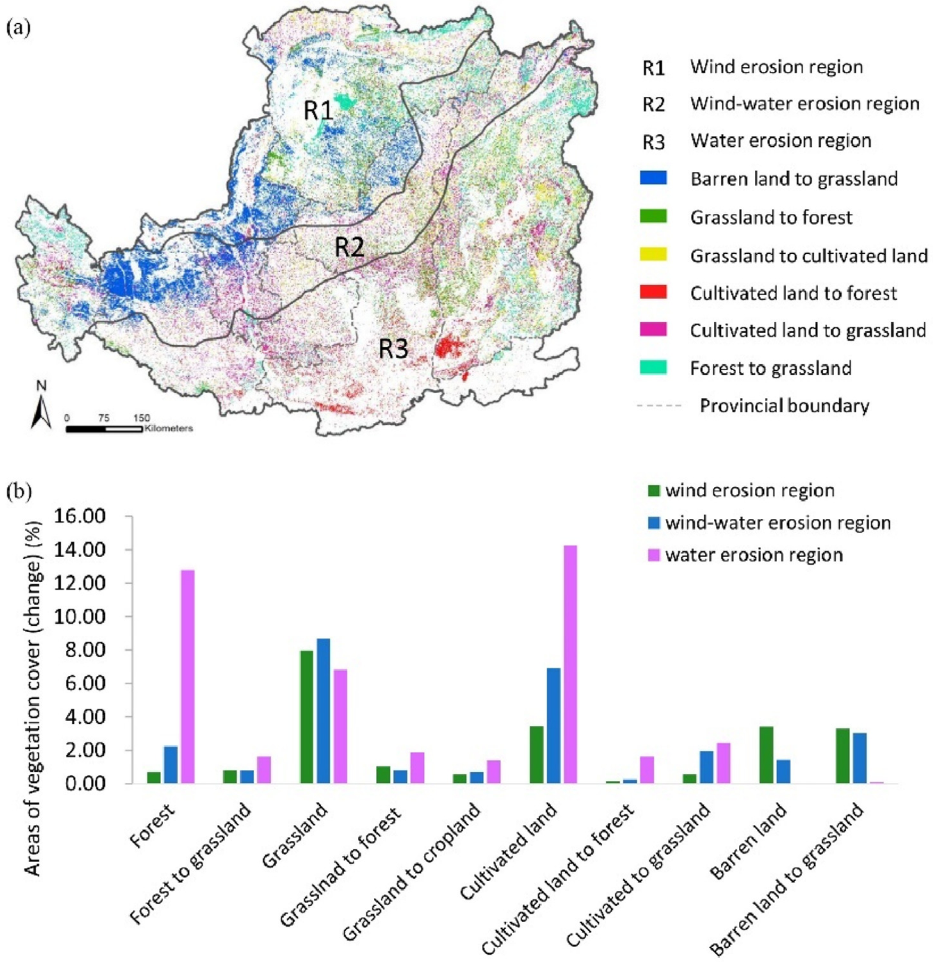

Fig. 1. The main vegetation cover changes (a) and its relative areas (b) from 2000 to 2015 on three soil erosion regions of the Loess Plateau, China.

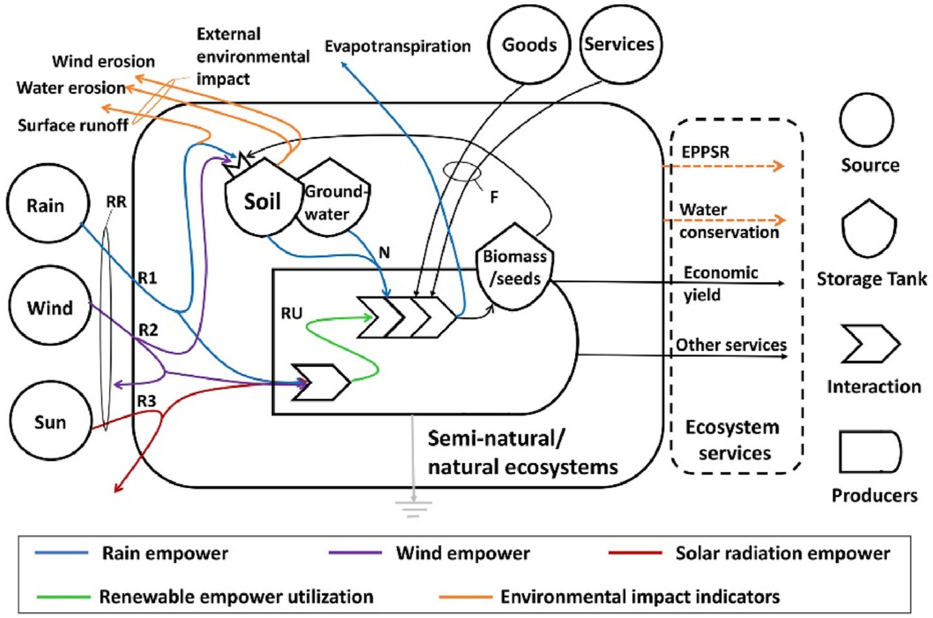

Fig. 2. Emergy system diagram model for the ecosystems of the Loess Plateau. RR refers to the renewable empower input; R1, R2, R3 refer to rain empower, wind empower, and solar radiation empower, respectively; RU refers to the renewable empower utilized by the system; N, and F refer to local nonrenewable empower, and external empower, respectively. EPPSR refers to erosive potential production per 100 surface runoff.

autumn, while wind erosion occurs in winter and spring in the LP (Tsunekawa et al., 2014).

Although many ecological engineering projects (e.g., the Grain for Green Project and Natural Forest Conservation Project) have been conducted to control soil erosion by the Chinese government, it remains one of the most critical environmental problems on the LP (Tsunekawa et al., 2014). The main vegetation cover change patterns (Table A1) on the LP from 2000 to 2015 can be classified into two categories: (1) vegetation restoration patterns, including grassland to forest (3.72%), cultivated land to forest (2.04%) and to grassland (4.95%), and barren land to grassland (6.44%). (2) Vegetation degradation patterns, including forest to grassland (3.23%) and grassland to cultivated land (2.69%). Understanding the effects of these ecosystem changes in each soil erosion region on the RRE utilization efficiency and environmental impacts is urgently needed to implement more effective vegetation restoration and management in the future.

2.2. Emergy analysis

Emergy analysis, as a biophysical and environmental accounting method, can clarify the relative positions of different energy carrier in the thermodynamic hierarchy of the biosphere. The emergy of various services and products can be calculated by multiplying their relative Unit Emergy Values (UEVs) (Yang et al., 2013), which is defined as the input of solar equivalent joules per unit joules (gram) of energy (matter) output of any product or service (sej J^{-1}, sej g^{-1}). The emergy is calculated as follows:

$$E_m = \sum_i (Tr_i \, Ex_i) \; i = 1,\ 2,\ 3\ \&,\ n \tag{1}$$

$$Tr_i = U_i / Ex_i \tag{2}$$

E_m indicates the total emergy of the m service or product, with a unit of sej; Ex_i indicates the i_{th} input flow of matter or energy associated with the formation of the m service or product; Tr_i indicates the UEV of the i_{th} input and can be calculated by equation (2); U_i indicates the emergy related to the i_{th} input. By defining the UEV of the solar energy as 1 sej J^{-1}, all kinds of services and products can be quantified (Brown and Ulgiati, 2018). The empower is defined as the emergy flow per unit time. In this study, the time scale was set as one year to compare the differences in the empowers among different vegetation covers (ecosystems).

This study evaluated solar radiation empower, wind empower, and rain empower (Table A3) , because they are the major renewable natural resource sources for vegetation utilization in the LP. Meanwhile, the rain and wind are also the main factors causing soil erosion in the LP. The energy of these RREs per year was calculated through a suite of equations given in Table A3 and then converted to empower by multiplying relative UEVs according to Campbell et al. (2005) (UEV of most RREs except wind) and Campbell and Erban (2017) (wind UEV). If necessary, the UEVs were converted to a 12.0 E+24 sej yr^{-1} planetary emergy baseline (Brown et al., 2016). The maximum value of these RRE empowers (i.e., rain empower, solar radiation empower, wind empower) was taken as the renewable empower input in each grid cell (RR; Fig. 2) to avoid double counting, as they have the same energy source (Odum, 1996). For example, the solar radiation drives the air to move, thus forming the wind. The wind and solar radiation in turn promotes the transpiration of water from stomata of leaves and the evaporation of water from land surface, and then the rain is formed.

2.2.1. RRE utilization efficiency indicators

Since evapotranspiration is the mainly water resource consumption of an ecosystem and precipitation is the main renewable resource input of the ecosystem, following Campbell et al., 2005, the renewable/rain empower utilization (RU; Fig. 2) was calculated as follows:

$$\begin{cases} RU = ET;\ if\ ET < R1 - SR \quad (a) \\ RU = R1 - SR;\ if\ R1 - SR < ET\ (b) \end{cases} \tag{3}$$

where ET indicates the total evapotranspiration empower which might come from rainfall, soil and ground water; R1 indicates the rain empower; and SR indicates the surface runoff empower (Fig. 2). In condition (a), ET is less than the difference between R1 and SR, indicating that there is extra water from R1 that can be used to replenish the soil-ground water (Fig. 2). The water consumption of ET in this condition is believed to come from R1. In condition (b), ET is more than the difference between R1 and SR, indicating that the water conservation services of the ecosystem are negative. Under this scenario, the water consumption of ET is considered to come from rainfall and soil-ground water, and RU is equal to the difference between R1 and SR.

The renewable emergy utilization efficiency (REUE) and the rain utilization efficiency (RUE) are defined as the ratio between RU and RR and the ratio between RU and R1:

$$\mathrm{REUE} = \mathrm{RU}/\mathrm{RR} \tag{4}$$

$$\mathrm{RUE} = \mathrm{RU}/\mathrm{R1} \tag{5}$$

2.2.2. The environmental impact indicators

In this study, the environmental impacts of ecosystems include external environmental impacts and ecosystem services. The external environmental impact represents the intensity of environmental change, which is generated inside the system and is likely to have an adverse effect on the surrounding systems (Lin and Huang, 2013). For example, the regulation service of surface runoff can hardly be considered a valuable resource for most areas of the LP, because it could cause 0.01–2.00 cm of topsoil to be washed away and lead to an increase in the downstream sediment. This might cause some natural disasters, such as floods, mudflows and landslides (Tsunekawa et al., 2014). In this study, the surface runoff empower (SR) and the soil erosion empower (SE) were selected to represent the external environmental impact, and the calculation procedures are given in Table A3. The SE was divided into water erosion empower (WAE) and wind erosion empower (WIE) according to the erosion driving factors.

In general, the rougher the loess is, the lower its natural porosity and strength and the easier it is to be eroded by water, indicating a close relationship between soil particle composition and sediment yield. Such a relationship can be represented by an indicator of water erosive potential production per 100 surface runoff (EPPSR) (Tsunekawa et al., 2014). For example, Cao (1980) reported that the EPPSR increased with the increase in >0.05 mm particle content of the soil. A high value of EPPSR indicates that the loess is more susceptible to erosion and that the soil nutrients are easily lost, while a low value indicates that the loess is more resistant to erosion and is therefore conducive to the preservation of soil nutrients. EPPSR is calculated as:

$$\mathrm{EPPSR} = \mathrm{WAE}/\mathrm{SR} \times 100 \tag{6}$$

In this study, the EPPSR was selected to represent one of the ecosystem service indicators, since it indicates the degree to which the loess and nutrients are easily eroded and lost by water/rain. In addition, as an important ecosystem services index, the soil water conservation empower (SWCE) was also selected to represent the ecosystem service indictor. According to Feng et al. (2012), the SWCE is calculated as:

$$SWCE = R1 - ET - SR \tag{7}$$

2.3. Data used in this study and the production of different empower maps

The data used in this study was mainly collected from a reanalysis dataset named ERA5-Land (Table A4; Muñoz, 2019), including the data of solar radiation, wind speed, precipitation, evapotranspiration, potential evapotranspiration and surface runoff. By combining the model data with observation data using laws of physics, the ERA5-Land provides an accurate description of the evolution of land variables over several decades at an enhanced resolution (Muñoz, 2019). For example, it was reported that the ERA5-land has a good match percentage with 231 station data in United States and Canda (Sheridan et al., 2020), and with 41 station data in China (Zhang et al., 2019). The WAE was calculated using the Universal Soil Loss Equation (USLE; Table A3), and the related indexes, i.e., land cover factors and land management factors, were obtained from Li et al. (2018). The WIE was calculated using the Improved Wind Erosion Technology (RWEQ; Table A3) (Fryrear et al., 2000). The soil properties dataset and fractional vegetation coverage dataset were collected from Shangguan and Dai (2014) and Liang et al. (2020), respectively (Table A4).

According to the emergy system diagram model (Fig. 2), the RRE empowers in space was firstly quantified to clarify the empower inputs to each vegetation cover at each erosion region. The raw input data for these RREs included solar radiation, wind speed and precipitation. By multiplying related UEVs in each grid cell, RRE empower maps (i.e., solar radiation empower map, wind empower map, and rain empower map) were produced (the calculation procedures are shown in Table A3). The summary map, i.e., renewable empower map, was produced by calculating the maximum of these RRE empower maps (Mellino et al., 2014). The second step is to calculate the RRE utilization efficiency and environmental impacts at each grid cell. The ET, SR, WAE and WIE maps were produced by multiplying the relative UEVs (Tables A3). Then the RU, REUE, RUE, EPPSR and SWCE maps were produced according to equations (3)–(7). The last step was to calculate the average values of these RRE empowers, RRE utilization efficiencies and environmental impact indicators of each vegetation cover (ecosystem) in each erosion region. The average values of these variables between 1990 and 1999 (before vegetation restoration) and between 2010 and 2019 (after vegetation restoration) were used to avoid the year-to-year difference.

2.4. Data analysis

The maps of different variables were calculated using the R packages “raster”, “rgdal” and “sp” under the R 3.6.1 environment (Bivand et al., 2013) and the ArcGis 10.3 in this study. To evaluate the effects of the main vegetation cover (ecosystems) and its changes after vegetation restoration on RRE utilization efficiency and environmental impacts, the 30 m × 30 m land use/cover data of 2000 and 2015 of the LP were used (http://www.geodata.cn, Table A4; Fig A1) (Ning et al., 2018). The spatial resolution of all data source was resampled to 1 km × 1 km using the bilinear interpolation method before calculation. The average values of RRE empowers, RRE utilization efficiencies and environmental impact indicators of each ecosystem in each erosion region were calculated using the function “zonal” from the R package “raster”.

3. Results

3.1. The distributions of RRE empower on the LP

The solar radiation empower was higher in the western and northern regions than in other areas in the LP (Fig. 3a and b). It increased in the southern and northern regions from 2000 to 2015 (Fig A2a). The wind empower was higher in the northern region (Fig. 3c and d). It also increased more in this region than others from 2000 to 2015 (Fig A2b). The high value of the rain empower was distributed in the southeast, central and eastern regions (Fig. 3e and f). From 2000 to 2015, it decreased slightly in most areas (Fig A2c).

Similar to the rain empower, high values of the renewable empower were also mainly distributed in the southwest, central and eastern regions on the LP (Fig. 3g and h). From 2000 to 2015, it decreased in most areas (Fig. 4a). Among the various vegetation covers, the forest areas had the highest renewable empower input in all three erosion regions (Fig. 4b–d).

3.2. The RRE utilization efficiencies of ecosystems

ET had a stepped distribution on the LP, increasing from the northwest region to the southeast region (Fig. 5a and b). From 2000 to 2015, it decreased in almost all areas (Fig. 5c). Among the different ecosystems, the forest tended to have a higher ET than other vegetation covers in the wind and water erosion regions (Fig. 5d–f).

High values of REUE were mainly distributed in the western and eastern regions (Fig. 6a and b) and increased in most areas from 2000 to 2015 (Fig. 6c–f). The forest tended to have a lower REUE than the grassland and cultivated land in the wind-water and water erosion regions. The RUE of the forest was also lower than that of the grassland and cultivated land in all three erosion regions (Table A5). In the wind erosion region, the REUE of the barren land to grassland decreased less than that of unchanged barren land, and the forest to grassland increased more than that of unchanged forest from 2000 to 2015 (Fig. 6g). In the wind-water erosion region, the REUE of the barren land to grassland, forest to grassland and grassland to cultivated land increased more than that of unchanged forest and grassland respectively (Fig. 6h). In the water-erosion region, the REUE of cultivated land to forest and grassland to forest increased less than that of unchanged cultivated land and grassland, respectively (Fig. 6i). The changes in the RUE of all ecosystems from 2000 to 2015 in each erosion region were similar to those of the REUE.

3.3. Ecosystem service indicators

The SWCE was higher in the southern and eastern regions (Fig. 7a and b), and it decreased in most areas of the LP from 2000 to 2015 (Fig. 7c). Among the different ecosystems, the forest had a higher SWCE than the others in all three erosion regions (Table A7; Fig A6a-c). In the wind-water erosion region, the SWCE of barren land to grassland, forest to grassland and grassland to cultivated land decreased more than that of unchanged barren land, forest and grassland, respectively. In the water erosion region, the SWCE of the cultivated land to forest and to grassland and forest to grassland decreased less than that of unchanged cultivated land and forest, respectively.

High values of the EPPSR were mainly distributed in the western, central and southeast regions on the LP (Fig. 7g and h). The EPPSR of most areas of the LP increased from 2000 to 2015 (Fig. 7i).

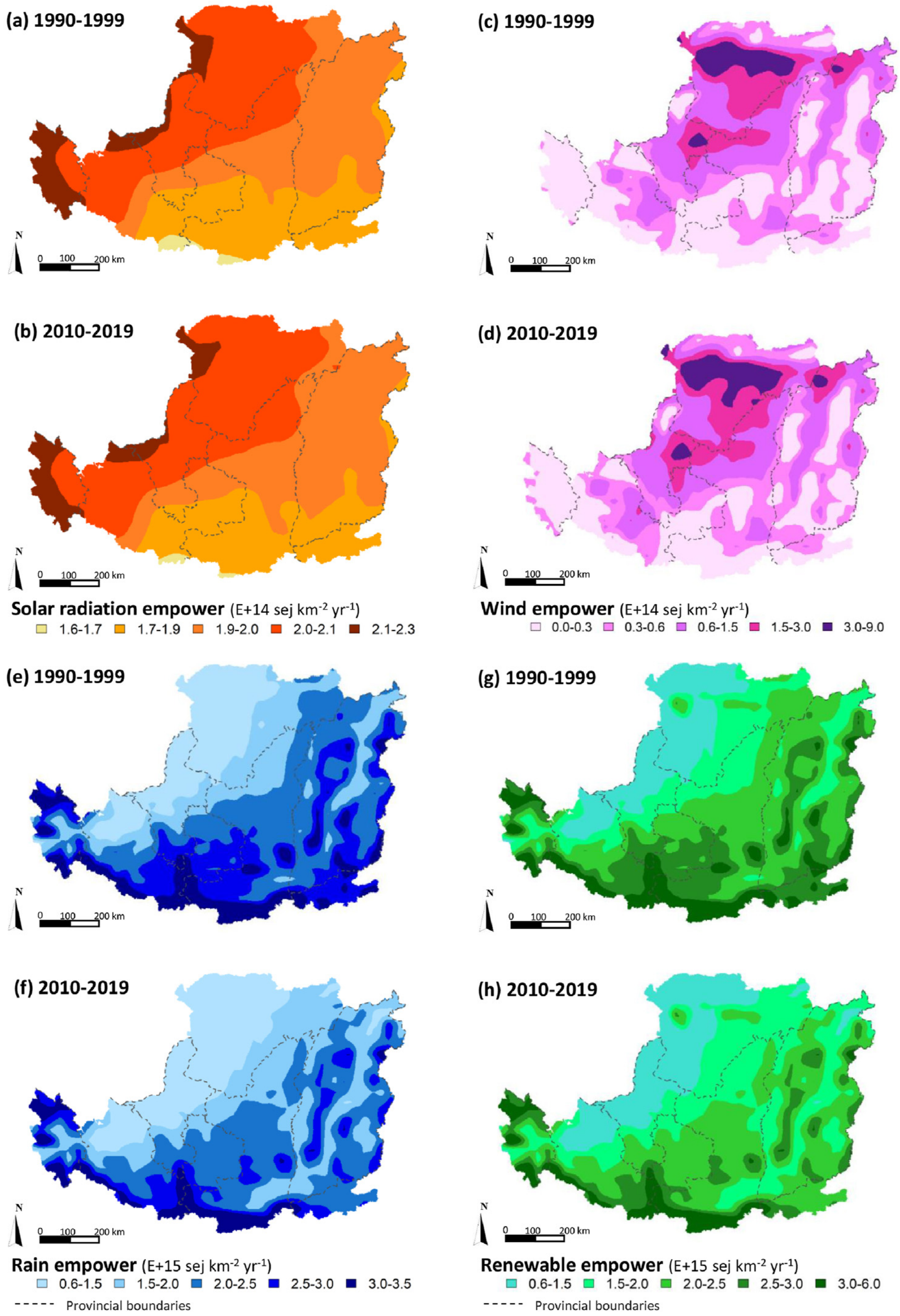

Fig. 3. The distributions of RRE empowers. (a, b) Solar radiation empower, (c, d) wind empower, (e, f) rain empower, and (g, h) renewable empower on the Loess Plateau, China. (a, c, e, g) were the average values of 1990–1999; (b, d, f, h) were the average values of 2010–2019.

In the wind erosion region, the EPPSR of the barren land to grassland, the cultivated land to grassland, and the forest to grassland increased less than that of unchanged barren land, cultivated land and forest respectively (Fig. 7j). In the water erosion region, the EPPSR of the grassland to cultivated land increased more than that of unchanged grassland (Fig 7l).

3.4. External environmental impact indicators

High values of the SR were mainly distributed in the southeast, central, and eastern regions on the LP (Fig. 8a and b). Among the different ecosystems, the forest had a higher SR than the others in all three erosion regions (Fig A7a-c, Table A6). From 2000 to 2015, the SR decreased in most areas of the LP (Fig. 8c). Compared to the unchanged forest, the SR of the forest to grassland decreased less in the wind-erosion region but decreased more in the wind-water and water erosion regions (Fig. 8d–f).

High values of the WAE were mainly distributed on the central and southeast regions of the LP (Fig. 8g and h). The WAE decreased in most areas of the LP from 2000 to 2015 (Fig. 8i). In the wind and wind-water erosion region, the WAE of the cultivated land to grassland decreased more than that of unchanged cultivated land

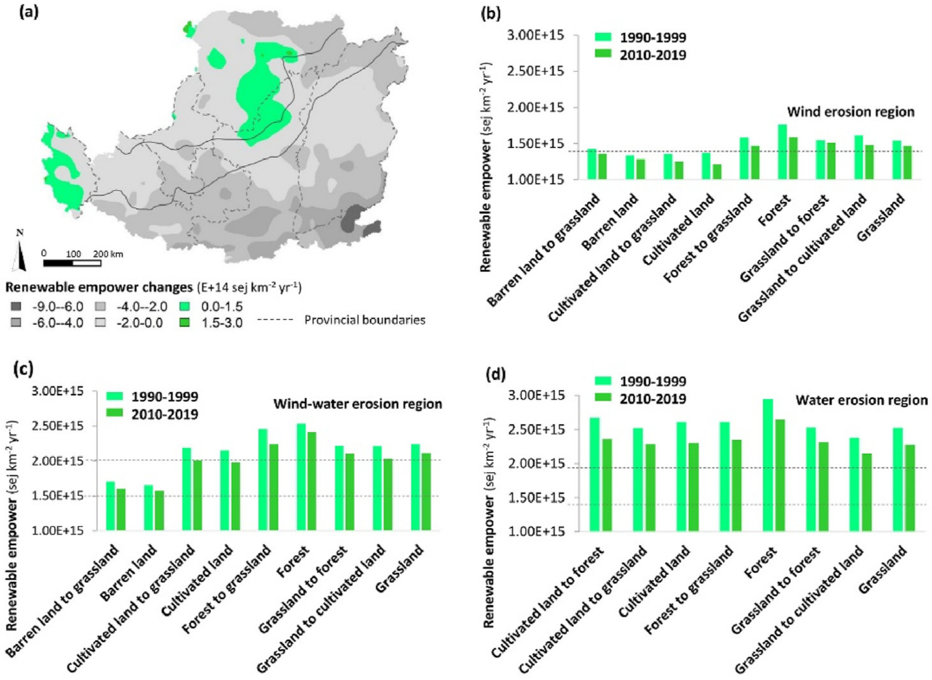

Fig. 4. The changes of renewable empower from 1990 to 1999 to 2010–2019 on the Loess Plateau, China (a), and the renewable empower of different vegetation ecosystems in 1990–1999 and in 2010–2019 in three soil erosion regions (b, c, d) respectively.

(Fig. 8j and k). While the WAE of the forest to grassland in the wind-water erosion region decreased less than that of the unchanged forest (Fig. 8k). In the water erosion region, the WAE of the cultivated land to grassland and grassland to forest decreased more than that of unchanged cultivated land and grassland, respectively (Fig 8l). While the WAE of the grassland to cultivated land decreased less than that of unchanged grassland from 2000 to 2015 (Fig 8l).

High values of WIE were mainly distributed on the northwest region of the LP (Fig 8m, n). In the wind and wind-water erosion region, the WIE of the barren land to grassland, cultivated land to grassland decreased more than that of unchanged barren land and cultivated land respectively (Fig 8p, q). While the WIE of the forest to grassland increased more in wind erosion region and decreased less in the wind-water erosion region than that of the unchanged forest (Fig 8p, q).

4. Discussion

4.1. The performance of the main ecosystems with respect to RRE utilization efficiencies and environmental impacts and relationship with MePP

The MePP suggested that a highly competitive self-organizing system always has a higher empower flux at an optimal efficiency than at a maximum efficiency (Odum, 1983), because part of the emergy dissipation was used to improve the networks or the environments to reinforce the production and efficiency of the system (Odum, 1996). The decrease in resource input could reduce dissipation and thereby improve resource utilization efficiency and yield a maximum possible product (Ulgiati et al., 2007).

In this study, the LP was divided into three soil erosion regions according to the uneven distribution of precipitation and wind empowers (Tsunekawa et al., 2014). Among them, grassland, cultivated land and barren land dominate in the wind and wind-water erosion regions, while forest and cultivated land dominate in the water erosion region (Fig. 1b, Table A2). In the water erosion region (where annual precipitation was over 400 mm) (Tsunekawa et al., 2014), forests consumed more renewable resources (indicated by a relatively high ET) yielding quick development of growth and positive feedback (Fig. 9, A8), i.e., more leaves and roots were produced to capture more energy and nutrients. In addition, this maximum empower self-organization process was accompanied by improved water and soil conservation functions (indicated by a relatively high SWCE and a low EPPSR). This in turn provided relatively bounteous resource environment (indicated by a relatively high precipitation and a lower REUE/RUE) for further development of the forest than the grassland. This kind of maximum empower self-organization strategy in the water erosion region is similar to what was found for young subtropical forest plantations with a relatively abundant resource environment (Li et al., 2013), which might also be a good reason for the dominance of forests in most water erosion areas on the LP. On the other hand, with a relatively low resource utilization efficiency, forests had a relatively higher SR and WAE than grassland and cultivated land (Fig. 9, A8). When resources became limited during 2010–2019, all forest, grassland and cultivated land increased their resource utilization efficiency, indicated by increased REUE and RUE, which is another strategy for maximum empower self-organization (Ulgiati et al., 2007, Figs. 4 and 6).

Does the MePP also function well in resource-limited wind and wind-water erosion regions? In which the annual precipitation is less than 400 mm. Results showed that the regionally dominant ecosystems, i.e., grassland and cultivated land, had a relatively higher REUE/RUE but a relatively lower ET than that of forest in the dry wind and wind-water erosion regions (Fig. 9, A8). This is consistent with the maximum efficiency self-organization strategy of the MePP clarified by Ulgiati et al. (2007), i.e., when the resource becomes increasingly scarce, the fast resource consumption of a system is no longer a winning strategy for survival while higher resource utilization efficiency is required (doing more with the resources available). Therefore, the MePP also had a good function

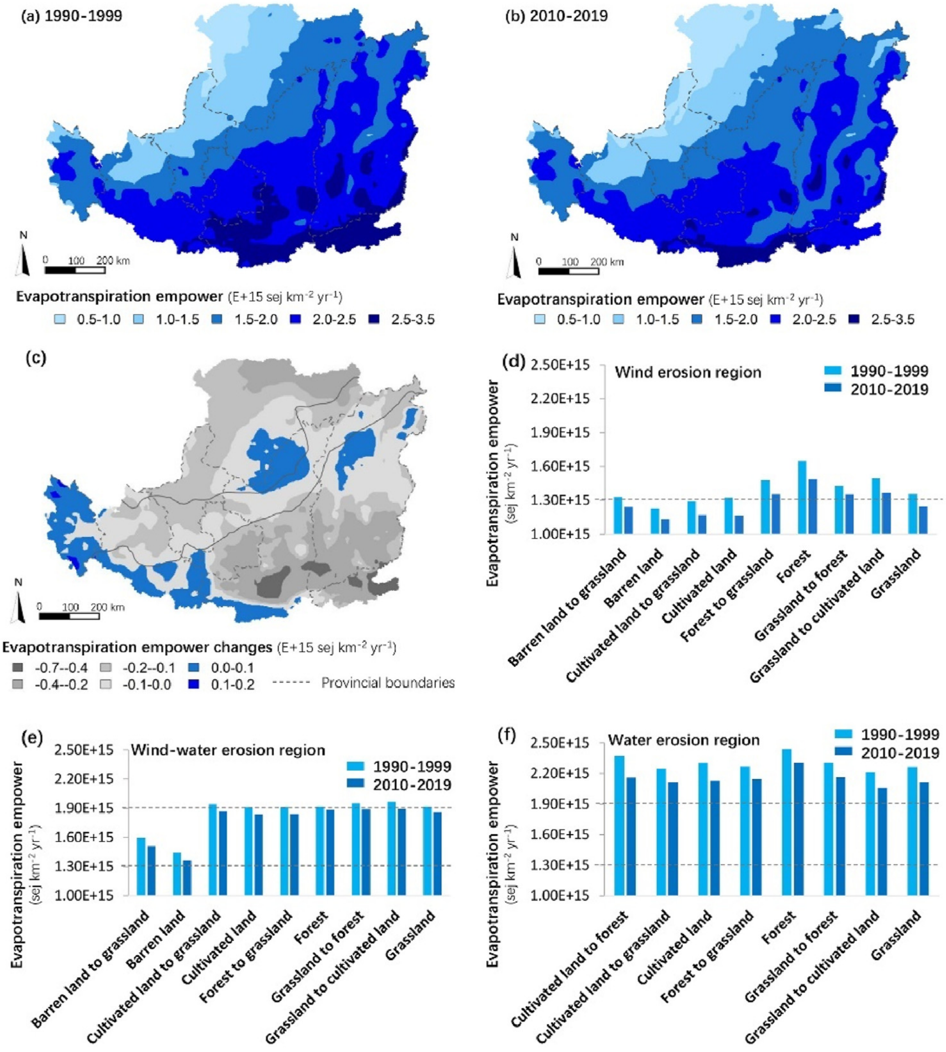

Fig. 5. The evapotranspiration empower (ET) on the Loess Plateau, China. (a, b, c) were the distributions of ET in 1990–1999 and in 2010–2019, and the changes between the two periods. (d, e, f) were the ET of different vegetation ecosystems in 1990–1999 and in 2010–2019 in three soil erosion regions, respectively.

in these two dry regions. When evaluating the effects of different vegetation restorations on the soil water balance at the catchment scale of the wind-water erosion region, Jian et al. (2015) also showed that the water utilization efficiency of grass and shrub species was superior to that of tree species. Although the forest had lower wind erosion than grassland in the wind and wind-water erosion regions, the total amount of soil erosion (combing the wind erosion and water erosion) of the forest was higher than the grassland (Fig A7). In addition, the higher or similar EPPSR of the forest than that of the grassland in the wind and wind-water erosion regions also indicated that in reducing the risk of soil erosion, the forest was no longer advantageous over the grassland in these two dry regions. The MePP, therefore, could also be one reason for the dominance of the grassland and cultivated land in both the wind and wind-water erosion regions.

4.2. The effects of ecosystem changes on RRE utilization efficiencies and environmental impacts

In the water erosion region, compared with the unchanged cultivated land and grassland, the vegetation restoration patterns (i.e., cultivated land to forest and to grassland, and grassland to forest) could reduce the RRE utilization efficiency (indicated by the REUE/RUE) (Fig. 6, A4) and improve water and soil conservation (indicated by the SWCE, EPPSR and WAE) (Fig. 7f, l, 8l). For the vegetation degradation patterns, i.e., forest to grassland, and grassland to cultivated land, however, the erosion risk increased compared to the unchanged forest and grassland (Fig 7l). This was consistent with the MePP that the self-organization development of ecosystem after vegetation restoration would first improve the water and soil conservation function, and provide a relatively bounteous resource environment for its further development (Li et al., 2013). Vice versa, ecosystem degradation will be accompanied by the destruction of its resource environment.

In the wind and wind-water erosion regions, the barren land to grassland, forest to grassland, and grassland to cultivated land could improve the REUE/RUE (Fig. 6, A6). This was also supported by the study of Zhang et al. (2016), who found that the grassland had higher water utilization efficiency than the forest in these regions, in which the forest only accounted for 20.25% of the grassland. From the environmental impact aspect, the cultivated land to grassland and the forest to grassland could reduce the water erosion and the soil erosion risk (indicated by the WAE and EPPSR) in the wind erosion region (Figs. 7j and 8j). Meanwhile, the barren

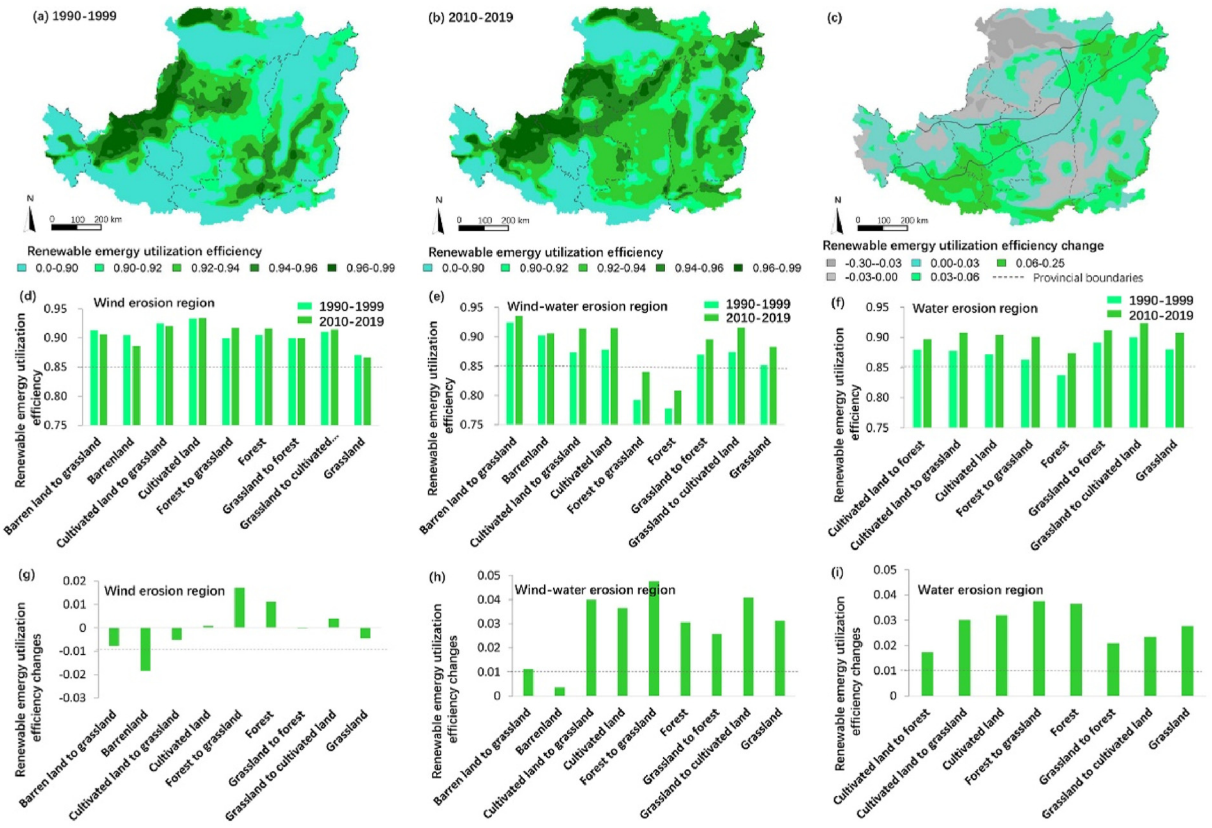

Fig. 6. The renewable emergy utilization efficiency (REUE) on the Loess Plateau, China. (a, b, c) were the distributions of REUE in 1990–1999 and in 2010–2019, and the differences between them. (d, e, f) were the REUE of different vegetation ecosystems in 1990–1999 and in 2010–2019 in three soil erosion regions, respectively. (g, h, i) were the changes of REUE of different vegetation ecosystems from 1990 to 1999 to 2010–2019 in three soil erosion regions, respectively.

land to grassland and cultivated land to grassland could also reduce the wind erosion (indicated by the WIE) in both the wind and wind-water erosion regions (Fig 9p, q). These results indicated that grassland and cultivated land could increase the water utilization efficiency, and grassland could also improve the environmental quality in water-limited regions, providing an evidence from a regional scale for the conclusion that grassland was more adaptable than forest in the water-limited dry regions (Chen et al., 2007).

4.3. The potential application of the multi-dimensional method

This study provided a new multi-dimensional method that combines landscape and systematic scale studies. By incorporating the main characteristics of the main issues concerned by the studied areas into the landscape and system integration model, it would give us a more comprehensive understanding of the interrelations between ecosystem services and the underlying system processing mechanisms in ecological fragile regions, like but not limited to LP. This is helpful to the land use planning and decision making in future. For example, considering the water shortage and soil erosion of the LP, this study selected the natural resource (rain) utilization efficiency, soil erosion, water conservation and other related ecosystem services as the main characteristics of the ecosystem. By comparing the differences of these indicators between three major ecosystems in different regions, this study revealed the main reasons for the optimal distribution of these ecosystems (i.e., forest and grassland) in different regions. Meanwhile, this study also suggested that the maximum resource acquisition is not always the optimal strategy for the development of ecosystem, especially in a resource-limited environment.

In dealing with the balance between Green and Grain and achieve grain yield increase in the LP is a problem urgently requiring an answer to satisfy the growing demand for food (Shi et al., 2020). Exploring the potential cultivated land might be a good way to solve this problem. From the environmental impact aspect, the forest was the optimal ecosystem in the water erosion region, and the forest to cultivated land and the grassland to cultivated land in this region were harmful to the environment of ecosystem (indicated by the WAE and EPPSR). Considering that the water erosion region is the main sediment source of the Yellow River and it still faces severe ecological problems (e.g., water erosion) (Tsunekawa et al., 2014), expanding large areas of the cultivated land in this region might not be sustainable. Compared to the water erosion region, the wind- and wind-water erosion regions have lower soil erosion (Fig. 8, Fig A7). However, the water shortage might be one of the major issues in these regions due to the high solar radiation, high wind and low rain input (the annual precipitation is below 400 mm) (Fig. 3). Therefore, how to improve the water utilization efficiency is of importance in these regions. This study showed that the grassland to cultivated land in the wind erosion region could decrease the REUE/RUE, decrease the SWCE, and increase the wind erosion (Figs. 7 and 8, A4). In addition, the SWCE of the grassland and cultivated land in the wind erosion region in 2010–2019 was found negative (Fig. 9). However, the grassland to cultivated land in the wind-water erosion region could increase the REUE/RUE and SWCE, without increasing the soil erosion (Figs. 7 and 8, A4). Therefore, the grassland to cultivated land might be more sustainable in the wind-water region than in the wind erosion region from the water utilization efficiency and water conservation. It was reported that many engineering

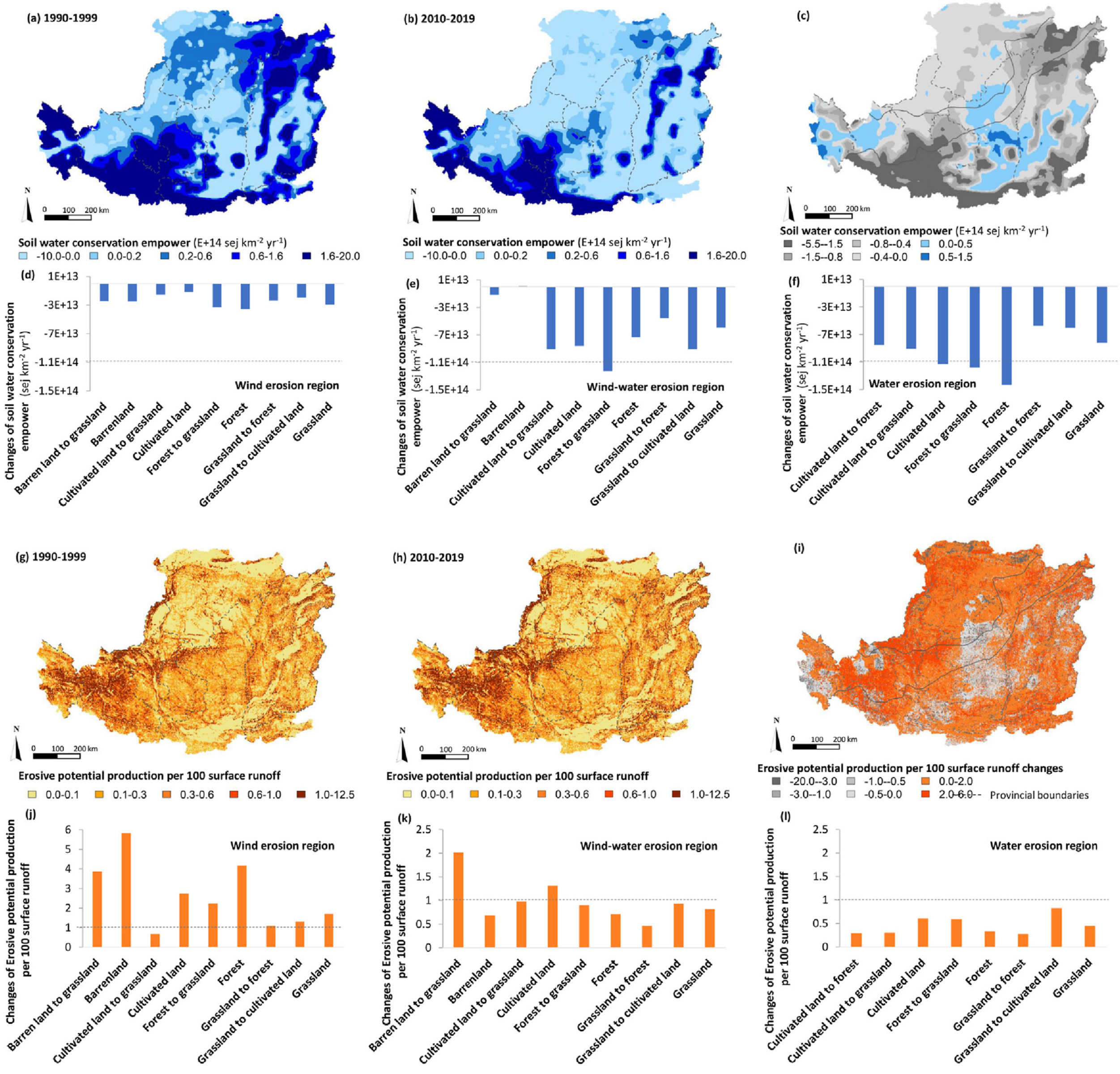

Fig. 7. The environment improvement indicators on the Loess Plateau, China. (a, b, c) were the distributions of soil water conservation empower (SWCE) in 1990–1999 and in 2010–2019, and the changes between the two periods. (d, e, f) were the changes of SWCE of different vegetation ecosystems from 1990 to 1999 to 2010–2019 in three erosion regions, respectively. (g, h, i) were the distributions of erosive potential production per 100 surface runoff (EPPSR) in 1990–1999 and in 2010–2019, and the changes between the two periods. (d, e, f) were the changes of EPPSR of different vegetation ecosystems from 1990 to 1999 to 2010–2019 in three erosion regions, respectively.

measures, e.g., terraced field, could effectively reduce some of the soil erosion in this region (Tsunekawa et al., 2014). Combining with some necessary measures to control soil erosion, expanding the area of cultivated land in the wind-water erosion region might be one choice for the coordinated development of grain yield increase and water and soil conservation in the LP.

5. Conclusions

Several interesting results have been found in this study. (1) In regions with relatively abundant water resources (i.e., water erosion region), forest could take more renewable resources for its rapid development and could reinforce production by improving the surrounding environment (i.e., conserving nutrients and water), although it had a lower water utilization efficiency than other ecosystems. (2) In the water-limited regions (i.e., wind and wind-water erosion regions), grassland was more suitable than forest since it had a higher water utilization efficiency and resource retention, and a lower soil erosion compared to forest. (3) Maximum resource acquisition is not always the optimal strategy for ecosystem development, especially in a resource-limited environment. These findings indicated that the MePP could be a general principle to drive ecosystem development in regional scale. This study also suggested that expanding cultivated land in the wind-water erosion region properly might be one choice for the coordinated development of grain yield increase and water and soil conservation on the LP. Based on emergy analysis, a new multi-dimensional method integrating landscape scale and system scale studies has been provided in this study. By incorporating the main characteristics of the major issues concerned in the studied area into the ecosystem processes and landscape integration model, the new method has a good application potential in guiding land use

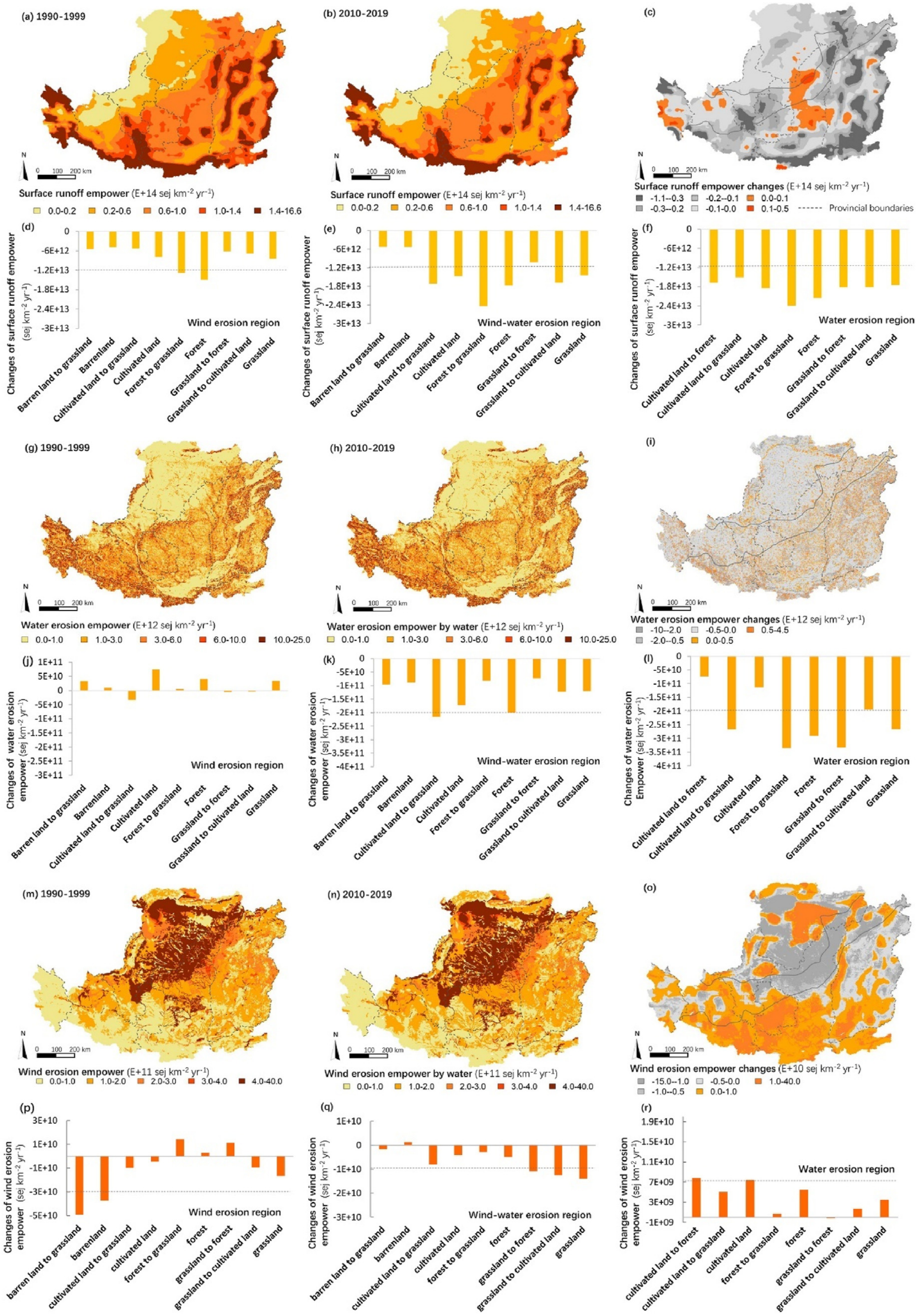

Fig. 8. The external environmental impact indicators on the Loess Plateau, China. (a, b, c) were the distributions of surface runoff empower (SR) in 1990–1999 and in 2010–2019, and the changes between the two periods. (d, e, f) were the changes of SR of different vegetation ecosystems from 1990 to 1999 to 2010–2019 in three erosion regions, respectively. (g, h, i) were the distributions of water erosion empower (WAE) in 1990–1999 and in 2010–2019, and the changes between the two periods. (j, k, l) were the changes of WAE of different vegetation ecosystems from 1990 to 1999 to 2010–2019 in three erosion regions, respectively. (m, n, o) were the distributions of wind erosion empower (WIE) in 1990–1999 and in 2010–2019, and the changes between the two periods. (p, q, r) were the changes of WIE of different vegetation ecosystems from 1990 to 1999 to 2010–2019 in three erosion regions, respectively.

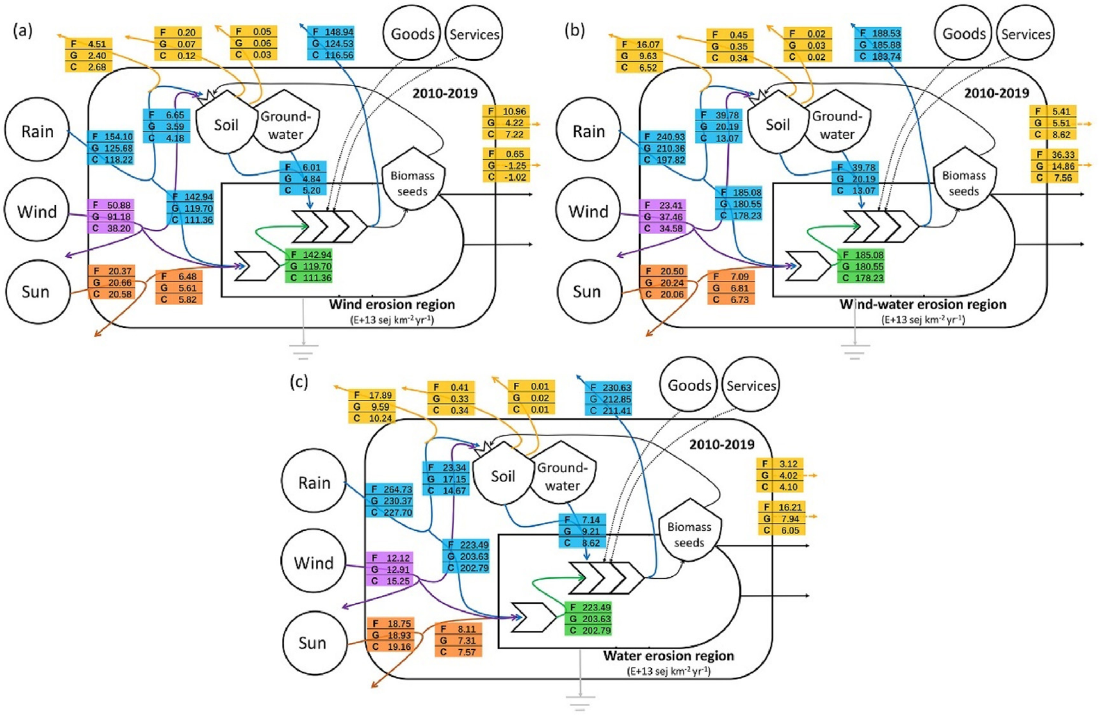

Fig. 9. The emergy system diagram models of forest, grassland and cultivated land in three erosion regions, respectively in 2010–2019 on the Loess Plateau, China. F = forest land, G = Grassland, and C=Cultivated land. The dotted lines refer to the erosive potential production per 100 surface runoff, and the value is dimensionless.

planning and decision making from both natural resources utilization and environmental impacts control aspects in ecological fragile areas. In which the natural resources are uneven distributed and scarce, like but not limited to the LP.

CRediT authorship contribution statement

Taotao Han: Conceptualization, Methodology, Software, Writing - original draft. **Hongfang Lu:** Conceptualization, Methodology, Writing - review & editing. **Yihe Lü:** Writing - review & editing. **Bojie Fu:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126102.

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