Quantification and Spatial Variation of Ecosystem Service Values of Tianshan Spruce Forests in Central Tianshan: A Postprint

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Abstract

This study examines the Tianshan spruce forest in the central Tianshan Mountains, and based on the functional value method, employs the Getis-Ord Gi* hot spot analysis method to perform quantitative visualization analysis of the spatial pattern of ecological service value. The results demonstrate that: (1) The total ecological service function value of the Tianshan spruce forest in the central Tianshan Mountains is 96.09$×$108 yuan·a-1, with water conservation, carbon sequestration and oxygen release, soil conservation, and biodiversity conservation constituting the dominant functions. (2) The ecological service value across different forest age classes exhibits the following pattern: middle-aged forest is highest, followed by near-mature forest, mature forest, and young forest, while over-mature forest has the lowest total value but the highest per-unit-area value. (3) The ecological service value across different forest farms exhibits the following pattern: Nanshan Forest Farm is highest, followed by Hutubi Forest Farm, Banfanggou Forest Farm, and Miquan Forest Farm, with Xinjiang Agricultural University Practice Forest Farm being the lowest. (4) The forest ecosystem service function values among different forest farms display significant clustering characteristics, with hot spot areas concentrated in Hutubi Forest Farm and Nanshan Forest Farm in the southwest, and cold spot areas concentrated in Miquan Forest Farm and Banfanggou Forest Farm in the northeast. These results provide a scientific basis for regional ecological resource optimization management and ecological protection policy formulation, and offer theoretical support for the sustainable development of the Tianshan forest ecosystem.

Full Text

Quantification and Spatial Differentiation of Ecosystem Service Value of Picea schrenkiana Forest in the Central Tianshan Mountains

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Abstract

This study examines the Picea schrenkiana forest ecosystem in the central Tianshan Mountains, Xinjiang, China. Using the functional value method and Getis-Ord Gi* hotspot analysis, we quantified and visualized the spatial patterns of ecosystem service values. The results show that the total value of ecosystem services for Picea schrenkiana forests is 96.09$×10^{8}$ Yuan per year, with water conservation, carbon sequestration and oxygen release, soil conservation, and biodiversity protection serving as the dominant functions. Ecosystem service values vary significantly by forest age, with middle-aged forests exhibiting the highest value, followed by near-mature, mature, and young forests; over-mature forests show the lowest total value but the highest per-unit area value. Among the five forest farms, Nanshan Forest Farm demonstrates the highest ecosystem service value, followed by Hutubi, Banfanggou, and Miquan Forest Farms, with the Xinjiang Agricultural University Practice Forest Farm showing the lowest value. Significant spatial clustering of ecosystem service values occurs across forest farms, with hotspots concentrated in the southwestern Hutubi and Nanshan Forest Farms, while cold spots are concentrated in the northeastern Miquan and Banfanggou Forest Farms. These findings provide a scientific basis for optimizing regional ecological resource management, formulating ecological protection policies, and supporting the sustainable development of the Tianshan forest ecosystem.

Keywords: Picea schrenkiana forest; spatial pattern of ecosystem service values; ecosystem services; central Tianshan Mountains

1. Introduction

Ecosystem service functions refer to the various benefits that ecosystems provide to human society, either directly or indirectly, while maintaining their own ecological balance, including water conservation, soil conservation, carbon sequestration and oxygen release, and other functions. As a crucial component of terrestrial ecosystems, forests play a vital role in ecological security and socioeconomic sustainable development. In recent years, the classification, assessment, and accounting of ecosystem service functions have become important topics in global ecological economics research. Daily and Costanza et al. proposed definitions and classification methods for ecosystem service functions, establishing a theoretical foundation for subsequent research. In China, researchers began introducing relevant theories in the 1990s and developed ecosystem service value equivalent factor methods based on Chinese conditions.

Currently, domestic and international studies primarily employ functional value methods and equivalent factor methods for assessment. The functional value method offers high accuracy but requires substantial data, making it suitable for small-scale evaluations. The equivalent factor method is simple and efficient but insufficient in reflecting spatial heterogeneity and dynamic changes. Most existing research has focused on global, national, or watershed scales, with relatively few studies examining spatial distribution characteristics, regional differences, and synergistic or trade-off relationships among functions at the regional scale. The Tianshan mountain forest represents an essential component of Xinjiang' s terrestrial ecosystem, playing an irreplaceable role in maintaining ecological security and promoting regional economic development. Picea schrenkiana, as the most widely distributed and largest timber volume species in Xinjiang' s mountain forests, demonstrates significant ecological functions in water conservation, soil conservation, and climate regulation. Although previous studies have addressed multi-scale assessments of forest ecosystem service functions in Xinjiang, research on the spatial distribution characteristics and regional differences of forest ecosystem service functions in the central Tianshan Mountains remains insufficient, particularly regarding aggregation characteristics and spatial synergistic relationships among functions. Therefore, this study focuses on the Picea schrenkiana forest ecosystem in the central Tianshan Mountains, combining functional value methods with Getis-Ord Gi* hotspot analysis to quantify and evaluate ecosystem service function values and reveal their spatial distribution patterns and hotspot areas. The research aims to provide a scientific basis for regional ecological resource optimization management and ecological protection policy formulation, while offering theoretical support for the sustainable development of the Tianshan forest ecosystem.

2. Materials and Methods

2.1 Study Area

The study area is located in the northern foothills of the central Tianshan Mountains in Xinjiang (43°01 ~43°97 N, 86°46 ~87°67 E), primarily distributed in the mid-mountain zone at elevations of 1500–2200 m. The region belongs to a semi-arid coniferous forest climate zone, with an average annual temperature of 6.55°C, unevenly distributed precipitation concentrated in the same season as heat, an average annual precipitation of 600 mm, abundant sunlight with annual sunshine duration exceeding 2040 hours, and terrain that slopes higher in the south and lower in the north. The soil type is mountain gray-brown forest soil. The vegetation is dominated by Picea schrenkiana and grasses, with representative understory plants including Aegopodium alpestre, Polygonum viviparum, Poa nemoralis, Cicerbita azurea, and Stellaria soongorica. Based on forest resource inventory data, the central Tianshan Picea schrenkiana forest was divided into five forest farms: Nanshan, Miquan, Banfanggou, Xinjiang Agricultural University Practice Forest Farm, and Hutubi. Forest stands were classified by age into young, middle-aged, near-mature, mature, and over-mature forests. Required social public data included reservoir construction cost per unit capacity, water purification costs, fertilizer prices, and oxygen prices, sourced from government agencies, industry reports, and official websites, with data from 2019. Supplementary data were obtained from published research papers and professional journals. Field survey data on tree height, diameter at breast height (DBH), soil nutrient content, vegetation diversity, and canopy density were collected through sampling in 2019.

2.2 Evaluation Indicators

Based on the "Specifications for Assessment of Forest Ecosystem Services in China" (hereinafter referred to as the "Specifications") and corresponding formulas, this study adopted six specific evaluation indicators: water conservation, soil conservation, carbon sequestration and oxygen release, nutrient accumulation, atmospheric environment purification, and biodiversity protection (Table 1).

2.3 Data Sources

Data sources included forest resource inventory data and vector data, social public data, literature and research findings, and field monitoring data. Forest resource inventory data were utilized to obtain stand characteristics. Social public data included reservoir construction cost per unit capacity (6.07 Yuan $\cdot$ m^{-3}), excavation and transportation costs per unit area (12.6 Yuan $\cdot$ m^{-3}), diammonium phosphate fertilizer price (2400 Yuan $\cdot$ t^{-1}), potassium chloride fertilizer price (2200 Yuan $\cdot$ t^{-1}), organic matter price (320 Yuan $\cdot$ t^{-1}), nitrogen content in diammonium phosphate (18.00%), phosphorus content (46.01%), potassium content in potassium chloride (60.00%), water purification cost (2.79 Yuan $\cdot$ t^{-1}), and oxygen price (1000 Yuan $\cdot$ t^{-1}). The carbon tax rate adopted was 150 USD per ton, based on Swedish carbon tax rates. These data were sourced from the China Water Resources Yearbook, Ministry of Water Resources budget quotas, China Agricultural Information Network, fertilizer product specifications, Xinjiang government wastewater treatment fees, and the National Health Commission. Field data from 2019 were obtained through plot surveys, including tree height, DBH, soil nutrient content, vegetation diversity, and canopy density.

2.4 Measurement Methods

This study employed a distributed calculation method, dividing the central Tianshan region into five primary calculation units: Nanshan Forest Farm, Miquan Forest Farm, Banfanggou Forest Farm, Xinjiang Agricultural University Practice Forest Farm, and Hutubi Forest Farm. Each primary unit was further divided into five secondary calculation units by forest age. Calculations were performed according to formulas in the Specifications to generate homogeneous data for each unit, which were then aggregated for comprehensive analysis. Using the ArcGIS platform, hotspot analysis (Getis-Ord Gi*) was applied to statistically identify significant hotspot and cold spot areas.

3. Results

3.1 Physical Quantification and Valuation of Ecosystem Services

3.1.1 Physical Quantification The total water regulation volume of the Picea schrenkiana forest ecosystem in the central Tianshan Mountains was 2.83×10^{8} m^3, with water purification volume also at 2.83×10^{8} m^3. Carbon sequestration amounted to 1.21×10^{6} t, oxygen release to 3.24×10^{6} t, nutrient accumulation to 1.86×10^{4} t (with nitrogen fixation at 1.13×10^{4} t, phosphorus fixation at 0.04×10^{4} t, and potassium fixation at 0.03×10^{4} t), and negative ion provision reached 2.79×10^{24} units. The ranking of per-unit-area physical quantities for each indicator matched that of total physical quantities (Table 3).

3.1.2 Valuation The total ecosystem service value of Picea schrenkiana forests in the central Tianshan Mountains was 96.09×10^{8} Yuan per year. Water conservation value was highest at 34.06×10^{8} Yuan, accounting for 35.45% of the total. Carbon sequestration and oxygen release value ranked second at 31.87×10^{8} Yuan (33.16%). Soil conservation value was 14.34×10^{8} Yuan (14.93%), biodiversity protection value was 1.75×10^{8} Yuan (1.82%), nutrient accumulation value was 0.20×10^{8} Yuan (0.21%), and atmospheric environment purification value was lowest at 0.20×10^{8} Yuan (0.21%). Overall, water conservation, carbon sequestration/oxygen release, and soil conservation accounted for 83.54% of total ecosystem service value, demonstrating clear dominance (Figure 2).

3.2 Ecosystem Service Values by Forest Age

Calculated values varied significantly among age classes. Middle-aged forests exhibited the highest value at 386.84×10^{8} Yuan (40.26% of total), followed by near-mature forests at 347.87×10^{8} Yuan (36.20%), mature forests at 177.98×10^{8} Yuan (18.52%), young forests at 30.34×10^{8} Yuan (3.16%), and over-mature forests at 17.91×10^{8} Yuan (1.86%). Middle-aged and near-mature forests combined contributed 76.46% of total value, playing a crucial role in the ecosystem. However, per-unit-area value showed a different pattern: over-mature forests > mature forests > near-mature forests > middle-aged forests > young forests (Table 5).

3.3 Ecosystem Service Values by Forest Farm

Both physical quantities and values varied among forest farms, generally correlating positively with forest area and volume. Nanshan Forest Farm showed the highest ecosystem service value at 375.97$\times10^{8}$ Yuan (39.13% of total), followed by Hutubi at 272.61$\times10^{8}$ Yuan (28.37%), Banfanggou at 205.09$\times10^{8}$ Yuan (21.34%), Miquan at 65.56$\times10^{8}$ Yuan (6.82%), and Xinjiang Agricultural University Practice Forest Farm at 41.71$\times10^{8}$ Yuan (4.34%). Nanshan Forest Farm dominated in carbon sequestration/oxygen release and water conservation, while Hutubi Forest Farm excelled in soil conservation (Table 6).

Spatial clustering analysis revealed distinct patterns. Hotspot areas were concentrated in southwestern Hutubi and Nanshan Forest Farms, particularly for water conservation, soil conservation, and carbon sequestration/oxygen release. Cold spots were concentrated in northeastern Miquan and Banfanggou Forest Farms (Figure 3). Hotspot and coldspot areas each accounted for approximately 30% and 35% of the total area, respectively, reflecting regional imbalances in ecosystem service capacity (Table 7).

Overlay analysis of the three primary service functions (water conservation, soil conservation, and carbon sequestration/oxygen release) identified four hotspot categories (Figure 4). Non-hotspot areas accounted for the largest proportion (45.67%), while Class III hotspots (all three functions) were smallest at 8.29%. Class I, II, and III hotspots were primarily concentrated in Hutubi and Nanshan Forest Farms (Table 8).

4. Discussion

This study quantified ecosystem service values for Picea schrenkiana forests in the central Tianshan Mountains using Specifications-based formulas and identified spatial patterns through hotspot analysis. The total ecosystem service value was 96.09$\times10^{8}$ Yuan per year, with water conservation, carbon sequestration/oxygen release, soil conservation, and biodiversity protection as dominant functions. These findings align with Yang et al.' s synthesis of Chinese forest ecosystem service valuations, which identified water conservation, carbon sequestration/oxygen release, soil conservation, and biodiversity protection as dominant services in China' s forests. They also support Li et al.' s theory that water conservation is primary in forest ecosystem services. Studies by Sun et al. and Li et al. on Xinjiang' s mountain forests and Altai Mountains similarly identified water conservation, carbon sequestration/oxygen release, biodiversity protection, and soil conservation as key functions, confirming Picea schrenkiana forests' vital contributions to water resources, carbon sequestration, and ecological security. Notably, soil conservation function was particularly strong in our study area, consistent with research by Li et al. and Huang et al. demonstrating that natural forest protection programs significantly enhance soil conservation capacity, with effects becoming more pronounced over time.

The per-unit-area ecosystem service value in our study area was lower than in Hunan, Chongqing, and Hebei provinces, consistent with Qi et al.' s finding that China's forest ecosystem services show an "east-high west-low, south-high north-low" distribution pattern. This pattern relates closely to regional climate, forest types, and biodiversity. Our study area lies in western mountainous regions with arid climate, simple forest types, and lower vegetation cover and biodiversity compared to eastern and southern forests. Atmospheric environment purification accounted for the lowest proportion of ecosystem services, differing somewhat from some studies. As Yang noted, mountain forests typically show weaker atmospheric purification than urban forests due to their distance from urban and industrial pollution sources and lower exposure to harmful gases and particulates. Consequently, this study only evaluated negative ion provision for atmospheric environment purification, excluding PM2.5 and other pollutants, resulting in lower values than other regions.

Ecosystem service values varied significantly by forest age, with middle-aged forests highest, followed by near-mature, mature, and young forests, and over-mature forests lowest. However, over-mature forests showed the highest per-unit-area value. Middle-aged and near-mature forests, as the main components of the Picea schrenkiana forest ecosystem, occupy a critical stage in forest valuation. These forests are in rapid growth phases with high photosynthetic efficiency, superior carbon sequestration/oxygen release capacity, and vigorous transpiration that aids water conservation and microclimate regulation. Their rich species composition and complex structure maintain high biodiversity and strong natural regeneration capacity. Over-mature forests, despite lower total values, exhibit the highest per-unit-area value due to tall trees, extensive root systems, abundant litter, and stable ecological structure, significantly enhancing per-unit performance in water conservation and soil conservation. These results demonstrate that different age classes provide distinct ecosystem services, highlighting the importance of managing forest resources by age class to enhance regional ecosystem services and sustainability.

Ecosystem service physical quantities and values varied among forest farms, with Nanshan Forest Farm highest, consistent with Li et al.' s findings that ecosystem service quantities and values correlate closely with forest area and volume. Values ranked Nanshan > Hutubi > Banfanggou > Miquan > Xinjiang Agricultural University Practice Forest Farm, proportional to forest area. Cluster analysis revealed similar hotspot patterns across service functions, with hotspots concentrated in the largest Nanshan and Hutubi Forest Farms and cold spots in Miquan and Banfanggou Forest Farms. Overlay analysis showed Class I, II, and III hotspots also concentrated in Nanshan and Hutubi Forest Farms, particularly in the largest Nanshan Forest Farm.

This study used forest inventory data from central Tianshan forest farms to objectively reflect ecosystem service conditions. However, limitations exist: the assessment method relies heavily on forest area, tree height, and age, some parameters were difficult to obtain, and only six service functions were valued, potentially affecting accuracy. Forest ecosystems are dynamic and constantly evolving, making short-term monitoring data limited. Additionally, substitute market prices used in the replacement cost method fluctuate with time and social demand, requiring adjustment of ecological value coefficients to improve assessment precision. Quantifying forest ecosystem service values helps the public intuitively understand their importance, enhances environmental awareness, and promotes scientific forestry development.

5. Conclusions

1) The total ecosystem service value of Picea schrenkiana forests in the central Tianshan Mountains is 96.09$×10^{8}$ Yuan per year, with water conservation, carbon sequestration/oxygen release, soil conservation, and biodiversity protection as the dominant functions.

2) Ecosystem service values vary significantly by forest age, with middle-aged forests highest, followed by near-mature, mature, and young forests; over-mature forests show the lowest total value but highest per-unit-area value. Middle-aged and near-mature forests contribute most substantially and represent the core stage for ecosystem service provision.

3) Nanshan Forest Farm exhibits the highest value, followed by Hutubi, Banfanggou, and Miquan Forest Farms, with Xinjiang Agricultural University Practice Forest Farm lowest. Significant spatial clustering occurs across forest farms, with hotspots concentrated in southwestern Hutubi and Nanshan Forest Farms and cold spots concentrated in northeastern Miquan and Banfanggou Forest Farms.

References

[1] Yan Zhengyang, Li Zhichao, Wang Shunxing, et al. Evaluation of forest ecosystem services material quantity and value of Luoyang, western Henan Province, China[J/OL]. Journal of Northwest Forestry University. [2024-09-05]. http://kns.cnki.net/kcms/detail/61.1202.S.20240628.1117.004.html.

[2] Zhang Xinyu, Guo Shiyun, Wang Yaping, et al. Research on the value of forest ecosystem service function and its spatial analysis in Xiong' an New Area[J]. Journal of Henan Agricultural University, 2022, 56(4): 661-673, 684.

[3] Zhang Ning, Zhang Zhitao, Wang Yuehua, et al. Accounting of forest land and forest resources in Jilin Province of northeastern China[J]. Journal of Beijing Forestry University, 2024, 46(6): 57-69.

[4] Xu Yun. Evaluation of forest ecosystem service function and value in Huizhou City of Guangdong Province[J]. Forest Resources Management, 2023, 52(3): 140-

145.

[5] Chen Yue, Gao Fan, Peng Zuodeng. The impact of natural forest protection project on natural forest resources and ecosystem services in Beijing-Tianjin-Hebei region[J]. Journal of Northwest Forestry University, 2024, 41(3): 1-9.

[6] Velasco Muñoz J F, Aznar Sánchez J A, Schoenemann M. An analysis of the worldwide research on the socio-cultural valuation of forest ecosystem services[J]. Sustainability, 2022, 14(4): 2089, doi: 10.3390/su14042089.

[7] Başkent E Z. Assessment and valuation of key ecosystem services provided by two forest ecosystems in Turkey[J]. Journal of Environmental Management, 2021, 285: 112-135.

[8] Taye F A, Folkersen M V, Fleming C M. The economic values of global forest ecosystem services: A meta-analysis[J]. Ecological Economics, 2021, 189: 107-145.

[9] Naime J, Mora F, Sánchez Martínez M. Economic valuation of ecosystem services from secondary tropical forests: Trade-offs and implications for policy making[J]. Forest Ecology and Management, 2020, 473: 118-126.

[10] Hynes S, Chen W, Vondolia K. Valuation of the kelp forest ecosystem services in Norway[J]. Ecological Economics, 2021, 179: 106-133.

[11] Xiao Zhongqi, Zhang Yutao, Li Jimei. Assessment of service function value of forest ecosystem in Xinjiang Province, China[J]. Journal of Xinjiang University: Natural Science Edition, 2019, 36(4): 483-490.

[12] Huang Jihong, Lu Xinghui, Guo Zhongjun. Service functions of the natural forest ecosystem in Burqin Forest Farm, Xinjiang[J]. Arid Zone Research, 2014, 31(5): 866-873.

[13] Sun Qingxiang, Zhou Huarong. Service function and value evaluation of the Altai Mountains forest ecosystem[J]. Arid Land Geography, 2020, 43(5): 1327-1336.

[14] Wang Bing, Niu Xiang, Song Qingfeng. Forest ecosystem service assessment and path design of value-oriented realization in China[J]. Environmental Protection, 2020, 48(14): 28-36.

[15] Feng Jiguang, Ding Lubin, Wang Jingsheng, et al. Case-based evaluation of forest ecosystem service function in China[J]. Chinese Journal of Applied Ecology, 2016, 27(5): 1375-1382.

[16] Cong Rizheng, Wang Bing, Gu Jiancai, et al. Evaluation of forest ecosystem services values of Helan Mountain National Nature Reserve, Ningxia[J]. Journal of Arid Land Resources and Environment, 2017, 31(11): 136-140.

[17] Yan Yujiang, Li Jiangui, Yeerkeng Tangnuer, et al. Assessment of the value of natural forest ecosystem service functions in Xinjiang[J]. Shaanxi Forestry Science and Technology, 2023, 51(4): 69-74.

[18] Cong Rizheng, Wang Bing, Niu Xiang, et al. Assessment on the atmosphere purification function of forest ecosystem in Shaanxi Province[J]. Journal of Northwest Forestry University, 2017, 32(5): 75-82.

[19] Raihan A, Begum R A, Said M N M. A meta-analysis of the economic value of forest carbon stock[J]. Geografia, 2021, 17(4): 321-333.

[20] Raihan A, Begum R A, Mohd Said M N. Assessment of carbon stock in forest biomass and emission reduction potential in Malaysia[J]. Forests, 2021, 12(10): 1294, doi: 10.3390/f12101294.

[21] Xi Li, Li Siyao, Xia Xiaoying, et al. Effects of altitude, stand age, and canopy density on soil fertility in Picea schrenkiana forest[J]. Chinese Journal of Ecology, 2023, 42(10): 2477-2485.

[22] Wang Bing. Construction and utilization of continuous inventory system for forest ecology[J]. Journal of Beijing Forestry University, 2015, 37(1): 1-8.

[23] Lan Jie, Zhang Yutao, Shi Qingdong, et al. Assessment of service functions value of natural forest ecosystem in Xinjiang[J]. Journal of Northwest Forestry University, 2018, 33(4): 289-296.

[24] Li Minghui, He Fenghua, Pan Cunde. Spatial distribution pattern of different strata and spatial associations of different strata in the Schrenk spruce forest, northwest China[J]. Acta Ecologica Sinica, 2011, 31(3): 620-628.

[25] Xiao Qiang, Xiao Yang, Ouyang Zhiyun, et al. Value assessment of the function of the forest ecosystem services in Chongqing[J]. Acta Ecologica Sinica, 2014, 34(1): 216-223.

[26] Li Jimei, Zhang Yutao, Bai Zhiqiang, et al. Assessment of service functions value of mountain forest ecosystem in Xinjiang Province, China[J]. Journal of Southwest Forestry University, 2016, 36(4): 97-102.

[27] Fu Lihua, Yu Shitao, Cheng Shun, et al. Evaluation of forest ecosystem service values in Saihanba Forest Farm in Hebei Province[J]. Forestry and Ecological Science, 2019, 34(4): 386-392.

[28] Gao Fengxia, Han Hui. Assessment of urban forest ecological benefits in the western semi-arid region of southern and northern mountains of Lanzhou City[J]. Ecological Science, 2021, 40(6): 106-115.

[29] Li Guowei, Zhao Wei, Wei Yawei, et al. Evaluation on the influence of natural forest protection program on forest ecosystem service function in Changbai Mountain[J]. Acta Ecologica Sinica, 2015, 35(4): 984-992.

[30] Qi Xinxian, Huang Xianjin, Lai Li. An empirical study of Meta-analytical value transfer of forest ecosystem service in China[J]. Scientia Geographica Sinica, 2018, 38(4): 522-530.

[31] Zhang Jiawang, Dong Xibin, Guo Ben, et al. Different succession stages of natural Larix gmelinii forest multivariate distribution of spatial structure

parameters[J]. Journal of Northeast Forestry University, 2024, 52(3): 1-9.

[32] Yang Haijiang, Gou Xiaohua, Tang Chengrui, et al. Research progress on the valuation of forest ecosystem services in China during 2010 to 2021[J]. Chinese Journal of Ecology, 2024, 43(1): 244-253.

[33] Liu Shengtao, Gao Peng, Liu Panwei, et al. An ecosystem services assessment of Tai Mountain[J]. Acta Ecologica Sinica, 2017, 37(10): 3302-3310.

[34] Li Shaoning, Wang Bing, Guo Hao, et al. Assessment of forest ecosystem services value in Dagangshan[J]. Science of Soil and Water Conservation, 2007, 5(6): 58-64.

[35] Li Lianqiang, Yang Huixia, Ding Guoquan, et al. Material quality assessment and trade-off-synergies of forest ecological service in Xianrendong National Nature Reserve, Liaoning Province of northeastern China[J]. Journal of Beijing Forestry University, 2023, 45(9): 83-94.

[36] Huang Longsheng, Wang Bing, Niu Xiang, et al. Evaluation of ecological effects of the natural forest protection program in key state-owned forest districts in northeast China and Inner Mongolia[J]. Science of Soil and Water Conservation, 2017, 15(1): 89-96.

[37] Luo Jia, Tian Yuxin, Zhu Xin, et al. Evaluation of the service function of the public welfare forest ecosystem in Hunan Province[J]. Hunan Forestry Science and Technology, 2020, 47(4): 26-35.

[38] Zheng Yu, Chen Dazhao, Zhu Anming, et al. Study on evaluation of physical quantity and value quantity of forest ecological service function in Hangzhou[J]. Forest Investigation Design, 2023, 52(1): 54-58.

[39] Bayley D, Brickle P, Brewin P. Valuation of kelp forest ecosystem services in the Falkland Islands: A case study integrating blue carbon sequestration potential[J]. One Ecosystem, 2021, 6: e62811, doi: 10.3897/oneeco.6.e62811.

Note: Figure translations are in progress. See original paper for figures.