Evaluation of water conservation capacity of loess plateau typical mountain ecosystems based on InVEST model simulation

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Abstract: With increasing demand for water resources and frequently a general deterioration of local water resources, water conservation by forests has received considerable attention in recent years. To evaluate water conservation capacities of different forest ecosystems in mountainous areas of Loess Plateau, the landscape of forests was divided into 18 types in Loess Plateau. Under the consideration of the factors such as climate, topography, plant, soil and land use, the water conservation of the forest ecosystems was estimated by means of InVEST model. The result showed that 486417.7 hm$^2$ forests in typical mountain areas were divided into 18 forest types, and the total water conservation quantity was $1.64 \times 10^{12}$ m$^3$, equaling an average of water conversation quantity of $9.09 \times 10^{10}$ m$^3$. There is a great difference in average water conversation capacity among various forest types. The water conservation function and its evaluation is crucial and complicated issues in the study of ecological service function in modern times.

1. Introduction

With increasing demand for water resources and frequently a general deterioration of local water resources, water conservation by forests has received considerable attention in recent years [1-3]. The capacity for water conservation by forest ecosystems is an important attribute. Forest ecosystems intercept accumulator precipitation through the canopy, litter and soil layers replenish groundwater [4] and regulate aquifer and river flow[5-6].

The methods of water balance and rainfall storage are conventional methods to evaluate the water conservation function [7-8]. Taking into account spatial differences of soil permeability between different land-use types, water conservation capacity of different plots is evaluated quantitatively in the grid as a unit combined with the influence of topography, surface roughness on the surface runoff, evaluation [9-10]. The Model usually consists of producing water module and water conservation module. The idea that differs from rainfall storage is that the model considers that the interception of vegetation and litter for rainfall is ultimately lost through evaporation, which contributes little to water conservation. So water conservation of soil is only considered in this the model, which is a water conservation value of spatial and temporal scales [11].

The objectives of this study is to quantitatively evaluate the water conservation capacity of different forest types of Loess Plateau typical mountain area, InVEST model was applied to simulate and...
discuss the differences between different forest types in the Loess Plateau typical mountain area on the basis of the factors such as climate, topography, vegetation, soil and land use.

2. Materials and Methods

2.1 Method of forest landscape type division
The forest landscape type was relatively homogeneous units, which was distinguished from the forest at the landscape scale and it was the basis of studies of forest landscape spatial pattern [12-13]. Zoning methods of forest landscape were various. According to different data sources the methods can be divided into that based on CategoryIIof the seventh forest inventory and remote sensing images [14]. The forest landscape types of Loess Plateau typical mountain area were divided combining the two methods in this research. The database was established on 54 factors of CategoryIIof the seventh forest inventory of Loess Plateau “Eleventh Five-year”, including ecological status, geographic location, vegetation and site conditions. The data of CategoryIIof the sixth forest inventory, such forest type, forest origin, dominant tree species and land type, was integrated with ArcGIS 9.3 geographic information software platform, and finally 31846 subcompartments were obtained as the basis of data on forest landscape division.

The division of the forest landscape types was determined by research and problems elaborated. In addition, it was also subject to the existing data of the study area. But overall, the stand was the smallest geographical unit for dividing forest. Therefore, land type, forest type, forest origin and the dominant tree species were chosen as the factors to divide the forest landscape of Loess Plateau typical mountain area.

2.2 Model structure and data requirements
The InVEST model (The Integrate Valuation of Ecosystem Services and Tradeoffs Tool) is an ecosystem service assessment tool invented by Stanford University, WWF and The Nature Conservancy. In this study water conservation capacity of different forest types in the Loess Plateau typical mountain area was evaluated by a water conservation model of the InVEST model. The annual output of water was calculated by the water production model, the flow path and the topographic index was calculated according to the DEM and the runoff residence time on the grid was calculated using soil permeability and surface runoff flow coefficient. Finally water conservation was calculated. The water conservation referred to rainfall removing the evaporation and surface runoff into the ground water. Model-driven data included topographic data, average annual precipitation, annual potential evapotranspiration, landscape pattern maps, soil depth, root depth, plant available water content and evapotranspiration coefficient.

Topographic data: Topographic data derived from 90m accuracy DEM of Loess Plateau typical mountain area. Using ArcGIS software, DEM was shadowed, convossed, cut and filled (Fig.1).

Precipitation: The precipitation was expressed by TRMM series. The TRMM monthly rainfall series were derived from real-time (3h) TRMM and other satellite rainfall from space analysis, with the accuracy of 0.25°. The rainfall data of TRMM series were used in this model after the inverse-distance weighting method interpolation (Fig. 2).

Potential evaporation: Potential evaporation (PET) was the same as reference evapotranspiration (ET0) in the model (Thomas 2008). In areas where data was difficult to obtain, InVEST model recommended using the Modified-Hargreaves method to calculate potential evapotranspiration:

The potential evapotranspiration (Fig. 3) calculated by this method was almost the same as the result of potential evapotranspiration trends of China calculated by Storey and Jokimbi [15].

Available water content of soil (AWC): AWC (Fig. 4) was calculated by the non-linear fitting model established on the basis of soil texture and soil organic matter [16]:

\[
AWC(\% ) = 54.509 - 0.132 \times Sand\% - 0.003 \times (Sand\%)^2 - 0.055 \times Silt\% - 0.006 \times (Silt\%)^2 - 0.738 \times Clay\% + 0.007 \times (Clay\%)^2 - 2.688 \times OM\% + 0.501 \times (OM\%)^2
\]

Where: AWC——available water content of soil; OM——organic matter.
Soil saturated hydraulic conductivity: By region (vegetation type, soil type) cross-validation with the existing results, with the calculation results closer to the measured value of the relevant region and the soil particle composition data of the second national soil survey, soil saturated hydraulic conductivity of Loess Plateau typical mountain area was obtained by Rossta software.

![Fig. 1. DEM of Loess Plateau typical area](image1)

![Fig. 2. Average precipitation of Loess Plateau typical area](image2)

![Fig. 3. PET of Loess Plateau typical area](image3)

![Fig. 4. Available water content of soil](image4)

2.3 Model calculation

First of all, calculate the annual output of flow of each cell.

\[ Y_j = (1 - \frac{AET_j}{P_x}) \times P_x \]  

(2)

\( Y_j \) — the annual output of water in cell x of forest landscape type j, mm. \( AET_j \) — the annual actual evapotranspiration in cell x of forest landscape types j, mm. \( P_x \) — annual precipitation in cell x, mm.

Secondly, use Budyko to calculate the evapotranspiration of the water balance.
\[ \frac{AET_{xj}}{P_r} = \frac{1 + \omega_r + R_{xj}}{1 + \omega_r + \frac{1}{R_{xj}}} \]  

\[ R_{xj} \]— Budyko dryness index in cell x of land use type j. It is defined as the ratio of potential evapotranspiration and precipitation. \( \omega_r \)— the ratio of annual water need and precipitation of the plant. It is defined as the parameter to describe natural climate—soil properties.

Finally, calculate the water amount into the soil layer according to formula.

\[ \text{Retention} = \min(1, \frac{249}{\text{Velocity}}) \times \min(1, \frac{0.9 \times TI}{3}) \times \min(1, \frac{K_{sat}}{300}) \times \text{Yield} \]  

\[ \text{Retention} \]— water amount of soil. \( \text{Velocity} \)— coefficient flow rate. \( TI \)— topographic index. \( K_{sat} \)— Soil saturated hydraulic conductivity. \( \text{Yield} \)— water production.

3. Results

3.1 Division of forest landscape type

Based on ArcGIS and survey data, topographic maps and remote sensing image of the Loess Plateau typical mountain area, mainly focusing on landscape matrix layer characteristics, combining dominant tree species with forest origin, forest landscape types of Loess Plateau typical mountain area were divided into 18 types.

There were 18 types including 31846 subcompartments with the area of 486417.7hm². The area of economic forest was maximum in the entire forest landscape types while natural mixed coniferous forests were the smallest. The average area of natural \textit{Quercus acutis} subcompartment was maximum while the average area of artificial \textit{Populus davidiana} subcompartment was the smallest. The results were shown in Table 1.

| Forest types | Forest Origin | Dominant tree species | NO. of subcompartment | Area (ha) | Rate of area (%) |
|--------------|---------------|-----------------------|------------------------|-----------|-----------------|
| Coniferous forest | Natural forest | Pinus tabuliformis (P01) | 365 | 4892.95 | 1.01 |
| | | Pinus tabuliformis (P02) | 933 | 22420.22 | 4.61 |
| | | Pinus tabuliformis (P03) | 4754 | 57118.34 | 11.74 |
| | Plantation | Larix principis (P04) | 479 | 7367.35 | 1.51 |
| | | Pinus tabuliformis (P05) | 3262 | 45553.15 | 9.37 |
| | | Quercus acutis (P06) | 3377 | 97631.36 | 20.07 |
| | Natural forest | Betula platyphylla (P07) | 341 | 11334.59 | 2.33 |
| | | Populus davidiana (P08) | 543 | 11604.86 | 2.39 |
| | | Other broad-leaved tree (P09) | 979 | 21600.63 | 4.44 |
| | | Quercus acutis (P10) | 654 | 11604.02 | 2.39 |
| | Broad-leaved forest | Robinia pseudoacacia (P11) | 1066 | 11773.15 | 2.42 |
| | | Populus davidiana (P12) | 1955 | 9638.13 | 1.98 |
| | | Other broad-leaved tree (P13) | 524 | 4961.14 | 1.02 |
| | | Economic forest (P14) | 9191 | 109367.4 | 22.48 |
| | | Coniferous forest (P15) | 180 | 3990.74 | 0.82 |
| | | Broad-leaved forest (P16) | 563 | 13860.54 | 2.85 |
| | | Coniferous forest (P17) | 2091 | 32289.31 | 6.64 |
| | Coniferous and broad-leaved mixed forest | Natural forest | 180 | 3990.74 | 0.82 |
| | | Broad-leaved forest (P18) | 589 | 9409.84 | 1.93 |
3.2 Water conservation of different types of forest landscape

InVEST water conservation model was operated in ArcGIS to assess water conservation function of Loess Plateautypical mountain area. Under the statistics of partition statistics of forest landscape type, it indicated that the total water conservation capacity was $1.64 \times 10^{12}$ m$^3$ and the average amount was $9.09 \times 10^6$ m$^3$. There is a great difference in average water conversation capacity among various forest types, and the highest one was $1.09 \times 10^7$ m$^3$ for the artificial larch plantation; while the smallest one is $2.36 \times 10^5$ m$^3$ for the plantation of other broadleaved tree species. The highest one of total water holding capacity was $8.31 \times 10^{11}$ m$^3$ for the natural forest of oak, while the smallest one is $6.15 \times 10^8$ m$^3$ for the plantation of other broadleaved tree species. The results were shown in Table 2.

| Forest landscape types | Maximum water conservation quantity/m$^3$ | Average water conservation quantity/m$^3$ | Total water conservation quantity/m$^3$ |
|------------------------|-------------------------------------------|------------------------------------------|----------------------------------------|
| P 01                   | $1.57 \times 10^6$                        | $3.82 \times 10^5$                       | $1.29 \times 10^9$                     |
| P 02                   | $8.97 \times 10^6$                        | $1.86 \times 10^6$                       | $3.45 \times 10^{10}$                  |
| P 03                   | $2.33 \times 10^7$                        | $5.79 \times 10^6$                       | $2.15 \times 10^{11}$                  |
| P 04                   | $2.32 \times 10^6$                        | $1.10 \times 10^6$                       | $6.08 \times 10^9$                     |
| P 05                   | $1.81 \times 10^7$                        | $4.35 \times 10^6$                       | $9.24 \times 10^{10}$                  |
| P 06                   | $2.94 \times 10^7$                        | $1.09 \times 10^7$                       | $8.31 \times 10^{11}$                  |
| P 07                   | $3.16 \times 10^6$                        | $8.80 \times 10^5$                       | $7.65 \times 10^9$                     |
| P 08                   | $3.20 \times 10^6$                        | $7.57 \times 10^5$                       | $6.76 \times 10^9$                     |
| P 09                   | $6.21 \times 10^6$                        | $1.27 \times 10^6$                       | $2.14 \times 10^{10}$                  |
| P 10                   | $3.85 \times 10^6$                        | $6.70 \times 10^5$                       | $4.71 \times 10^9$                     |
| P 11                   | $3.20 \times 10^6$                        | $6.61 \times 10^5$                       | $4.76 \times 10^9$                     |
| P 12                   | $2.85 \times 10^6$                        | $5.11 \times 10^5$                       | $3.47 \times 10^9$                     |
| P 13                   | $1.51 \times 10^6$                        | $2.36 \times 10^5$                       | $6.15 \times 10^8$                     |
| P 14                   | $3.82 \times 10^7$                        | $5.25 \times 10^6$                       | $3.51 \times 10^{11}$                  |
| P 15                   | $1.09 \times 10^6$                        | $2.96 \times 10^5$                       | $9.33 \times 10^9$                     |
| P 16                   | $3.91 \times 10^6$                        | $1.11 \times 10^6$                       | $1.10 \times 10^{10}$                  |
| P 17                   | $9.93 \times 10^6$                        | $2.07 \times 10^6$                       | $3.99 \times 10^{10}$                  |
| P 18                   | $2.68 \times 10^6$                        | $5.54 \times 10^5$                       | $2.61 \times 10^9$                     |

4. Discussion and Conclusion

The water conservation function of forest ecosystems and its valuation are hot issues of ecosystem service research, but also extremely complex and difficult issues. The InVEST model can better assess the water conservation capacity in Loess Plateau typical mountain area. In addition to water conservation assessment showed in this study, InVEST model can also be used to analyze problems such as soil erosion, non-point source pollution and runoff to provide reference for soil and water conservation, which are subject to further development and utilization.

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References

[1] Ibbitt, R. and R. Woods. Re-scaling the topographic index to improve the representation of physical processes in catchment models[J]. *Journal of Hydrology*, 2004, **293**:205-218.

[2] Pagiola, S. Payments for environmental services in Costa Rica[J]. *Ecological Economics*, 2008,65 (4): 712-724.
[3] Odin, J. Evaluation of Empirical Formulae for Determination of Hydraulic Conductivity based on Grain-Size Analysis [J]. Agricultural Forest Meteorology, 2014, 188(2):56-63.

[4] Wang Aijuan, Zhang Wenbo. Study on research on canopy interception rainfall [J]. Journal of Soil and Water Conservation, 2009, 15 (04): 55-59.

[5] Maid LOTFALIAN, Ayden PARSAKHOO, Ayatollah KAVIAN, EyedAyatollah HOSSEINI. Runoff and sediment concentration of different parts of a road in Hyrcanian forests [J]. For. Sci. Pact, 2013, 15 (2): 144-151.

[6] Zhang Kun, Zhang Hongjiang, Chen Jinhua, et al. Effects of Forest Canopy Interception on Five Forest Types in Chongqing Simian Mountain [J]. Journal of Northwest A & F University: Natural Science Edition, 2011, 39 (17): 173-178.

[7] Yin Yi, Chen Haishan. Numerical simulation of effects of vegetation canopy interception on surface water and energy balance [J]. Meteorological Science, 2013, 33 (2): 119-129.

[8] Huang Xianlun, Fan Guangzhou, Zhou Dingwen, et al. Relationship between East Asian summer monsoon system and winter vegetation in Qinghai - Tibet Plateau [J]. Meteorological Science, 2010, 30 (3): 358-365.

[9] XIAO Pei-qing, YAO Wen-yi, SHEN Zhen-zhou, et al. Experimental study on erosion and sediment yield and hydrodynamic mechanism of alfalfa grassland [J], Chinese Journal of Water Resources, 2011, 42 (2): 232-237.

[10] He Changqing, Xue Jianhui, Wu Yongbo, et al. Rainfall redistribution of alpine oak forest in subalpine of Minjiang River [J]. Chinese Journal of Applied Ecology, 2008, 19 (9): 42-44.

[11] Wang Xiaoyan, Chen Hongsong, Wang Keling. Study on Soil Evaporation and Vegetation Transpiration in Different Land Uses on Red Soil Sloping Land [J]. Journal of Agricultural Engineering, 2007, 23 (12): 41-45.

[12] Asdak C, Jarvis P G, Van Gardingen P, Fraser A. Rainfall interception loss in unlogged and logged forest areas of central Kalimantan, Indonesia [J]. Journal of Hydrology, 1998, 206 (3 / 4): 237-244.

[13] Liu Wenjie, Li Pengju, Li Hongmei, et al. Xishuangbanna tropical seasonal rain forest canopy interception fog and soil water relationship [J]. Journal of Ecology, 2006, 26 (1): 9-15.

[14] Zhuo Li, Su Derong, Liu Zixue, et al. Experimental study on canopy interception of turf grass [J]. Journal of Ecology, 2009, 29 (2): 669-675.

[15] Wohlfahrt G, Bianchi K, Cernusca A. Leaf and stem maximum water storage capacity of herbaceous plants in a mountain meadow [J]. Journal of Hydrology, 2006, 319 (1 / 4): 383-390.

[16] Thomas, A. Development and properties of 0.25-degree gridded evapotranspiration data fields of China for hydrological studies [J]. Journal of Soil and Water Conservation, 2009, 15 (04): 55-59.