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Evaluation on glaciers ecological services value in the Tianshan Mountains, Northwest China

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Abstract: Mountain glaciers, which perform a unique and irreplaceable ecological service, provide the material basis and characteristic cultural foundation of the ecological environment and sustainable socio-economic development in arid areas. However, few studies have estimated the service value of glaciers in regulating ecological environment and providing human welfare. According to the statistics of the First and Second Chinese Glacier Inventory (FCGI/SCGI), this study analyzed the variations in glacier area and ice volume in the Tianshan Mountains in China and modeled the ecosystem service function of mountain glaciers. The service value per unit area and equivalent factor methods were combined to determine the annual value of the ecological service provided by glaciers in the study area. The results show that: (1) In the period 1970–2010, the glacier area decreased by 1274 km^2 (the ratio of area shrinkage was 13.9%) and the annual average decrease in ice volume was 4.08×10^9 m^3. The increase in glacier area at high altitudes (> 5200 m) may be due to the fact that glacier accumulation caused by increasing precipitation is greater than glacier melting caused by rising temperatures. (2) The annual value of the ecological service provided by glaciers in the study area is 60.2 billion yuan. The values of climate regulation, hydrological regulation, and freshwater resource supply account for 66.4%, 21.6%, and 9.3% of the total value respectively. The annual value of the ecological service provided by hydroelectric power is 350 million yuan. (3) From a comparative analysis of the glaciers, forest, grassland and wetland ecosystems, the supply of freshwater resources/physical production and ecological regulation represent the main contributions of the four types of system, and the ecosystem service value of glaciers per unit area is higher than that of other types of ecosystem. This research will improve the understanding of the impact of glaciers on human welfare and maintenance of the ecological environment and will promote the ecological security of the cryosphere, environmental protection, and the sustainable use of resources.

Keywords: glacier; ecological function; service value; estimate; Tianshan Mountains

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1 Introduction

One tenth of Earth's land surface is covered by glaciers. Glaciers are the products of the climate, which have a high sensitivity and feedback effect on climate change. Impacted by global warming, the glaciers in mid-low latitude regions of Asia have experienced a significant negative material balance process, and glacier shrinking is a dominant trend of recent glacier variation. Among them, 67% of the mountain glaciers are distributed in mid-low latitudes where the freshwater resources are most needed. China is a country that boasts not only the largest scale of glaciers in the mid-low latitude regions but also the greatest number of glaciers in the world's desert zone and among the water-shortage countries (Aizen *et al*., 1995; Shi *et al*., 2000; Sorg *et al*., 2012). Mountain glaciers are an irreplaceable and irreversible scarce resource because of their special spatio-temporal distribution and change process. As the water scarcity increases in the inland arid desert landscape, glaciers are considered as the "lifeline" of the arid areas; and are the material basis and characteristic cultural foundation for the population, resources, environment and sustainable socio-economic development in the arid areas, which perform a unique and irreplaceable ecological service function (Guo *et al*., 2015; Sun *et al*., 2015). Glaciers in Tianshan Mountains of China are important components of the water resources in Xinjiang. Affected by climate change and human activities, the hydrological effects, environmental effects, resource effects, ecological effects, disaster effects and social effects of glaciers are increasingly apparent, and glaciers have a wide and profound impact on regional ecology and environmental security and social economy (Shangguan *et al*., 2009; Wang *et al*., 2011).

Mountain glaciers, as a special and major component of the global ecosystem, are important for maintaining regional ecological stability and regulating stream runoff water supply. The functions of glacial ecology and socio-economic services are more than these, and glaciers have a complete and relatively independent service function system as other ecological systems do. For example, mountain glaciers have significant influence on the global climate and the regional meteorological parameters such as temperature, precipitation, and humidity. Furthermore, as a special underlying surface, larger reflectivity of glaciers might be inhibited on global warming to a certain degree (Li *et al*., 2003). At the same time, glaciers provide an ideal environment for periglacial plants and microorganisms, due to the unique environmental features such as low temperature and oligotrophy (Zhang *et al*., 2014). In addition, the glacier melting/accumulation process is involved in atmospheric exchange, and the leakages of methane was predicted to have a significant impact on the global climate as the glaciers recede and permafrost melts (Li *et al*., 2014). In fact, glaciers have played a role in "sealing" greenhouse gases. The physical and chemical processes of Atmospheric-Firn-Glacier ice evolution have sealed pollutants from human and natural emissions. Therefore, glaciers, as "condensers", are the important natural archives to study the history of pollution. Alpine glaciers have accumulated high concentrations of persistent organic pollutants (POPs) (Li *et al*., 2010), which confirm that glaciers have the function of purifying the global environment. In recent years, the service functions and value assessment of various types of ecosystem, such as grassland, forest and wetland, have been studied by many scholars in a more systematic research, which has gained plentiful and substantial achievements (Song, 2016, Stavi *et al*., 2016). On the contrary, the ecological and socio-economic service function of tion of glacier resources is not well-recognized by the public and has not been given enough attention (Xiao *et al.*, 2016). The functions of the water resources provision and climate regulation of the glaciers in the Manas River Basin were described quantitatively, and the value of the hydrological adjustment functions was estimated by alternative engineering methods (Zhang *et al.*, 2009). Part of the service value provided by glaciers in the study area was evaluated, and according to ecosystem services value units area of Chinese terrestrial ecosystem, the value of glaciers ecological service was estimated (Wang *et al.*, 2004; Mansur *et al.*, 2016). The equivalent factor of services value such as raw material supply, soil conservation and nutrient circulation, and biodiversity maintenance of the glaciers is mainly determined by expert experience, which results in the obvious limitations in the objective and quantitative analysis of the glaciers dynamic service value (Xie *et al.*, 2015). The unique natural characteristics and change process of glaciers determined by the service functions are obviously different from other ecosystems. The modeled and estimated value of the glacier ecosystem service can improve the understanding of the impact of glaciers on human welfare and maintenance of the ecological environment and will promote the research on regional ecosystems and even global ecosystem services.

Existing research on mountain glaciers is mainly focused on natural attributes of the processes and mechanisms such as morphology, distribution, ablation/accumulation, ice chemistry, and runoff replenishment (Guo *et al.*, 2015; Wang *et al.*, 2015; Shakun *et al.*, 2015; Pieczonka *et al.*, 2015; Margold *et al.*, 2015; Duan *et al.*, 2017). The research on ecological environment property and social attribute of glaciers is not deeply, especially for estimates of service value of glaciers in regulating ecological environment and providing human welfare. (Xie *et al.*, 2015; Xiao *et al.*, 2016). Therefore, this article, guided by disciplinary theories such as glaciology and ecological economics, conducts research on Tianshan Mountain Glacier in China. Based on the analysis of the changing characteristics of the glacier area in the Tianshan Mountains in China from 1970 to 2010, the value of glacial ecological services provided by glaciers was evaluated by combining GIS spatial analysis techniques, unit area service function price method, and the equivalent factor method. This research will promote the ecological security of the cryosphere, environmental protection, and the sustainable use of resources.

2 Study area

The Tianshan Mountain Range is the largest independent zonal mountain system in the world and also the most distant mountain range from the ocean. This range has a length of 2500 km, and a width of 250–350 km with the maximum of more than 800 km, spanning from east to west four countries of China, Kazakhstan, Kyrgyzstan and Uzbekistan. Trending generally from east to west, Tianshan Mountains stretch to 1700 km in China (Tianshan, China for short), accounting for more than two-thirds of the length of the Tianshan Mountains (Figure 1) (Zhang *et al.*, 2015). According to the First Chinese Glacier Inventory (FCGI), there are 9035 glaciers in the Tianshan Mountains, with a total area and an ice volume being 9225 km^2 and 1011 km^3, respectively. It is the cradle and water source of the Balkhash Lake, Tarim River, Junggar Basin and Turpan-Hami Basin.

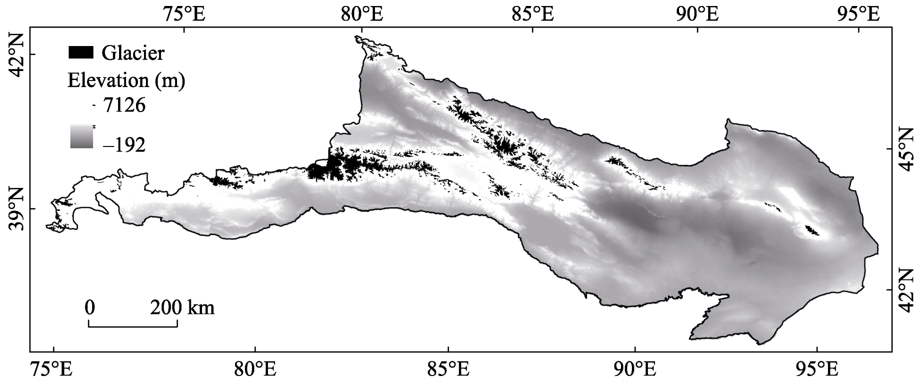

Figure 1 Location of the Tianshan Mountains, Northwest China

3 Research methods

Glacier change data in this article is taken from the First and Second Chinese Glacier Inventory (CGI) data and topographic maps of the Tianshan Mountains in China. Digital elevation model (DEM) is derived from Shuttle Radar Topography Mission (SRTM). The revision V4.1 with a horizontal resolution of 90 m is used in this study. The data are acquired from Chinese Academy of Sciences Computer Network Information Center International Scientific Data Mirroring Website (http://datamirror.csdb.cn).

3.1 Information extraction for glacier area change

According to the World Glacier Inventory (WGI), the FCGI dataset for the Tianshan Mountains was completed in 1987 by Lanzhou Institute of Glaciology and Geocryology of the Chinese Academy of Sciences. The data source was derived from topographic maps at scales of 1:50,000 and 1:100,000 using aerial photogrammetry techniques drawn during 1970–1980. However, limited by technological conditions, the precision of glacier boundary definition and area measurement accuracy were relatively low. To improve the accuracy, the aerial photographs adopted for the glacier inventory were collected. Combined with topographic maps, the glacier boundary contours are systematically inspected and revised. By using GIS software to preprocess the scanned topographic maps, such as geometric rectification, the glacier boundary is vectored and the glacier parameters such as the glacier code and the name are recorded, so as to form the spatial and attributive FCGI vector dataset. The data sources adopted in the SCGI dataset were Landsat TM/ETM+ remote sensing images with little cloud and snow cover during June–September from 2008 to 2010. The data was freely downloaded from U.S. Geological Survey website (USGS, http://glovis.usgs.gov). The methods used in the SCGI dataset have been described in detail by Liu *et al*. (2015). For the SCGI dataset of Tianshan Mountains, experienced researchers manually revised the boundaries of automatically derived glaciers based on ENVI software. Although the SCGI dataset was created using visual interpretation that can be viewed as true glacier values, there were still some errors, such as the offset of the pixel. Accuracy of glacier information interpretation is controlled by the influence of sensor and image registration errors. For this reason, the uncertainty formula proposed by Hall *et al*. (2003) is used to calculate the glacier area error:

$$\alpha = 2\lambda \times \sqrt{\lambda^2 + \varepsilon^2} \tag{1}$$

where α is the area error; λ is the image resolution (spatial resolution is about 30m); ε is the registration error (Calculated on one pixel). The results showed that the area error of the per glacier is ±0.0021 km^2. And the total area error of glaciers is ±88.20 km^2, which occupied 1.12% of total glacier area in the SCGI datasets. The change of glacier reserves can indicate the contribution of glacial meltwater to river runoff. The formula for calculating the correlation between glacier area and glacier reserves is obtained (Sun *et al.*, 2015).

$$V = 0.04S^{1.35} \tag{2}$$

where V is the glacier reserves (km^3); S is the glacier area (km^2).

3.2 Ecological service functions and value estimation method of glaciers

Based on the Millennium Ecosystem Assessment Method (Xie *et al.*, 2015), the ecological services of mountain glaciers were divided into four categories: Supply services, regulation services, support services and cultural services, and nine specific service functions were further subdivided (Table 1). Due to the diversity and complexity of the service function of the glacier ecosystem, a single evaluation method cannot be used to estimate. It is necessary to construct a reasonable mathematical model based on different service functions of the glacier ecosystem to estimate the service value. The direct use value of glaciers includes providing freshwater resource production value and non-competitive and non-excludable service value. The service value includes scientific research, environmental education, aesthetic appreciation, culture and art, and habitat services. The indirect use value of the glaciers is the benefit value obtained by the process of glacier changes or functions, which contains the value of regulating climate, regulating runoff, purifying environment and regulating the function of ecology. Among them, six functions, including supply of freshwater resources, hydroelectric power generation, hydrological regulation, climate regulation, aesthetic landscape, and scientific research and environmental education, are calculated by the unit-area functional price method. As the realization process of functions of the gas regulation, environment purification and biodiversity service of mountain glaciers are complex. It is difficult to objectively estimate the value by functional price method in the condition of basic experimental data absence. Therefore, this study uses the unit area equivalent factor method for these three functions.

3.2.1 Unit service function price method

(1) Freshwater supply. Mountain glaciers provide abundant and high quality freshwater resources for human society. According to the average annual change in glacial reserves from 1970 to 2010, the economic value of the service of annual freshwater resources supplied for human social systems was calculated by using the direct market approach.

$$V_w = V_G \times P_w \tag{3}$$

where V_w is the value of freshwater resources provided by glaciers (yuan); V_G is the average annual change in glacier reserves (m^3); P_w is the unit price of freshwater resources (yuan/m^3). The water price is based on the integrated water supply price of 1.36 yuan/m^3 in Urumqi City in 2010.

(2) Hydropower. Research shows that hydroelectric power generation is carried out in the

Alps, the United States, and Norway with adequate ice and snow water sources and high altitudes (Che *et al.*, 2004). In this paper, the potential value of hydroelectric power generation is calculated by shadow engineering method, and the annual glacial meltwater volume is converted into the total capacity of mountain reservoirs. Based on the seven typical mountain reservoirs in the Tianshan Mountains of China, the average annual power generation of the unit storage capacity is estimated, and the total annual power generation is finally converted into electricity expenses.

$$V_p = V_G \times E \times P_w \tag{4}$$

where V_p is the potential value of hydroelectric power generation provided by glacier meltwater (yuan); V_G is the average annual variation of glacier reserves (m^3); E is the unit storage capacity of generated energy (kw·h/m^3), and the generated energy of average annual in the unit reservoir capacity of Tianshan Mountains in China is 0.37 kw·h/m^3; P_w is the hydropower price (yuan/kw·h), and the hydropower price in this paper is replaced by the present grid purchase prices of small hydropower energy (0.235 yuan/kw·h) in Xinjiang.

(3) Hydrological adjustment. The "alpine solid reservoir" is sensitive to hydrothermal changes, and its accumulation/ablation process is accompanied by the conversion of substance and energy, which naturally regulates river runoff. The shadow engineering method is used to estimate the value of hydrological adjustment, and the average annual ice storage capacity is converted into the corresponding reservoir capacity, which is calculated in combination with the engineering cost required for the unit storage capacity.

$$V_a = V_G \times P_r \tag{5}$$

where V_a is hydrological adjustment value of glacial volume change to river runoff (yuan); V_G is the average annual variation of glaciers reserves (m^3); P_r is the engineering cost (yuan/m^3) of the unit storage capacity, and the cost of the unit storage capacity is 3.071 yuan/m^3 (Xie *et al.*, 2015).

(4) Climate regulation. Glacier as a special underlying surface with high albedo and the heat sink partial melting process has a certain degree of regulation of global and regional climate. Snow and ice albedo is the key factor affecting the melting, and it is also the key feedback factor for the close coupling of ice and climate. With the differences in climate and environment in different regions and changes in climate and environment, there is a great difference in surface albedo values such as dry snow, wet snow, snowfall, dry and clean glaciers, and hail and ice (Cai *et al.*, 2005; Li *et al.*, 2016). The phase transition process of glaciers from solid to liquid and gas consumes a lot of heat, which is actually a certain inhibitory effect on the increase of temperature. The process mainly includes the energy conversion of melting, evaporation and sublimation and sensible heat, and the energy balance of the ice surface is obviously different with the change of season and altitude. The value of climate regulation is estimated by direct market method. To facilitate the research, the sum of reflected solar radiation on the surface of the glaciers and the absorbed thermal energy is taken as the contribution of the glaciers to the suppression of global warming, and the thermal energy is converted into equivalent electrical energy. The annual service value of climate regulation is calculated by electricity price.

$$V_c = (S_G \times R \times \alpha_a \times \alpha_s + V_G \times p_G \times q_G) \times P_e \tag{6}$$

where V_c is the value of glacier climate adjustment (yuan); S_G is the total area of the glacier for SCGI; V_G is the average annual variation of glacier reserves (m^3); the parameters involved in the formula are all from related references. The annual solar radiation (R) in the Tianshan Mountains of China is 5000 $MJ/m^2 \cdot a$; snow and ice albedo (α_a) is 0.6; terrain shading rate (α_s) is 0.5; glacier density (p_G) is 0.9 g/cm^3; specific heat capacity of glacier melting (q_G) is 336,000 J/kg; P_e is the electricity price (yuan/ kw·h), referring to the average price of electricity in various industries in Urumqi in 2010 of 0.515 yuan/ kw·h.

(5) Aesthetic landscape. The rolling snow ridges of the Tianshan Mountains and the icy peaks of the mountains form a unique landscape, attracting a large number of Chinese and foreign tourists. The love, awe and praise of the people of all nationalities are entrusted by the glaciers and the snow-capped mountains, which provide creative inspiration and rich themes for ethnic songs, paintings, and literary creation such as poetry and fiction. In addition, religious personages have given the iceberg a certain amount of connotation, so it also has unique cultural and artistic value. The aesthetic value of the glaciers was estimated by questionnaires combined with the travel cost method. In the study, 500 questionnaires were mailed out to the local and foreign tourists and 482 valid questionnaires were collected. Based on this point, the proportion of the total travel cost of tourists for the purpose of glacier-related tourism is calculated, combined with the total annual tourism revenue in Xinjiang to estimate the value of aesthetic landscape provided by glaciers.

$$V_t = T \times R_g \tag{7}$$

where V_t is the aesthetic landscape and cultural value provided by the glacier (yuan); T is the total annual income of local tourism in the study area (yuan); R_g is the percentage of glacial-related tourism (%); the total tourism revenue of Xinjiang was 6.54×10^{10} yuan in 2010.

(6) Scientific research and environmental education. Glaciers are unique media and objects for the study of climate and environmental changes, and are often used as natural archives for the study of pollution history. The value of this service type is reflected in the annual amount of research funds provided by the national and local governments for the glacier related research in the Tianshan Mountains.

$$V_s = S_t \tag{8}$$

where V_s is the value of scientific research and environmental education provided by glaciers (yuan); S_t is the scientific research funding provided by the national and local for research projects of glaciers in the study area (in yuan). In order to simplify the statistics, this article uses the total funding of 1.87×10^7 yuan of the National Natural Science Foundation projects approved in 2010 as reference data.

3.2.2 Unit area value equivalent factor method

According to the equivalent weight factor of the value of services of Chinese terrestrial ecosystem proposed by Xie *et al*. (2015), and referring to the economic value of food production per hectare supplied by cropland ecosystem in Xinjiang from 2005 to 2014 (Mansur *et al*., 2016), we determined the equivalent of the above four ecological service functions of glaciers in the Tianshan Mountains in China by referring to the unit prices of ecological services provided by farmland, and the value of various types of glacial ecological services is finally estimated (Table 1).

Table 1 The value of all types of ecological service function of mountain glaciers in the Tianshan Mountains, Northwest China

Service function		Service value (yuan/a)		Percentage (%)
First-class targets	Second-class targets	Unit-area functional price method	Functional price method	
Supply service function	Freshwater supply	5.6×10^{9}	2.4×10^{9}	9.30
	Hydropower	3.5×10^{8}		0.58
Adjustment service function	Hydrological adjustment	1.3×10^{10}	8.0×10^{9}	21.58
	Climate regulation	4.0×10^{10}	6.1×10^{8}	66.40
	Gas regulation		2.0×10^{8}	0.33
	Purification environment		1.8×10^{8}	0.30
Support differentiated service functions	Biodiversity		1.1×10^{7}	0.18
Cultural service functions	Aesthetic landscape	7.8×10^{8}	1.0×10^{8}	1.29
	Scientific research and environmental education	1.9×10^{7}		0.03
Total		6.0×10^{10}	1.2×10^{10}	100

4 Result and analysis

4.1 The variation characteristics of glacier area

According to the FCGI and SCGI, there were 9035 glaciers with an area of 9225 km^2 and ice volume of 1011 km^3 in the Tianshan Mountains during the period 1970–1980; and the glaciers covering an area of 7884 km^2 have an ice volume of 728.9 km^3 from 2008 to 2010. The area and volume of glaciers decreased by 1274 km^2 and 4.08×10^{9} m^3, respectively and the surface of the glaciers has retreated by 13.9%. As shown in Figure 2, the position of glacial end has subsided from 2200 m to 2800 m in the past 40 years. And the area of glaciers at the elevation of 3800–4800 m accounts for more than 80% of the total area. The glacier changes below 3600 m are most sensitive, with area reductions accounting for 52.8% of the total change, while glacier area with elevations above 5200 m increases by 8.95%. As shown in Figure 3, the north and south directions are distributed with an absolute number of glaciers,

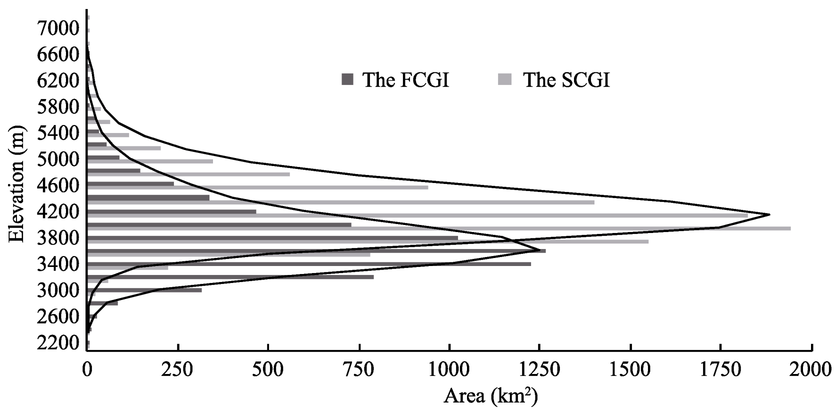

Figure 2 Changes of glacier area in different altitude ranges in the Tianshan Mountains, Northwest China

covering more than 81% of the total, of which the northeastern glacier area is the largest, and the western area is the smallest. The glaciers retreat from the southern area is more obvious, which is over 44.4%.

Comparing with other relevant research results, we found that the annual change rate of glaciers (–0.35%/a) in this paper is close to the statistical analysis of the variation rate of about 3000 glacier areas (–0.31%/a) of the Tianshan Mountains in China in the last 50 years (Wang *et al*., 2011), slightly lower than the calculation (Sun *et al.*, 2015) of the glacier area change rate (–0.4%/a) in Qilian Mountain based on the data of FCGI and SCGI dataset. This may be due to the fact that the scale of the glaciers in the Tianshan Mountains is much larger than that of the Qilian Mountains, and that small area or small-scale glaciers are more sensitive to the increase in temperature. The retreat of glaciers on south-facing slopes is more dramatic than that on the other, due to the fact that the southern side has acquired more solar radiation as a sunny slope. The glacier area has increased at high altitudes (>5200 m). Glacier development depends on the composite action between temperature and precipitation in the mountainous areas. It was shown that the climate of the northwest region presented a trend of warming and moistening under the background of global climatic change, leading to glacier accumulation caused by increasing precipitation in this area, which is greater than glacier ablation caused by rising temperatures.

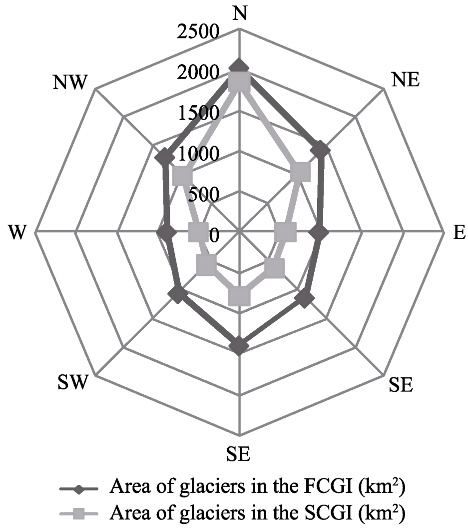

Figure 3 Orientational characteristics of glacial changes in the Tianshan Mountains, Northwest China

4.2 Analysis of glacier ecosystem service value

Based on the annual average amount of ice volume in the Tianshan Mountains from 1970 to 2010 and the glacier areas in 2008–2010, the functional price method and the equivalent weight factor method were used to estimate the annual value of eco-economy service provided by glaciers (Table 1). Statistics show that the annual ecological service value provided by glaciers in the Tianshan Mountains in China amounted to 56 billion yuan, ranking according to the level of service function value, followed by climate adjustment > hydrological adjustment > water supply > aesthetic landscape > hydropower > gas regulation > purification environment > research and environmental education > biodiversity. Among them, the value of climate inhibition caused by glacier surface albedo and melting decalescence accounted for 66.40% of the total value, and the value of river runoff regulation and freshwater resource supply accounted for 21.58% and 9.30% of the total value, respectively (Figure 4). The conclusion may be further explained that the glaciers in high and cold areas have a very significant inhibitory effect on climate warming. Glacial meltwater plays an important role in the stability of runoff replenishment in arid regions, industrial and agricultural production in oasis region, and ecological development. However, the value of the environment purification, gas exchange, biodiversity, scientific research and education of the Tianshan Glaciers in China is usually ignored or underestimated. It is estimated that its annual ecological service value can reach 1.28 billion yuan, which makes people more intuitively aware of the important ecological status of glacial protection. The former relevant research seldom involved the functions of glacier hydroelectric power generation services, but this study found that the annual average ecological service value of glacier meltwater using the comparatively great undulation of the landforms for hydroelectric power generation is about 350 million yuan. On the whole, in the context of global warming, mountain glaciers contribute much to the suppression of regional and global temperature rises. The realization mechanism of this service function may have important implications for global climate change research. Glacial meltwater, as an important and fairly stable component of river runoff recharge in arid regions, cannot be ignored.

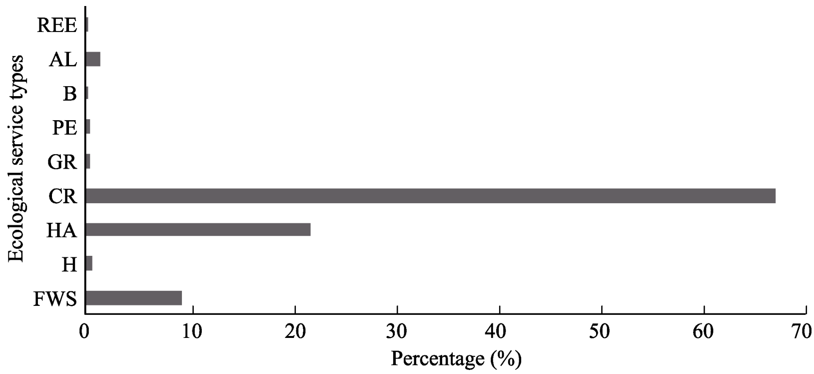

Figure 4 Percentage of the value of all types of ecological services in the Tianshan Mountains, Northwest China (FWS is freshwater supply, H is hydropower, HA is hydrological adjustment, CR is climate regulation, GR is gas regulation, PE is purification environment, B is biodiversity, AL is aesthetic landscape, and REE is scientific research and environmental education.)

This article uses two methods to estimate the value of water supply, hydrological regulation, climate regulation and aesthetic landscape. The results showed that the value by the equivalent factor method is lower than that by the functional price method, totaling about 43.5 billion yuan. Just as some scholars believe, many ecosystem service values are underestimated (Xie *et al*., 2015). The ecological service function of glaciers is mainly achieved by the conversion of material and energy in the process of strong albedo and glacier ablation / accumulation. In previous studies, the equivalent weight factor of the ecological services value provided by per unit glacier area was derived from the expert experience method, which inevitably led to bias in objectively estimating the ecological service value. The above glacial ecological service functions simply rely on static description and subjective quantification, and obviously lack the analysis of their changing mechanisms. Under the drivers of climate warming and human interference, the scarcity of glacier services has been increasing, and its ecological and socio-economic functions have shown an enhanced and weakened trend (Xiao *et al*., 2016). In addition, the accumulation / ablation of glaciers has obvious difference in time (dry/rainy seasons) and space (elevation, aspect, etc.), which makes the ecological service function also have some dynamic characteristics. If the experiments of glacial meteorological and ice chemistry are combined with 3S technology (RS, GIS and GPS), the dynamic and spatial heterogeneity of the ecological service function of glaciers can be well depicted.

5 Discussion

To compare the similarities and differences of mountain glacial ecosystem services and the three major terrestrial ecosystems in forest (Li *et al*., 2016), grassland (Ye *et al*., 2006; Sun *et al*., 2011) and wetland (Sun *et al*., 2008; Xie *et al*., 2011; Tian *et al*., 2015), this article specifically collects literatures about the estimate of value of terrestrial ecosystem service based on the ecological function price method in Xinjiang in recent years (Table 2). Although ecosystem types and service functions are different in various documents, and the comparative studies on the service function contribution rates are limited, they can still provide an important basis for the evaluation of the relative contribution degree, and a theoretical support for the optimization of the index system and the allocation of service functions. From a comparative analysis of the glaciers, forest, grassland and wetland ecosystems, the supply of freshwater resources/physical production and ecological regulation represent the main contributions of the four types of system, which account for 94.12%, 69.57%, 44.57% and 88.42%, respectively. In the forest and wetland ecosystems, the hydrological regulation/water conservation is the most valuable service function, and the purification environment/waste treatment is the greatest contribution in the grassland system. The biodiversity/habitat function provided by glaciers is much lower than that of other types of ecosystem. According to the principles of simplification and operability, in order to enhance the comparability of the service value of glaciers, forest, grassland and wetland per unit area, the original value of the other ecosystem services is converted to the economic value of 2010 by using the CPI index of different years. Compared with the ecological service value of ecological system per unit area, the service value of glacier per unit area in Tianshan Mountains (76 thousand yuan/ha·a) is the highest. The service value of ecosystems per unit area in wetland (Albea Lake, Boston Lake, Kekesu River) and forest (mountain forests in Xinjiang) show little difference, which are 40.5 thousand yuan/ha·a and 35.5 thousand yuan/ha·a respectively. Grassland (Xinjiang grassland, Yili river valley grassland) unit area ecological

Table 2 The economic value of different types of ecosystem services

Ecological service types of glacier	Percentage of service values (%)			
	Glacier	Forest	Grassland	Wetland
Freshwater supply or production of goods	17.3	1.48	4.82–21.26	0.99–18.86
Hydropower	1.07	–	–	–
Hydrological adjustment or water conservation	23.4	44.16	11–13.54	32.79–82.92
Climate regulation	56.1	–	12.39	–
Gas regulation or carbon fixation and oxygen release	0.32	23.93	2.75–11	4.11–35.08
Purification environment or waste treatment	0.35	5.01	14.75–18.02	0.02–12.06
Biodiversity or habitats	0.02	20.38	8.61–15.00	0.63–37.03
Aesthetic landscape or recreational entertainment	1.4	–	0.55–2.55	0.58–0.91
Scientific research and environmental education or cultural value	0.03	–	2.90	7.54–9.13

service value (8 thousand yuan/ha·a) is the lowest. Compared with other ecosystems, the mountain glacier resources have complete ecological service functions, and the function values of climate change inhibition and river runoff regulation are more valuable than those of other ecosystems. It is further confirmed that glaciers and meltwater have great influence on regional ecological environment security, industrial and agricultural development and social economy.

The terrestrial ecosystem can directly provide freshwater, food, and raw materials needed by human society, and it can also improve the ecological environment in the process of system material and energy conversion, coordinate human interference with the environment and counteract global climate change by conserving water sources, and regulating climate and gas exchange. The value of several ecological services (gas regulation, purification environment and biodiversity) provided by glaciers was estimated by the equivalent factor method in this paper, which is lower than that of other terrestrial ecosystems. On the one hand, this phenomenon is caused by the inherent differences in the service functions of different ecosystems, while on the other, it may be due to the distribution of the weights of various service functions in the quantitative factor method. The value of scientific research and cultural services of the ecosystem is obviously irreplaceable, and it is also the most basic test site for the study of various types of ecological service function. The realization of the ecological service function of terrestrial ecosystems is a complex process, which depends on the ecological foundations such as the composition of the ecological system structure and the mechanism of the material energy transformation. The greater potential service value and more service function of the ecosystem can be further explored by studying the relationship between the structure, ecological processes and service functions of each system.

6 Conclusions and prospect

(1) According to the statistics of the FCGI and SCGI dataset, the area and ice volume of glaciers in the Tianshan Mountains decreased by 1274 km^2 (the ratio of area shrinking was 13.9%) and 4.08×10^9 m^3 from 1956 to 2010, respectively. The increase in glacier area at high altitudes (> 5200 m) may be due to glacier accumulation caused by increasing precipitation is greater than glacier melting caused by rising temperatures.

(2) This study modeled the ecosystem service function of mountain glaciers and used the service value per unit area and equivalent factor methods to determine the annual value of the ecological service provided by glaciers in the Tianshan Mountains in China. The annual value of the ecological service provided by glaciers in the study area is 60.2 billion yuan. The values of climate regulation, hydrological regulation, and freshwater resource supply account for 66.4%, 21.6%, and 9.3% of the total value, respectively. The annual average ecological service value of hydropower is approximately 350 million yuan, and the other types of regulation and service function value are about 1.28 billion yuan.

(3) From a comparative analysis of the glaciers, forest, grassland and wetland ecosystems, the supply of freshwater resources/physical production and ecological regulation represent the main contributions of the four types of system, which account for 94.12%, 69.57%, 44.57% and 88.42%, respectively. In the forest and wetland ecosystems, the hydrological regulation/water conservation is the most valuable service function, and the purification en-

vironment/waste treatment makes the greatest contribution in the grassland system. The biodiversity/habitat function provided by glaciers is much lower than that of other types of ecosystem.

For about half a century, many scholars have made fruitful achievement in the fields of glacier physics, glacier fluctuations responding to climate change, mechanisms and simulations in glaciology, ice formation processes and climatic and environmental records, glacier hydrology and meteorology, quaternary glacial landforms and periglacial geomorphology, altifrigetic subnival vegetation and eco-environment in arid area. This provides an important scientific basis for the regional water resources management and efficient utilization and sustainable development policy planning in China. However, studies on the functions of glacier ecosystem services and of the economic value assessment are rarely involved. This is a shortcoming in academic research. And under the global warming and the fast retreat of glaciers, it is also extremely unfavorable for us to manage glacier water resources and understand the influence of glaciers on regional and global ecological balance.

References

Aizen V B, Aizen E M,Melack, J M, 1995. Climate, snoe cover, glaciers, and runoff in the Tienshan, Central Asia. *Water Resources Bulletin*, 31(6): 1113–1129.

Cai F, Zhu Q L, He H L *et al.*, 2005. Estimation and spatio-temporal distribution of monthly mean surface albedo in China. *Resources Science*, 27(1): 114–120. (in Chinese)

Che T, Jin R, Li X *et al.*, 2004. Glacial lakes variation and the potentially dangerous glacial lakes in the Pumqu Basin of Tibet during the last two decades. *Journal of Glaciology and Geocryology*, 26(4): 397–402. (in Chinese)

Duan K Q, Yao T D, Shi P H *et al.*, 2017. Simulation and prediction of equilibrium line altitude of glaciers in the eastern Tibetan Plateau. *Scientia Sinica Terrage*, 47(1): 104–113. (in Chinese)

Hall D K, Bayr K J, Schner W *et al.*, 2003. Consideration of the errors inherent in mapping historical glacier positions in Austria from ground and space (1893–2001). *Remote Sensing of Environment*, 86(4): 566–577.

Guo W, Liu S, Xu L *et al.*, 2015. The second Chinese glacier inventory: Data, methods and results. *Journal of Glaciology*, 61(226): 357–372.

Li J M, Zhang Y T, Bai Z Q *et al.*, 2016. Assessment of service functions value of mountain forest ecosystem in Xinjiang Province, China. *Journal of Southwest Forestry University*, 36(4): 97–102. (in Chinese)

Li Q L, Wang N L, Wu X B *et al.*, 2010. Sources and distribution of polycyclic aromatic hydrocarbons of different glaciers over the Tibetan Plateau. *Science China*: *Earth China*, 40(10): 1399–1409. (in Chinese)

Li Y H, Zan L Y, Chen L Q, 2014. Advances in the study of methane in the Arctic Ocean. *Advances in Earth Science*, 29(12): 1355–1361. (in Chinese)

Li Z Q, Han T D, Jin Z F *et al.*, 2003. Summary of 40-year observed variation facts of climate and Glacier No.1 at headwater of Urumqi River, Tianshan, China. *Journal of Glaciology and Geocryology*, 25(2): 117–123. (in Chinese)

Liu S Y, Yao X J, Guo W Q *et al.*, 2015. The contemporary glaciers in China based on the Second Chinese Glacier Inventory. *Acta Geographica Sinica*, 71(1): 3–16. (in Chinese)

Mansur S, Nasima N, Arslan M, 2016. Analysis on the change of land uses/cover ecological service value in Tomur National Nature Reserve. *Geographical Research*, 35(11): 2116–2124. (in Chinese)

Margold M, Stokes C R, Clark C D, 2015. Ice streams in the Laurentide Ice Sheet: Identification, characteristics and comparison to modern ice sheets. *Earth-Science Reviews*, 143: 117–146.

Pieczonka T, Bolch T, 2015. Region-wide glacier mass budgets and area changes for the Central Tien Shan between similar to 1975 and 1999 using Hexagon KH-9 imagery. *Global and Planetary Change*, 128: 1–13.

Shangguan D H, Liu S Y, Ding Y J *et al*., 2009. Glacier changes during the last forty years in the Tarim Interior River basin, Northwest China. *Progress in Natural Science*, 19(6): 727–732.

Shakun J D, Lea D W, Lisiecki L E *et al*., 2015. An 800-kyr record of global surface ocean delta O-18 and implications for ice volume-temperature coupling. *Earth and Planetary Science Letters*, 426: 58–68.

Shi Y F, Liu S Y, 2000. Estimation on the response of glaciers in China to the global warming in the 21st century. *Chinese Science Bulletin*, 45(7): 668–672.

Stavi I, Bel G, Zaady E, 2016. Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems: A review. *Agronomy for Sustainable Development*, 36(2): 1–12.

Song C, 2016. Spatial assessment of ecosystem functions and services for air purification of forests in South Korea. *Environmental Science & Policy*, 63: 27–34.

Sorg A, Bolch T, Stoffel M *et al*., 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change*, 2(10): 725–731.

Sun H L, Chen Y N, Li W H *et al*., 2011. Study on types and ecological services values of the grassland in the Ili River Basin, Xinjiang, China. *Journal of Desert Research*, 31(5): 1273–1277. (in Chinese)

Sun M P, Liu S Y, Yao X J *et al*., 2015. Glacier changes in the Qilian Mountains in the past half century: Based on the revised First and Second Chinese Glacier Inventory. *Acta Geographica Sinica*, 70(9): 1402–1414. (in Chinese)

Sun Y F, Liu W Z, 2008. Evaluation on the service functional values of the wetland ecosystem in the Bosten Lake Basin, Xinjiang. *Arid Zone Research*, 25(5): 741–744. (in Chinese)

Tian R W, Cai X B, Maryamgul *et al.*, 2015. Evaluation on ecosystem services of Xinjiang Aletai Kekesu Wetland Natural Reserve. *Wetland Science*, 13(4): 491–494. (in Chinese)

Wang M, Xu B, Cao J *et al*., 2015. Carbonaceous aerosols recorded in a southeastern Tibetan glacier: Analysis of temporal variations and model estimates of sources and radiative forcing. *Atmospheric Chemistry and Physics*, 15(3): 1191–1204.

Wang S J, Zhang M J, Li Z Q *et al*., 2011. Response of glacier area variation to climate change in Chinese Tianshan Mountains in the past 50 years. *Acta Geographica Sinica*, 66(1): 38–46. (in Chinese)

Wang X H, Zhang Z Q, 2004. Effect of land-use change on ecosystem services value in Heihe river basin. *Ecology and Environment*, 24(4): 608–611. (in Chinese)

Xiao C D, Wang S J, Qin D H, 2016. A preliminary study on cryosphere service function and its value estimation. *Climate Change Research*, 12(1): 45–52. (in Chinese)

Xie G D, Zhang C X, Zhang L M *et al.*, 2015. Improvement of the evaluation method for ecosystem service value based on per unit area. *Journal of Natural Resources*, 30(8): 1243–1254. (in Chinese)

Xie Z Y, Li W H, Xie Z J *et al.*, 2011. Evaluation of the ecological service Ebinur Lake Wetland Nature Reserve. *Arid Land Geography*, 34(3): 532–540. (in Chinese)

Ye M, Xu H L, Wang X P *et al*., 2006. An assessment of the value and valuation of the grassland ecosystem in Xinjiang. *Acta Prataculturae Sinica*, 15(5): 122–128. (in Chinese)

Zhang H F, Ouyang Z, Zheng H *et al.*, 2009. Valuation of glacier ecosystem services in the Manas River Watershed Xinjiang. *Acta Ecologica Sinica*, 29(11): 5877–5881. (in Chinese)

Zhang S H, Hou S G, Qin X *et al.*, 2014. Progress in research on resources of glacial microbiology. *Environmental Science & Technology*, 18(12): 62–67. (in Chinese)

Zhang Z Y, He X L, Liu L *et al.*, 2015. Spatial distribution of rainfall simulation and the cause analysis in China's Tianshan Mountains area. *Advances in Water Science*, 26(4): 500–508. (in Chinese)