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Construction of a System of Indices for Determining the Contribution of Biodiversity to Human Well-Being in the Sanjiangyuan Area: A Spatiotemporal Distribution Study

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Abstract: The contribution of biodiversity to human well-being is key to exploring the relationships between biodiversity, ecosystem services (ES), and human well-being. In this work, a composite index, termed the human well-being index (HWI), was constructed for evaluating the contribution of biodiversity to human well-being in the Sanjiangyuan area. This index consists of material, ecological regulation, and spiritual and cultural contributions, represented by the material index (MI), the ecological regulation index (ERI), and the spiritual and cultural index (SCI), respectively. The system was further used to evaluate the spatiotemporal distribution of human well-being at the county level in 2000, 2010, and 2020. HWI increased steadily across Sanjiangyuan over the study period, especially in the western and northeastern counties; its center of gravity shifted in the northward direction. The MI increased (decreased) in the west and northeast (southeast); its center of gravity shifted in the northeast direction. All counties showing changes in the ERI were located in the eastern part of Sanjiangyuan. The center of gravity of ERI did not change significantly. The SCI increased steadily across the study area, but was high in the west and low in the east; the center of gravity shifted in the northwest direction. The study findings can contribute toward quantifying biodiversity contributions to human well-being and the formulation of biodiversity conservation policies.

Keywords: biodiversity; human well-being; spatiotemporal differentiation; remote sensing; Sanjiangyuan

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1. Introduction

In the past decades, governments and research institutions have been committed to improving human well-being with clear sustainable development goals, including improving the quality of education, healthcare, and the environment [1,2]. Although biodiversity has long been recognized as an integral part of the sustainable development agenda by countries around the world [1,3–6], its relationship with human well-being has not been scientifically verified or systematically explored. Recently, some scholars have focused on building links between biodiversity studies, ecosystem services, and human well-being. Such links can help address scientific hotspots and strongly support sustainability-related decision making [7,8]. The use of ecosystem services (ES) as a proxy to understand the link between biodiversity and human well-being is important, as both of these parameters are undergoing tremendous changes [9].

Human well-being is a multidimensional construct that includes both subjective and objective measures. Because of this multidimensionality, human well-being has eschewed any generic definition; it embraces the concepts of knowledge, friendship, self-expression, belonging, physical integrity, economic security, freedom, affection, wealth, and leisure [10]. For example, according to the Millennium Ecosystem Assessment (MA), human well-being comprises five dimensions or elements: (i) essential substances for a good life, (ii) safety, (iii) health, (iv) good social relations, and (v) freedom of choice and action [11]. However, there are many other subjective and objective variables that can be included [12]. Biodiversity is a measure of variety at the ecosystem, species, and genetic levels [13]. According to a report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), biodiversity is crucial for human well-being, as it provides food security and quality of life, as well as cultural and spiritual fulfillment [14–16]. Moreover, biodiversity can benefit human well-being in terms of health, security, and freedom of choice and action [17]; hence, it underpins the ecosystem services critical to human health and well-being [18]. It may be said that biodiversity is the foundation of human well-being. Although biodiversity does not account for all human well-being, it is a crucial contributor in various ways [19,20]. One of the strategic goals of the United Nations' Aichi Biodiversity Targets is to 'enhance benefits to all from biodiversity and ES,' which emphasizes the relationship between biodiversity and human well-being. However, the sustainable development of mankind and the global ecosystem are both under serious threat [21], and biodiversity conservation is often regarded as "another issue to be addressed" [9,22]. Therefore, there is a considerable risk of socioeconomic development being promoted through the destruction of biodiversity, negatively affecting ecosystem services and human well-being [9]. Thus, it is crucial to develop a quantitative method for assessing the contributions of biodiversity to human well-being, so as to enhance awareness of the importance of biodiversity [23].

Ecosystem functions and services are affected by its biodiversity; it is intuitive that human well-being and biodiversity should be linked. To date, two alternative (though not mutually exclusive) perspectives on the relationship between biodiversity and human well-being have shaped public discourse and scientific research. One view emphasizes human or economic development, in which natural, human, social, and other capital stocks are marketed to generate desired streams of economic output at the expense of biodiversity loss. The second, newer perspective emphasizes that biodiversity is the basis of systems that generate human well-being by positively affecting ecosystem functioning [9]. In the 1960s, human well-being was generally assessed via socioeconomic indicators, such as the gross domestic product [24]. The Human Development Index (HDI) proposed by the United Nations Development Programme in 1990 is a composite statistic index of life expectancy, education, and standard of living [25], and it is currently the best-known indicator of human well-being [26]. However, the HDI neglects ecological and environmental factors in favor of socioeconomic factors [27]. Owing to the growing interest in human well-being in various disciplines, the link between the ecological environment and human well-being has become a popular theme in disciplines such as ecology and geography [23,28]. For example, the Happy Planet Index proposed by the New Economics Foundation is a function of subjective life satisfaction, ecological footprint per capita, and life expectancy at birth [29,30]. The Environmental Sustainability Index is composite of 21 environmental indicators, including natural resources and environmental pollution. Mace et al. [31] constructed an index that included wild-species diversity, soil microbe diversity, and other indicators of biodiversity. Until 2003, the MA stated that ecosystems and biodiversity are closely related to human well-being [32]. In addition, many studies have shown that biodiversity is a source of ES and human well-being; moreover, biodiversity loss severely weakens the ES [33,34]. Considerable work has been done on the definitions, connotations, and quantification of ES. For instance, De Groot et al. [35] created a comprehensive ES assessment framework consisting of ES such as climate regulation, flood control, water supply, pollination, and tourism, and focuses on available and quantifiable data. In the UK National Ecosystem Assessment, 14 indicators (including woodlands, urban green spaces, and parks) have been used for the evaluation of cultural ES [36]. IPBES combined biodiversity and ES in a notion called "nature's contributions to people" (NCP) [7], which encompasses all provisioning, regulating, and cultural services [37].

In summary, our understanding of the connotations and quantification of ES is progressively expanding, both in depth and extensivity. This has laid a foundation for the construction of a system of indices to evaluate the contributions of biodiversity to human well-being. However, human well-being is itself an abstract concept with wide-ranging connotations [38]. Studies regarding the links between biodiversity and human well-being usually have a narrow focus, and no standard criteria exist for the selection of indicators for such a system of indices. Moreover, from the NCP perspective, empirical research on the contributions of biodiversity to human well-being and their corresponding indicators is lacking [39]. Hence, this study utilized the perspective of biodiversity conservation to assess human well-being as an ES. In this study, based on the principles of index system construction, we established a three-order index system for the contribution of biodiversity to human well-being from the aspects of material contribution, ecological regulation contribution, and spiritual and cultural contribution based on the NCP perspective, and determined the index weights using the expert scoring method to realize a quantitative analysis. The proposed index system has good operability and generalizability. It fully considers the zonality, scale dependence, and compositional imbalance features of the spatial distribution of biodiversity according to different evaluation regions and scales. Appropriate weights can be set to objectively reflect the actual situations of the study area and clarify the contribution of biodiversity to human well-being in the specific region. Hence, based on the available literature, we took biodiversity conservation as the starting point and human well-being as the end point of the assessment, with ES as the bridge, to construct an evaluation index system to determine the contribution of biodiversity to human well-being in the Sanjiangyuan area of the Tibetan Plateau, and analyzed the spatiotemporal differences in human well-being in this region. Our findings can further our understanding of the contribution of biodiversity to human well-being and its spatiotemporal distribution characteristics. Furthermore, this study can serve as a reference for government decision making regarding biodiversity conservation, ecosystem management, and human well-being.

2. Overview of the Study Area and Data Sources

2.1. Overview of the Study Area

This work focuses on the Sanjiangyuan area, which is located in the hinterlands of the Tibetan Plateau in China (Figure 1). The area is a key source of freshwater in China, and it has the highest concentration of biodiversity in the Tibetan Plateau. Moreover, it is highly sensitive to climate change on the continental, hemispheric, and global levels. Owing to its unique geographic location, abundant natural resources, and important ecological functions, the Sanjiangyuan area is vital for the ecological security of China. It has a special place in the construction of the ecological civilization in China, and its conservation has long-term implications for the national ecological security of China and the Chinese people. The Sanjiangyuan National Nature Reserve in Qinghai Province was established in 2000, and in 2005, the Chinese government approved the Master Plan for the Ecological Protection and Restoration of Qinghai Sanjiangyuan Nature Reserve, which bolstered ecological conservation in the area. In 2011, the first *National Comprehensive Experimental Zone* for Ecological Conservation in China was created in Sanjiangyuan. This was followed by the creation of a new national park system in 2015, which calls for the absolute protection of the ecosystems and cultural heritage sites in the park, along with the provision of spiritual, scientific, educational, and recreational services to the general public. These measures created a conducive base for this study, wherein we evaluated the contributions of biodiversity to human well-being from 2000 to 2020 in the Sanjiangyuan area, comprising 18 counties.

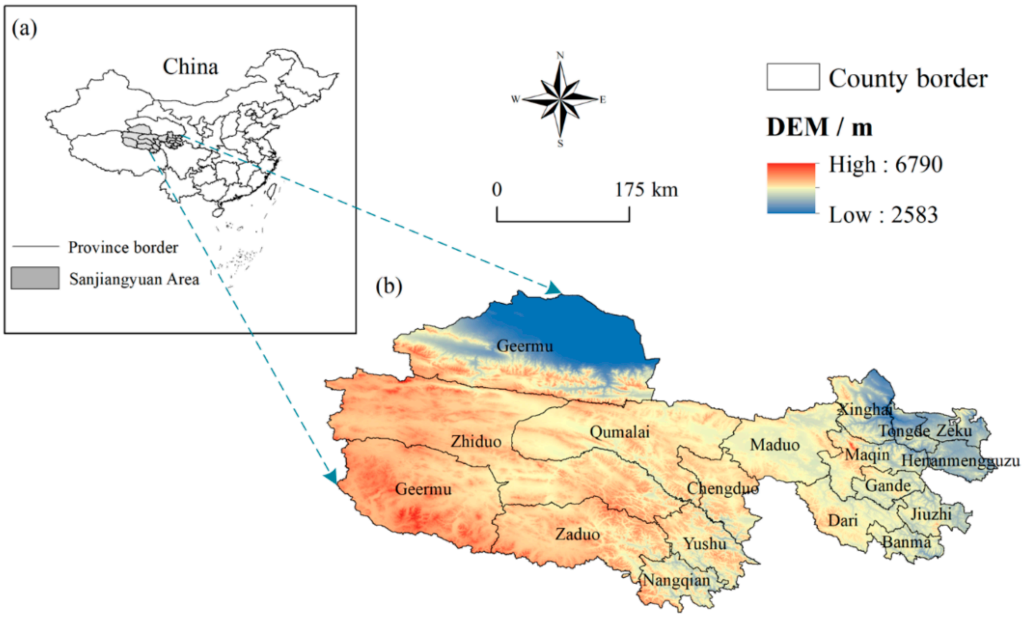

Figure 1. Map of the study area ((**a**): overview; (**b**): DEM, digital elevation model).

2.2. Data Sources

The following data sources were used in this study:

1. Geographic data: Land use data were sourced from the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences (https://www.resdc.cn/ (accessed on 21 August 2021)), at a resolution of 30 m. The digital elevation model (DEM) data were derived from the 90 m DEM raster of the ASTER GDEMS dataset (http://www.gscloud.cn/ (accessed on 11 September 2021)), from which the elevation in the study area was extracted. The boundary data for the nature reserve were sourced from the national natural reserve monitoring dataset of the Satellite Application Center for Ecology and Environment of the Chinese Ministry of Ecology and Environment (http://www.secmep.cn/ (accessed on 5 June 2020)).
2. Ecological data: For vegetation, net primary productivity and terrestrial evapotranspiration data were obtained from Global Land Surface Satellite data from the National Earth System Science Data Center (http://www.geodata.cn/ (accessed on 15 September 2021)). Precipitation data for the Sanjiangyuan area were obtained from the national 0.05° grid meteorological data produced by the China Meteorological Administration's National Meteorological Information Center (http://www.nmic.cn/ (accessed on 8 January 2021)) and interpolated according to annual average precipitation data from regional meteorological stations.
3. Socioeconomic data: Agriculture and livestock output values and volumes were obtained from the Qinghai Statistical Yearbook and China Animal Husbandry Yearbook data on natural and cultural heritage, and important wetlands were obtained from the China Statistical Yearbook. Statistics on numbers of species in the wild and on the Red List of Endangered Species were from national biodiversity surveys.

3. Methods

3.1. Construction of the System of Indices

Based on the IPBES NCP framework [7,37], we created a composite index representing the contributions of biodiversity to human well-being, which consists of a material index (MI), ecological regulation index (ERI), and spiritual and cultural contributions index (SCI). The selection of second- and third-order indicators drew on mainstream international index systems [40,41], as well as Chinese index systems [39,42]. These indicators are directly related to the local biodiversity, and are highly generalizable and practical. During the construction of this index, multiple visits were made to the Sanjiangyuan area to consult local experts and conduct field surveys. The indices that provide an objective reflection of regional characteristics were determined from discussions with local experts and managers, and the weight of each indicator was determined by expert scoring (the scores of some experts are shown in Appendix A). This culminated in the construction of a system for assessing the contributions of biodiversity to human well-being in the Sanjiangyuan area (Table 1).

Table 1. System of indices for assessing the contributions of biodiversity to human well-being in the Sanjiangyuan area, China.

First-Order Indicator/Weight	Second-Order Indicator/Weight	Third-Order Indicator/Weight	Calculation Method	References
MI/0.20	Agricultural goods supply/0.40	Area of farmland ecosystems/0.44	Percentage of arable land (%)	[43,44]
		Agricultural output/grain output/0.56	Annual agricultural output (CNY 10,000)/output (tons)	
	Livestock product supply/0.60	Livestock output/meat output/1	Annual livestock output (CNY 10,000)/output (tons)	[45]
ECI/0.60	Species and genetic security/0.22	Species richness/0.48	Number of species	[46,47]
		Number of Red List species/0.52	Number of Red List species	
	Status of important ecosystems/0.23	Proportion of natural grasslands/0.30	Grassland area percentage (%)	[48]
		Proportion of wetlands/0.29	Wetland area percentage (%)	
		Nature reserve area proportion/0.41	Percentage of national nature reserve area (%)	
	Ecological regulation functions/0.28	Vegetation coverage/0.35	Percentage of vegetated areas (%)	[49]
		Carbon sequestration/0.35	Net primary productivity	
		Water conservation/0.30	Precipitation–evapotranspiration (mm)	[50]
	Ecosystem quality/0.27	Naturalness/0.51	Percentage of natural land (%)	[9,51]
		Connectivity between important ecological spaces/0.49	Connectivity between important ecological spaces (forest, grassland, etc.)	[52,53]
SCI/0.20	Natural heritage/0.40	Number of UNESCO natural and cultural heritage sites and UN-recognized wetlands/1	Number of UNESCO natural and cultural heritage sites and UN-recognized wetlands	[54]
	Blue and green urban spaces/0.60	Urban green area per capita/0.50	Area of green spaces in residential buffer zones divided by non-agricultural population (square meter)	[55–57]
		Urban blue space per capita/0.50	Area of blue spaces in residential buffer zones divided by non-agricultural population (square meter)	

MI: material index; ERI: ecological regulation index; SCI: spiritual and cultural contributions index (SCI); UNESCO: United Nations Educational, Scientific and Cultural Organization.

3.2. Calculation of Indices

3.2.1. Calculation of the Human Well-Being Index (HWI)

The HWI is a composite of three indices—MI, ERI and SCI—with each index having a specific weight [39]. In the following subsections, we explain why each of the indicators shown in Table 1 can be used as indicators of biodiversity, and also explain how these biodiversity indicators contribute to human well-being. As the HWI is a composite of multiple biodiversity indicators, the higher the value of HWI, the greater the contribution of biodiversity to human well-being. The HWI is calculated as follows:

$$HWI_i = w_1 \times MI_i + w_2 \times ERIi + w_3 \times SCI_i \quad (1)$$

where HWI_i is the comprehensive index of the contribution of biodiversity to well-being in county i; MI_i, ERI_i, and SCI_i are the MI, ERI, and SCI in county i, respectively; and w_1, w_2, and w_3 are their respective weights.

3.2.2. Calculation of MI

Biodiversity is a basis of human well-being and a source of important materials for production and life, including food, medicine, hygiene, health, and chemicals [43]. Species diversity ensures the availability of necessary nutrients for human health, while ecosystem stability can improve resilience against natural disasters. Based on the characteristics of the Sanjiangyuan area, MI was defined as the supply of agricultural and livestock products. Maintaining suitable farmland ecosystems can provide direct value, such as agricultural products, and indirect value, such as regulation and cultural services [44]. Ensuring food supplies and developing animal husbandry can benefit human nutrition and health, as well as improve economic income and subjective well-being [45]. The equation for MI is as follows:

$$MI_i = w_1 \times APSi + w_2 \times LS_i \quad (2)$$

where MI_i is the MI of county i; APS_i and LS_i are the supply of agricultural products and livestock products in county i, respectively; and w_1 and w_2 are their respective weights. The supply of agricultural products is given in terms of the percentage of arable land and agricultural output, and the supply of livestock products is given in terms of livestock output.

3.2.3. Calculation of ERI

Biodiversity is the foundation of many important ES. Communities with multiple ecosystem functions and high levels of ES typically have more species. Diverse biological communities contribute to ecosystem stability, productivity, and nutrient supply. Thus, based on the characteristics of the Sanjiangyuan area, ERI was considered to be the sum of four second-order indicators: species and genetic security, status of important ecosystems, ecological regulation functions, and ecosystem quality. The equation is as follows:

$$ERI_i = w_1 \times SS_i + w_2 \times IE_i + w_3 \times ER_i + w_4 \times EQ_i \quad (3)$$

where ERI_i is the ERI of county i; SS_i, IE_i, ER_i, and EQ_i are the species and genetic security, status of important ecosystems, ecological regulation function, and ecosystem quality of county i, respectively; and w_1, w_2, w_3, and w_4 are their respective weights.

Species and genetic security are crucial components of biodiversity, as they promote productivity, maintain ecosystem stability [46], and enhance the well-being and satisfaction of local cultures associated with native species [47]. In this work, species richness and the number of the International Union for Conservation of Nature (IUCN) Red List species were used as measures of species and genetic security, as they represent species diversity and ecosystem diversity, respectively. Regionally important ecosystems are the areas with the highest biodiversity; hence, the distribution and protection of important ecosystems is vital for species diversity [48]. The status of important ecosystems was assessed by the percentages of natural grasslands, natural wetlands, and nature reserves. Ecological regulation was expressed using vegetation coverage, carbon sequestration, and water conservation. Vegetation cover was calculated using county land use data, and carbon sequestration was represented by net primary productivity [49]. Water gain and loss were represented by water conservation, which was calculated using a water balance equation [50], as follows:

$$TQ = \sum_{i=1}^{j} (P_i - R_i - ET_i) \times A_i \times 10^3. \quad (4)$$

where TQ is the volume of water conserved (m^3); P_i is the precipitation (mm); R_i is surface runoff (mm); ET_i is evapotranspiration (mm); A_i is the area of ecosystem (km^2); i is the ecosystem type of the study area; and j is the number of ecosystem types in the study area.

Improving regional ecosystems is conducive to promoting ecological stability, enhancing ecosystem service functions, and improving human well-being [9,51]. Ecosystem quality consists of naturalness and connectivity; the former reflects the authenticity of the ecosystem, while the latter reflects the integrity of the ecosystem. Naturalness was expressed as the percentage by area of natural ecosystems in the county, specifically land that had not been anthropogenically developed. Ecosystem connectivity refers to the degree to which an ecosystem facilitates or hinders ecological flows and is important in measuring landscape ecological processes [52]. Moreover, maintaining good connectivity is vital for protecting biodiversity and maintaining ecosystem stability and integrity. The probability of connectivity (*PC*) reflects landscape connectivity and patchiness, and is widely used in landscape planning [53]. This indicator expresses connectivity as the likelihood of direct dispersal between two habitat nodes to evaluate the intensity, frequency, and flexibility of direct migration of the species being studied. The equation for calculating the *PC* is

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \times a_j \times p_{ij}}{A_L^2}, \quad (5)$$

where n is the total number of habitat nodes in the landscape; a_i and a_j are the areas of patches i and j, respectively; p_{ij} is the maximum value of the connectivity of all paths between patches i and j; and A_L is the total land area of the study area. In this study, we used ArcGIS 10.2 software, Conefor Inputs for ArcGIS 9.x, and Conefor Sensinode 2.5.8 to conduct connectivity analysis on forests, arable land, nature reserves, and grassland patches, using terrestrial ecological land as habitat patches.

3.2.4. Calculation of SCI

The spiritual and cultural contributions, given by the SCI, mainly refer to non-material contributions from ecosystems, such as entertainment, tourism, cultural arts, and spiritual experiences. This contribution was evaluated considering two aspects: natural heritage, and blue and green urban spaces. Natural heritage has existential and historical value; it can play a unique cultural function, encourage cultural protection, promote physical and mental health, provide recreational functions, and improve subjective well-being [54]. Blue and green urban spaces have functions such as air purification, noise reduction, localized cooling, and aesthetic services, and they can meet the spiritual needs of residents by improving environmental quality [55]. As it has been repeatedly demonstrated that increased contact with natural environments (that is, blue and green spaces) has significant positive effects on physical and mental health, such spaces play an important role in fulfilling the spiritual needs of urban residents [17,56,57]. The equation for determining the spiritual and cultural contributions is as follows:

$$SCI_i = w_1 \times NH_i + w_2 \times UBG_i \quad (6)$$

where SCI_i is the *SCI* of county i; NH_i and UBG_i are the number of natural heritage areas and the accessibility of blue and green urban spaces in county i, respectively; and w_1 and w_2 are their respective weights. The natural heritage indicator was represented by the number of UNESCO natural and cultural heritage sites and UN important wetlands. Blue and green urban spaces reflect how accessible green spaces and wetlands are for urban residents. Given the scale of urban areas in the Sanjiangyuan area, accessibility of blue and green urban spaces was calculated as the area of green spaces and wetlands within 2 km of urban areas as a percentage of the total area in the 2-km buffer zone.

3.3. Calculating Shifts in the Center of Gravity

The standard deviation ellipse (SDE) is commonly used in the field of spatial statistics as a method to quantify the spatial distribution of geographic elements [58]. By setting the "center of gravity" of HWI as a spatial variable, SDE can be used to elucidate the overall characteristics of HWI, as well as the spatiotemporal changes of its constituent dimensions. The equation for determining the center of gravity is as follows:

$$X = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}; Y = \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i}, \quad (7)$$

where (X, Y) is the weighted average center of gravity, (x_i, y_i) are the center coordinates of the county vector, and W_i represents the weight. This study used the direction distribution function of ArcGIS 10.2 to calculate the position of the center of gravity and analyze the overall changes in well-being and its spatial distribution.

4. Results and Analysis

4.1. HWI

The spatiotemporal distribution of HWI in the Sanjiangyuan area from 2000 to 2020 is shown in Figure 2. The classification was achieved using the natural breaks method in ArcGIS 10.2. The overall HWI scores in the Sanjiangyuan area in 2000, 2010, and 2020 were 0.66, 0.68, and 0.70, respectively, which represents an overall increase of 6.06%. This result may be attributed to the designation of Sanjiangyuan as a national park, which occurred in two distinct phases, and the implementation of community co-management and poverty alleviation policies in the area, which improved local standards of living, ecological environment, and the well-being of local residents. Furthermore, significant spatiotemporal disparities in HWI were observed. Figure 2a shows that, in 2000, Yushu City in the south-central region had the highest HWI (mean = 0.73), followed by four counties and cities in the south, including Banma and Nangqian counties, whose average HWIs were 0.7 or higher. These high HWI scores obtained could be attributed to the extensivity of agriculture in Yushu City, as well as its abundant biodiversity and high forest coverage, which also had a positive influence on HWIs of its surrounding counties. Gande County in the east had the lowest HWI score (mean = 0.60), and the surrounding areas also had relatively low scores. Figure 2b shows that, in 2010, HWI throughout the Sanjiangyuan region increased slightly, with small changes in western counties and cities, and a slight decrease in some eastern areas. In addition, Zeku, Xinghai, and Madoi counties in the northeast greatly improved in terms of HWI. This could be ascribed to the decade-long implementation of the China Western Development strategy, which first benefited the northeastern part of Sanjiangyuan. However, the HWI scores of eastern counties including Gande and Maqin remained low due to their mountainous terrain. Figure 2c shows that HWIs in Sanjiangyuan had significantly increased by 2020 and continued to exhibit an upward trend in some counties, such as Zhiduo and Xinghai. In the 10 years since 2010, these areas were designated as a national ecological barrier zone, wherein = development is either limited or prohibited. Furthermore, the implementation of community co-management led to increased emphasis on green development. Consequently, these areas showed significant improvement in their HWIs in the decade since 2010.

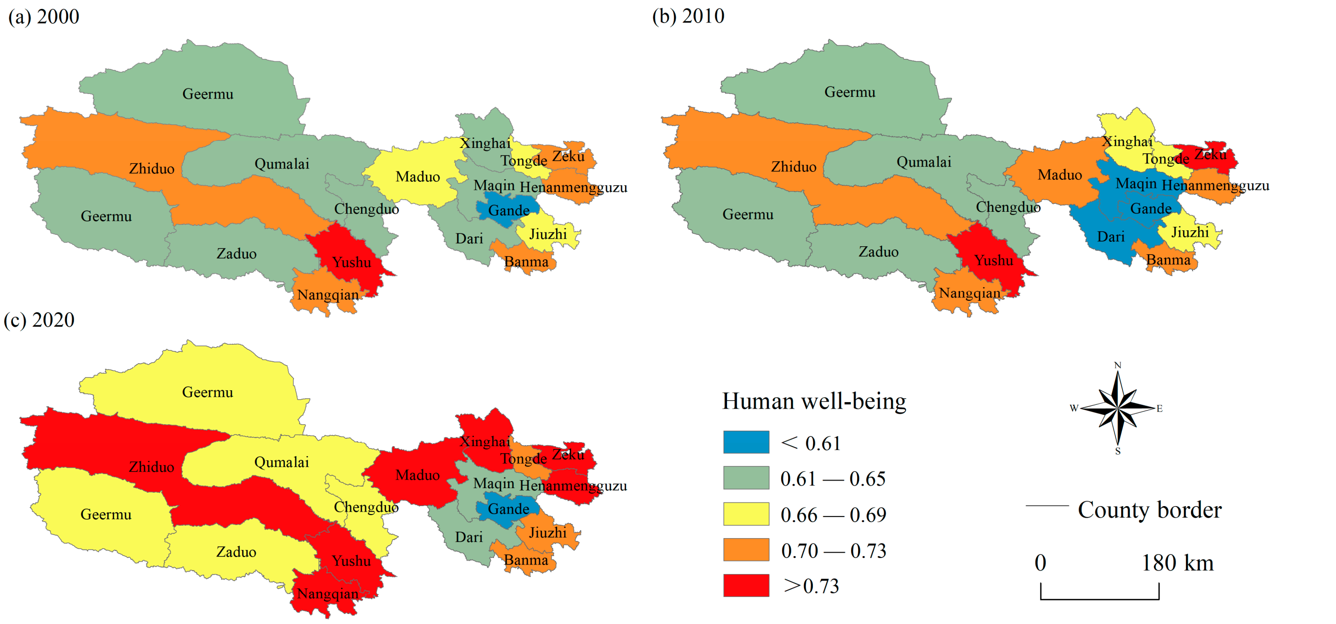

Figure 2. Spatiotemporal differences in the human well-being index (HWI) in the Sanjiangyuan area during 2000–2020.

Subsequently, we analyzed the spatial variations and shifts in the center of gravity of HWI; the results are shown in Figure 3. In terms of spatial changes, HWI significantly improved in 13 counties and was unchanged in the other 5. The changes in HWI were more notable in the west and north, whereas they were minimal in the central and eastern regions. During the study period, the center of gravity of HWI shifted from the south to the north, but remained in Madoi County. This is because China relies on nature reserves in the northwest regions to conserve biodiversity in their continual efforts towards the construction of an ecological civilization. This has resulted in the establishment of the Sanjiangyuan and Qilianshan National Nature Reserves, and hence, northwestern China leads the country in terms of integrated conservation, water conservation, restoration of alpine grasslands, conservation of alpine species, and wetland construction. These ecological projects have resulted in significant improvements in HWI.

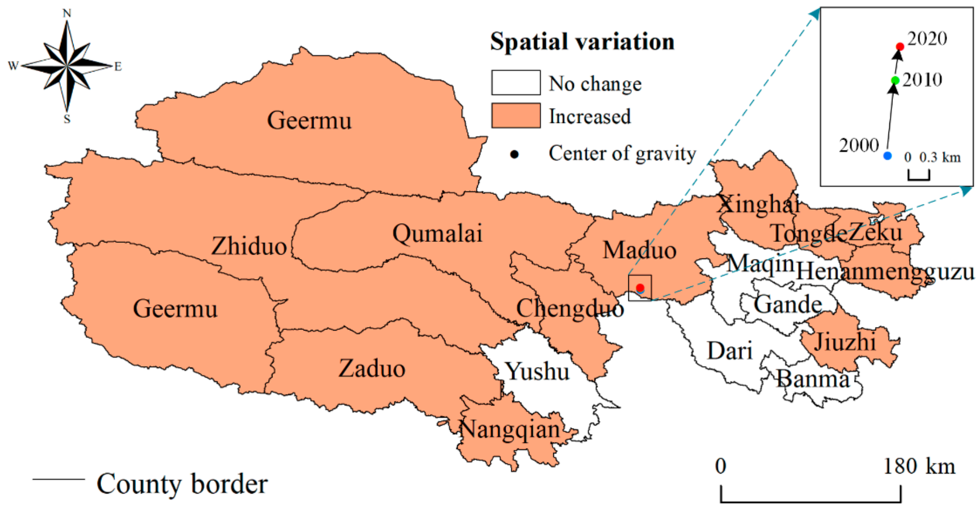

Figure 3. Spatial changes and shifts in the center of gravity of the human well-being index (HWI) in the Sanjiangyuan area during 2000–2020.

4.2. MI

The distribution of MI from 2000 to 2020 is shown in Figure 4; the distribution categories were obtained using the natural breaks method in ArcGIS 10.2. The overall MI scores in the Sanjiangyuan area were 0.49, 0.55, and 0.58 for 2000, 2010, and 2020, respectively. Hence, there was a steady increase in MI (18.37% overall). MI also showed the largest change between the three first-order indices. The changes in MI were initially fast, and then decelerated. This could be attributed to the extensive development of agriculture and animal husbandry between 2000 and 2010, which transitioned into an approach focused on ecological conservation during the 2010–2020 period. The development of livestock and agricultural farming effectively declined by the implementation of ecological redlines, core conservation zones, and ordinary conservation zones, in tandem with precise rotational grazing and fallowing.

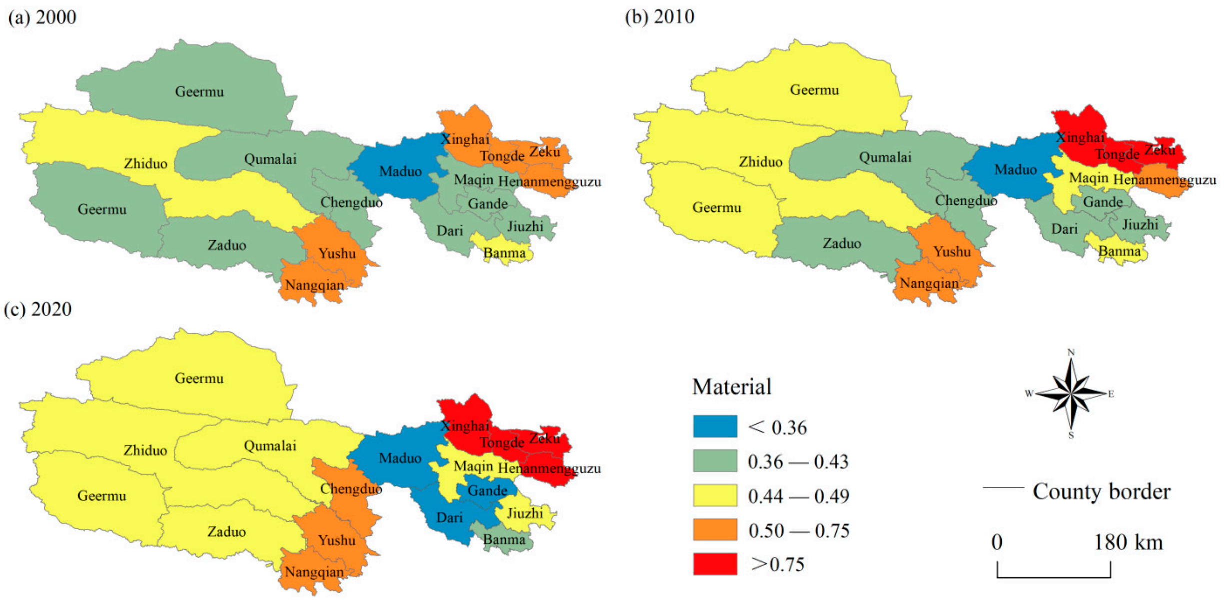

Figure 4. Spatiotemporal differences in the material index (MI) in the Sanjiangyuan area during 2000–2020.

Additionally, there were stark spatiotemporal differences in MI. Figure 4a shows that, in 2000, counties with strong material supply capabilities were concentrated in the east. Tongde County had the highest MI in the northeast (mean = 0.74), followed by that in the adjacent areas, whose mean MIs were all above 0.6. This may be explained by the proximity of these counties to Xining (the capital of Qinghai Province), where the market demand for material supplies is strong. Central Madoi County had the lowest material contribution index score (mean = 0.31), and the scores of counties in the east and west were also low. As shown in Figure 4b, by 2010, MIs throughout the Sanjiangyuan area had increased rapidly, with changes mainly being observed in Golmud (Geermu) City in the west and some counties and cities in the northeast. The MI for Xinghai County in the northeast was the highest (mean = 0.92). However, the MIs of most areas did not change greatly during this period. Figure 4c shows that the spatial distribution changed significantly in 2020 compared with that in 2010. The number of counties with poor material supply capabilities decreased, but the material supply capabilities of some eastern counties, such as Dari and Gande, declined. This is because these counties are located in the conservation zone, where strict restrictions have been imposed on the supply of agricultural and livestock products since 2010.

Subsequently, we analyzed the spatial variations and shifts in the center of gravity of MI (Figure 5). The MIs of 11 counties increased significantly owing to the improvements in transportation and location factors, which facilitated the transport of agricultural and livestock products from these counties. The MIs of four counties remain unchanged, while those of the remaining three counties showed a decrease owing to these counties being located in the conservation zone.

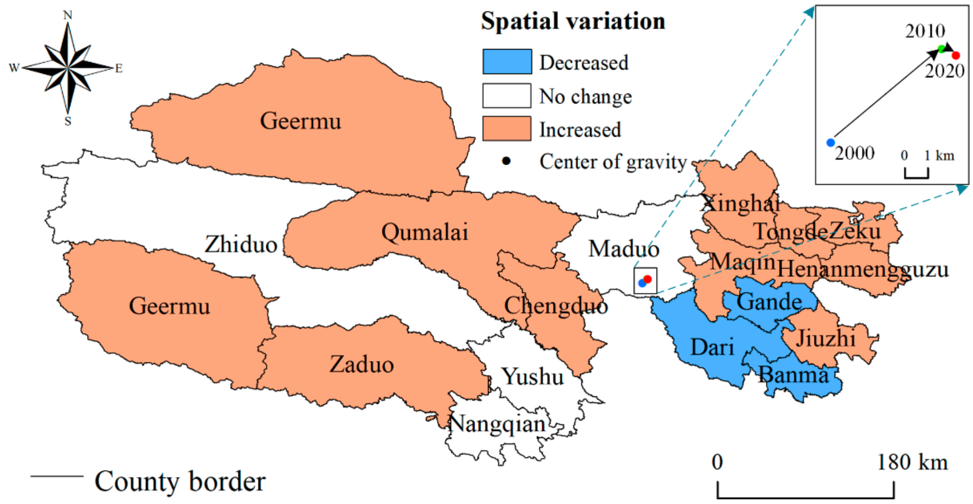

Figure 5. Spatial changes and shifts in the center of gravity of the material index (MI) in the Sanjiangyuan area during 2000–2020.

Spatially, MI increased significantly in the west and northeast. During the study period, the center of gravity for MI shifted towards the northeast and then to the southeast, while remaining in Madoi County. The center of gravity ultimately showed a net shift towards northeast. This was caused by the increased MIs of counties close to Qinghai, the provincial capital, which has excellent transportation networks and also a great demand for livestock and agricultural goods.

4.3. ERI

The spatial distribution of the ERIs from 2000 to 2020 are shown in Figure 6; the distribution categories were obtained using the natural breaks method in ArcGIS 10.2. The overall ERI scores for the Sanjiangyuan area were 0.76, 0.77, and 0.78 in 2000, 2010, and 2020, respectively. The ERI increased by only 2.63% as a whole, and showed the smallest change between the three first-order indices. The increase in ERI was caused by the increasing strength of conservation measures in Sanjiangyuan, including the establishment of the national park and a series of ecological remediation and conservation measures (e.g., turning pastureland into grassland, grazing prohibition and fencing, balancing of livestock and fodder, restoration of "black soil beach" degraded grasslands, and control of grassland pests). Significant spatiotemporal disparities were also observed in the ERI. Counties with high ERIs were concentrated in the southeast (Figure 6a); among them, Banma County had the highest ERI (mean = 0.91), followed by its adjacent counties, which had a mean ERI score above 0.8. Golmud (Geermu) City in the west had the lowest ERI score (mean = 0.66), followed by Qumalai and Xinghai counties. This is because the topography of Golmud City predominantly consists of high-altitude areas such as plateaus and the Tanggula Mountains, which results in low biodiversity. Figure 6b shows that, in 2010, the overall ERI of the Sanjiangyuan area declined, and the distribution of ERI between the counties was irregular. Nevertheless, Yushu City in the south-central region had the highest ERI (mean = 0.92), owing to its high biodiversity, high forest and grassland coverage, and being the source area of the Yangtze, Yellow, and Lancang rivers. Figure 6c shows that the ERIs changed significantly between 2010 and 2020, especially in eastern counties and cities, where they improved. Except for Zhiduo County, ERI did not change greatly in the western areas.

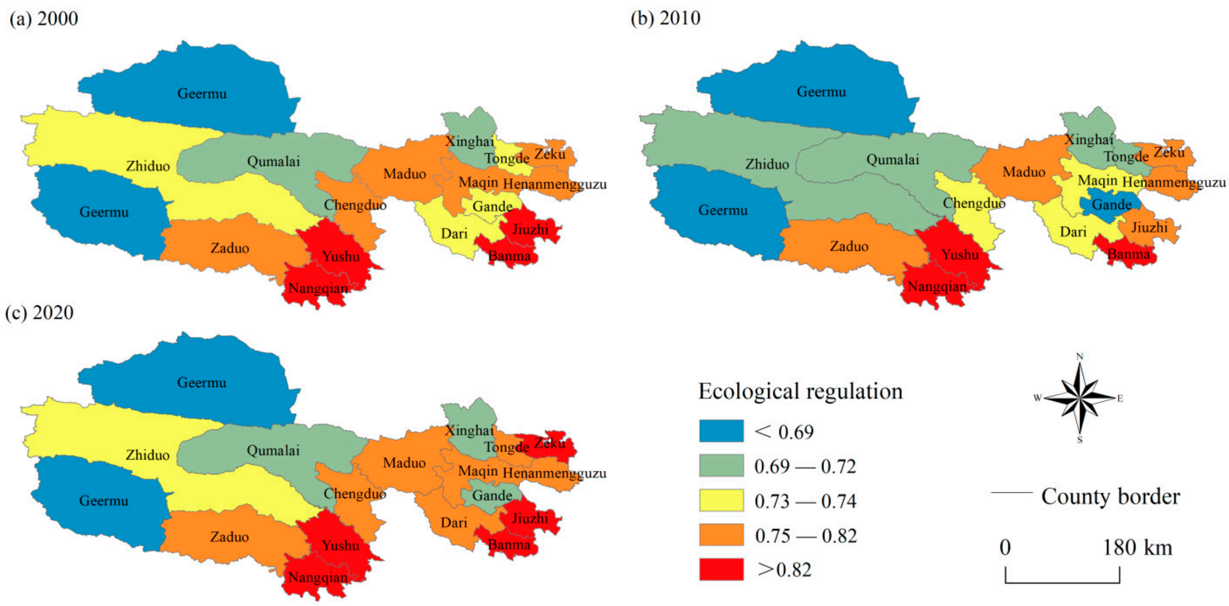

Figure 6. Spatiotemporal differences in the ecological regulation index (ERI) in the Sanjiangyuan area during 2000–2020.

Subsequently, we analyzed the spatial variations and shifts in the center of gravity of the ERI (see Figure 7). The ERI did not change significantly in 14 counties; improvements occurred in 3 counties located in the eastern part of the study area. Only Gande County showed a significant decline in the ERI. During the study period, the center of gravity of the ERI shifted from the east to the west, with a net shift to the west. The center of gravity remained in the southern part of Madoi County throughout the study period, and the shift was very small. Although ES generally improved across the Sanjiangyuan area during the study period, significant spatial disparities still remained. The ERI was high in the southeastern region and low in the northwestern region, likely because of the NW–SE-trending temperature and humidity gradient across the Sanjiangyuan area.

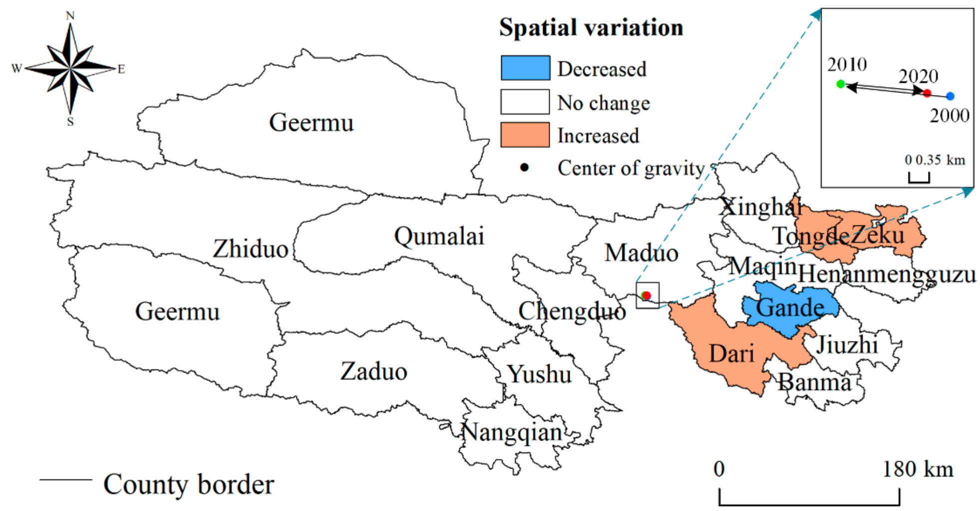

Figure 7. Spatial changes and shifts in the center of gravity of the ecological regulation index (ERI) in the Sanjiangyuan area during 2000–2020.

4.4. SCI

The spatial distribution of SCI from 2000 to 2020 is shown in Figure 8; the distribution categories were obtained using the natural breaks method in ArcGIS 10.2. The overall SCI scores for the Sanjiangyuan area were 0.50, 0.53, and 0.55 during 2000, 2010, and 2020, respectively (a continuous increase of 10% overall). However, there were notable spatiotemporal differences in SCI, with overall trends opposite to those of MI and ERI. Figure 8a shows that, in 2000, Zhiduo County had the highest SCI (mean = 0.87), followed by Golmud (Geermu) City and Qumalai County, all of which are located in the west. The high SCI of Zhiduo County could be explained by the presence of Hoh Xil National Nature Reserve, which contains one of the best well-preserved ecological environments in the world, and is one of the largest, most species-rich nature reserves in China.

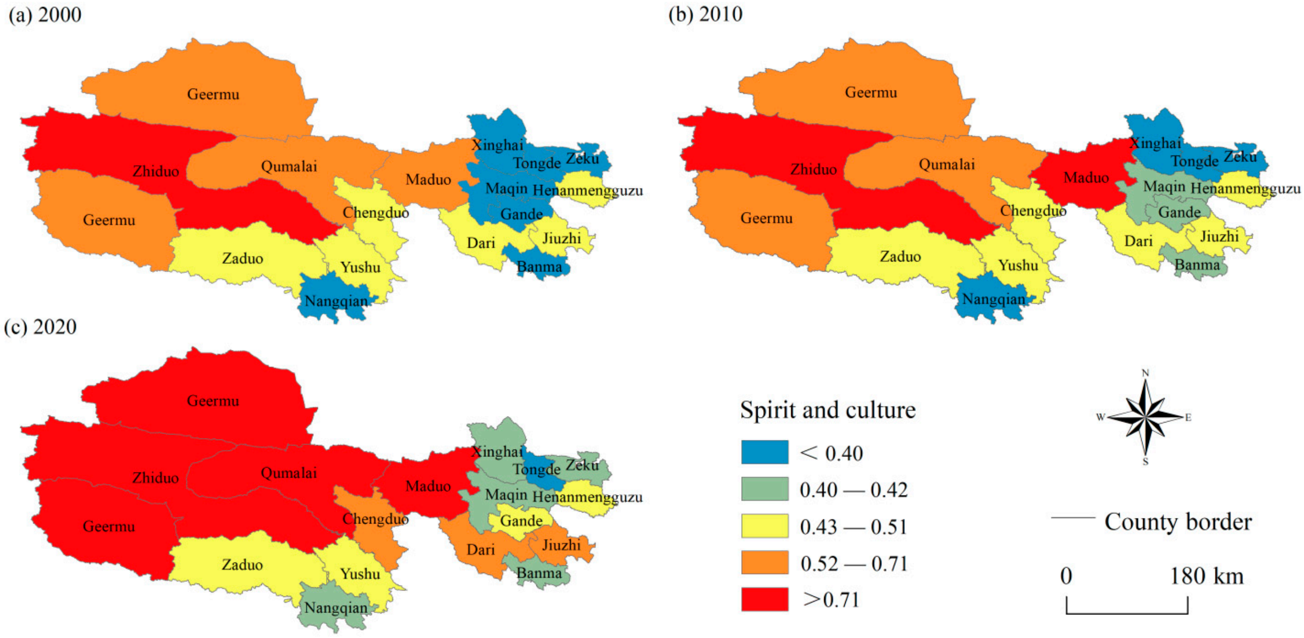

Figure 8. Spatiotemporal distribution of the spiritual and cultural index (SCI) in the Sanjiangyuan area during 2000–2020.

Tongde County in the east had the lowest SCI score (mean = 0.38), and its surrounding counties also had low scores (below 0.4). Figure 8b shows that, in 2010, SCI increased slowly in the Sanjiangyuan area. SCIs for the regions/counties in the west were unchanged, whereas those for the regions in the east increased significantly. The area with the highest SCI changed from Zhiduo County to Maduo County (mean = 0.94) in the center of the Sanjiangyuan area. This is because Maduo County is the source area of the Yellow River; it is also the host of Lakes Zhaling and Eling, which are included in the *List of Ramsar Wetlands of International Importance*.

Figure 8c shows that SCIs throughout the Sanjiangyuan area increased significantly by 2020, but the counties and cities with significant increases were relatively scattered. This could be ascribed to the systematic implementation of ecological conservation policies across Sanjiangyuan after 2010, which caused SCI to increase in all counties of this area.

Subsequently, we analyzed the spatial variations and shifts in the center of gravity of the SCI in the Sanjiangyuan area (Figure 9). The SCI did not change significantly in five counties. Net increases in the SCI occurred in 12 counties. No counties experienced an overall decline in the SCI. During the study period, the center of gravity of the SCI shifted in the SW–NE direction, and then in the SE–NW direction (net shift in the SE–NW direction). The center of gravity remained in southwestern Maduo County throughout the study period. Due to the implementation of conservation-oriented policies, all the counties began to intensify their efforts in the conservation of natural heritage sites and green areas. Consequently, the SCI scores of the study area, which were previously unbalanced and heterogenous, increased and became nearly uniform across the counties.

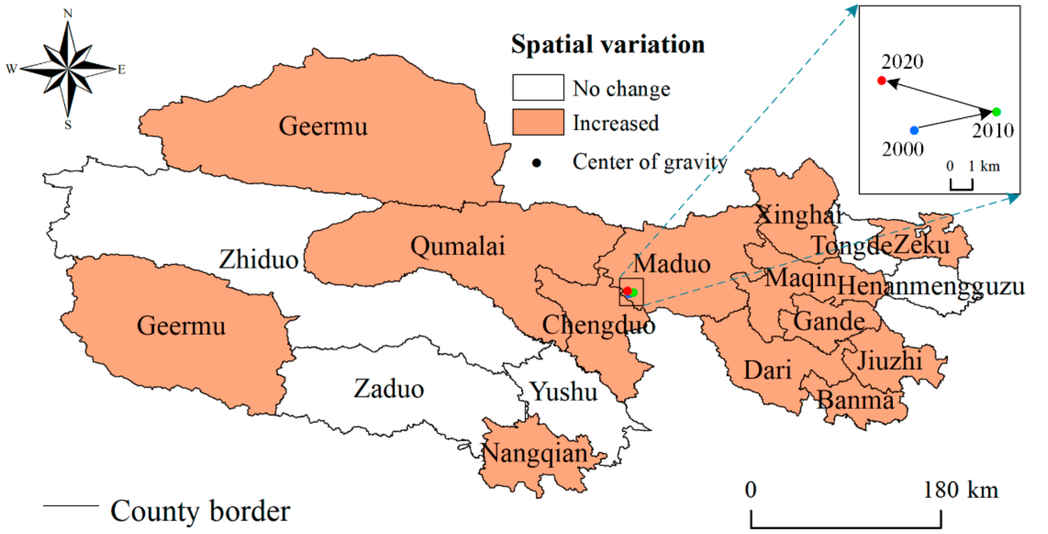

Figure 9. Spatial changes and shifts in the center of gravity of the spiritual and cultural index (SCI) in the Sanjiangyuan area during 2000–2020.

5. Discussion

5.1. Comparison to Other Frameworks Pertaining to the Contribution of Biodiversity to Human Well-Being

Studies on the contributions of biodiversity to human well-being are fundamentally important to understanding the links between biodiversity, ES, and human well-being [59]. The relationship between biodiversity and human well-being has been a focal point for public discussion and scientific research since the publication of the Brundtland report by the UN in the early 1990s [60]. For instance, Pires studied the extent to which biodiversity research in Brazil addresses the linkage between biodiversity, ES, and human well-being [61]. Tapio and Willamol [62] studied a few environmental conservation frameworks and found that they generally focus on the detrimental effects of environmental problems caused by human activities on biodiversity and human well-being. Although some studies have been performed on the relationship between the natural environment and human health [63–65], they do not delve into the processes by which biodiversity affects human health and well-being. Recently, a conceptual framework for the pathways by which biodiversity affects human health and well-being was constructed [66], which seeks to understand the pathways and mechanisms involved using biophysical, social, and psychological processes. Although our conceptual understanding of the pathways by which biodiversity contributes to human well-being has improved, most of the existing literature is qualitative in nature. Currently, there is no consensus on how the contributions of biodiversity to human well-being can be quantified. The MA created a novel perspective whereby biodiversity is positioned as the foundation for ecosystem functioning and its services [67], based on existing research on the functional importance of biodiversity. The IPBES [7,68,69] framework proposes the notion of NCP, so as to consider the relationship between man and nature in a holistic manner. However, the current NCP-based regional assessment reports predominantly consist of qualitative descriptions and policy suggestions [70]. Mace et al. [31] addressed the discrepancies caused by assessment frameworks such as the MA by embedding biodiversity into a four-part framework, making it simultaneously a regulator of ecosystem functions, ES, and ecosystem health [9]. Overall, studying the contribution of biodiversity to human well-being is crucial to exploring the relationship between biodiversity, ES, and human well-being, but the current regional assessment reports based on NCP are mainly qualitative descriptions and policy recommendations [70]; indeed, empirical research on the contribution of biodiversity to human well-being and its corresponding indices is lacking [40].

Based on current assessment systems for the contribution of biodiversity to human well-being, we linked biodiversity to human well-being by using ES as a metaphorical bridge, and constructed an NCP-based system of indices for evaluating the contribution of biodiversity to human well-being [7,39], which is applicable to global and regional scales. A case study was performed on the Sanjiangyuan area in China using this framework. As compared to previous frameworks, our framework used an extensive range of indices. Furthermore, it accounted for the zonality and scale dependence of biodiversity distributions; for instance, the spatial distribution of ERI was based on finely gridded data (such as water conservation data). Our framework also accounted for local variations in how biodiversity contributes to human well-being; one example would be the consideration of the percentage of wetland areas, which is a pertinent indicator of the local ecosystem in Sanjiangyuan. The various dimensions of 'happiness' among the rural population were also considered in our framework, as it includes objective measures (such as the supply of agricultural and livestock products) and subjective measures (such as the area of blue and green urban spaces). To facilitate the use of this framework on larger scales, and to account for policy differences and spatial heterogeneities among administrative zones, we discussed and analyzed each administrative zone, and analyzed the various contributions of biodiversity to human well-being in Sanjiangyuan at the county level. These results were then used to analyze the spatiotemporal changes in human well-being, to provide effective suggestions for ecosystem management at the government level. For example, the implementation of ecosystem conservation and restoration projects in Sanjiangyuan (such as 'turning pastureland into grassland' and 'balancing of livestock and fodder') have caused the ERIs to improve steadily over time. These environmental improvements indirectly increase human well-being, as they promote the development of local agriculture and tourism, which, in turn, increase the income levels and physical health of the local residents. The results of the present study demonstrate that the spatial variations in human well-being are generally consistent with ES and socioeconomic development in the Sanjiangyuan area. Our framework can also be used to quantify the contribution of biodiversity to human well-being in other regions. Furthermore, by conducting comparisons with other regions, the applicability and generalizability of the proposed system of indices can be improved.

5.2. Limitations and Outlook

This study has certain limitations; it needs to be expanded in the following three areas. First, owing to the difficulties in acquiring data, a variety of proxy indicators were used to characterize some of the contributions of biodiversity to human well-being. For example, the indicator for organic products in the material contributions was agricultural output. Moreover, ecological regulation was represented by vegetation coverage, carbon sequestration, and water production; however, there are many other types of ecological regulations. Data restrictions also contributed to the service functions, such as nutrient cycling and atmospheric regulation, not being characterized effectively. In addition, the regional characteristics of the Sanjiangyuan area were not given enough consideration, and the indicators did not reflect special regional cultural attributes, such as regional religions. Future research should use data from multiple sources to develop a more complete index system that better reflects the complex socio-ecological system of this area to more accurately determine the contributions of biodiversity to well-being. Second, the spatiotemporal characteristics of the contributions of biodiversity to human well-being are affected by changes to the natural environment, social economy, policies, and other factors. Future studies should examine these socio-ecological driving forces by exploring their spatiotemporal evolution and clarifying their dynamic relationship with human well-being. Third, although the expert assessment method overcomes data dependence in the indicators to an extent, it still lacks consideration of the well-being needs of a wide range of stakeholders. Therefore, future research should integrate the needs and desires of multiple types of stakeholders. Incorporating the input of experts from relevant fields and local decision makers, preferences of stakeholders such as rural residents, and a combination of bottom-up and top-down subjective empowerment methods will further contribute to improved assessment of human well-being in relation to biodiversity.

6. Conclusions

Based on the NCP framework, in this study, a system for assessing the contributions of biodiversity to human well-being was constructed, and spatiotemporal changes in the system indices in the Sanjiangyuan area of China were determined between 2000 and 2020. The results showed that HWI in the Sanjiangyuan area increased during the study period, and obvious inter-county disparities were observed. Golmud (Geermu) City and Zaduo County in the west and Xinghai County and others in the northeast showed significantly improved well-being, indicating that the overall center of gravity of HWI shifted northward. Between 2000 and 2020, MIs throughout the Sanjiangyuan area continuously increased, mainly in Golmud (Geermu) City and Qumalai County in the west and Tongde and Zeku County in the northeast; however, they decreased in Gande, Dari, and Banma counties in the southeast. The center of gravity of the MI had a net shift in the northeast direction. During the study period, the ERIs first increased and then decreased; overall, a slight increase was observed. ERIs only changed in eastern counties; these increased for Tongde, Zeku, and Dari, and decreased for Gande. The center of gravity of the ERIs did not change significantly. The SCIs increased steadily during the study period and exhibited a lopsided spatial distribution, with high scores being observed for the western regions and low for the eastern regions. The SCIs in Madoi County, Xinghai County, and other northern counties increased greatly. The center of gravity of the SCI showed a net shift to the northwest. In conclusion, the findings of this study will provide support for the quantification of biodiversity contributions to human well-being, as well as the formulation of biodiversity conservation policies.

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Appendix A

Table A1. Expert 1.

First-Order Indicator	Weight	Second-Order Indicator	Weight	Third-Order Indicator	Weight	Calculation Method
Material contribution	0.3	Agricultural goods supply	0.3	Farm ecosystem area	0.4	Percentage of arable land (%)
				Agricultural products output value/grain output volume	0.6	Annual agricultural output value (10,000 yuan)/ Output (tons)
		Livestock product supply	0.7	Livestock output value/meat output volume	1	Annual livestock output value (10,000 yuan)/ Output (tons)
Ecological regulation contribution	0.5	Species and genetic security	0.2	Species richness	0.5	Number of species
				No. of Red List species	0.5	Number of Red List species
		Significant ecosystem status	0.2	Natural grassland area proportion	0.3	Grassland area percentage (%)
				Wetland area proportion	0.3	Wetland area percentage (%)
				Nature reserve area proportion	0.4	Percentage of national nature reserve area (%)
		Ecological regulation functions/0.28	0.3	Vegetation coverage	0.3	Percentage of vegetated areas (%)
				Carbon sequestration	0.4	Net primary productivity
				Water conservation	0.3	Precipitation – Evapotranspiration (mm)
		Ecosystem quality/0.27	0.3	Naturalness	0.5	Percentage of natural land (%)
				Important ecological location connectivity	0.5	Important ecological location (forest, grassland, etc.) connectivity
Spiritual and cultural contribution	0.2	Natural heritage	0.4	UNESCO natural and cultural heritage & no. of UN important wetlands	1	UNESCO natural and cultural heritage & no. of important UN wetlands
		Urban blue-green spaces	0.6	Per capita urban green area	0.5	Area of green space in residential buffer zone/non-agricultural population (%)
				Per capita urban water surface area	0.5	Water surface area in residential buffer zone/non-agricultural population (%)

The weights used in this paper were obtained by the expert scoring method. Compared with the objective weighting methods such as the entropy weight method, the expert scoring method is inevitably subjective to a certain extent. However, the indicators in the index system for this study were obtained at considerably different scales in different ways, and the amount of information contained in each indicator varied significantly. The use of the entropy weight method would have caused excessive differences in weights among the indicators, leading to a decrease in the accuracy of the index system developed. Therefore, we adopted the expert scoring method to determine the weights. The advantage of this method is that both the relative importance of the indices and the actual situations of the study area can be considered, and a certain level of subjectivity is acceptable.

Table A2. Expert 2.

First-Order Indicator	Weight	Second-Order Indicator	Weight	Third-Order Indicator	Weight	Calculation Method
Material contribution	0.15	Agricultural goods supply	0.5	Farm ecosystem area	0.5	Percentage of arable land (%)
				Agricultural products output value/grain output volume	0.5	Annual agricultural output value (10,000 yuan)/ Output (tons)
		Livestock product supply	0.5	Livestock output value/meat output volume	1	Annual livestock output value (10,000 yuan)/Output (tons)
Ecological regulation contribution	0.7	Species and genetic security	0.2	Species richness	0.4	Number of species
				No. of Red List species	0.6	Number of Red List species
		Significant ecosystem status	0.3	Natural grassland area proportion	0.3	Grassland area percentage (%)
				Wetland area proportion	0.3	Wetland area percentage (%)
				Nature reserve area proportion	0.4	Percentage of national nature reserve area (%)
		Ecological regulation functions/0.28	0.4	Vegetation coverage	0.4	Percentage of vegetated areas (%)
				Carbon sequestration	0.4	Net primary productivity
				Water conservation	0.2	Precipitation—Evapotranspiration (mm)
		Ecosystem quality/0.27	0.1	Naturalness	0.5	Percentage of natural land (%)
				Important ecological location connectivity	0.5	Important ecological location (forest, grassland, etc.) connectivity
Spiritual and cultural contribution	0.15	Natural heritage	0.5	UNESCO natural and cultural heritage & no. of UN important wetlands	1	UNESCO natural and cultural heritage & no. of important UN wetlands
		Urban blue-green spaces	0.5	Per capita urban green area	0.5	Area of green space in residential buffer zone/non-agricultural population (%)
				Per capita urban water surface area	0.5	Water surface area in residential buffer zone/non-agricultural population (%)

During the construction of the index system, a total of three expert workshops were organized to gather the opinions of the experts in biodiversity conservation, ecosystem services, human well-being, and the interrelationships of these aspects; the weights of each indicator were determined by scoring. We also visited the Sanjiangyuan area (the study area) several times to consult the experts and carry out field investigations. We held discussions and exchanged thoughts with the local experts and managers. We invited 10 experts to perform the scoring task. In the beginning, each expert was provided with details of our research topic and the study area. Then, we provided them with the scoring sheets and requested them to score the indicators based on the relative importance and the significance of the indicators to human well-being increase in the study area. The numerical range of the scores was 0 to 1. Finally, we determined the weights of the specific indicators by averaging the scores given by all experts. The results were presented to the 10 experts for their revision and confirmation. They approved our weight design.

To improve the readability of the index construction process, we have presented some scoring sheets filled in by experts in Appendix A to help the readers understand the overall scheme of weight assignment.

Table A3. Expert 3.

First-Order Indicator	weight	Second-Order Indicator	Weight	Third-Order Indicator	Weight	Calculation Method
Material contribution	0.3	Agricultural goods supply	0.4	Farm ecosystem area	0.4	Percentage of arable land (%)
				Agricultural products output value/grain output volume	0.6	Annual agricultural output value (10,000 yuan)/ Output (tons)
		Livestock product supply	0.6	Livestock output value/meat output volume	1	Annual livestock output value (10,000 yuan)/Output (tons)
Ecological regulation contribution	0.6	Species and genetic security	0.15	Species richness	0.5	Number of species
				No. of Red List species	0.5	Number of Red List species
		Significant ecosystem status	0.15	Natural grassland area proportion	0.3	Grassland area percentage (%)
				Wetland area proportion	0.3	Wetland area percentage (%)
				Nature reserve area proportion	0.4	Percentage of national nature reserve area (%)
		Ecological regulation functions/0.28	0.35	Vegetation coverage	0.3	Percentage of vegetated areas (%)
				Carbon sequestration	0.5	Net primary productivity
				Water conservation	0.2	Precipitation—Evapotranspiration (mm)
		Ecosystem quality/0.27	0.35	Naturalness	0.5	Percentage of natural land (%)
				Important ecological location connectivity	0.5	Important ecological location (forest, grassland, etc.) connectivity
Spiritual and cultural contribution	0.1	Natural heritage	0.3	UNESCO natural and cultural heritage & no. of UN important wetlands	1	UNESCO natural and cultural heritage & no. of important UN wetlands
		Urban blue-green spaces	0.7	Per capita urban green area	0.5	Area of green space in residential buffer zone/non-agricultural population (%)
				Per capita urban water surface area	0.5	Water surface area in residential buffer zone/non-agricultural population (%)

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