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Using Net Primary Productivity to Characterize the Spatio-Temporal Dynamics of Ecological Footprint for a Resource-Based City, Panzhihua in China

Shuhui Zhang 1, Fuquan Li 2,* , Yuke Zhou 3,*, Ziyuan Hu 2, Ruixin Zhang 4, Xiaoyu Xiang 1 and Yali Zhang 1

1 College of Geosciences, Chengdu University of Technology, Chengdu 610059, China; zhscdu0301@gmail.com (S.Z.); xiaoyuxiang0828@163.com (X.X.); zhangyali@stu.cdut.edu.cn (Y.Z.)
2 No.7 Geological Brigade, Shandong Bureau of Geology and Mineral Resources Exploration and Development, Linyi 276000, China; hzy0618@163.com
3 Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic and Nature Resources Research, Chinese Academy of Sciences, Beijing 100101, China
4 College of Geoscience and Surveying Engineering, China University of Mining and Technology-Beijing, Beijing 100083, China; zhangruixin0604@163.com
* Correspondence: lifqdyx@163.com (F.L.); zhouyk@igsnrr.ac.cn (Y.Z.)

Abstract: An ecological footprint is a primary indicator in measuring the sustainability of regional development, especially in resource-based cities. Here, we built an ecological footprint-based framework to assess the sustainability for a resource-based city of Panzhihua, in China. In this framework, a suite of long-term ecological parameters (2000–2020), essentially including Net Primary Productivity (NPP), land cover, as well as social statistical data, was used as the input indices of a provincial hectare ecological footprint model. The model outputs are composed of the ecological footprint (EF), ecological footprint per capita (PEF), ecological capacity (EC), ecological capacity per capita (PEC), ecological deficit/surplus (ED/S), and per capita ecological deficit/surplus (PED/S). Then the sustainable development capability of the city was comprehensively evaluated using a suite of ecological indices, including the ecological pressure index (EPI), ecological footprint per ten thousand GDP (EFG), ecological sustainability index (ESI), and ecological coordination index (ECI). The study reveals that, from 2000–2020, (1) PEC and PED/S presented an increasing trend (0.2401 hm²/person and 2.1421 hm²/person, respectively), while PEF decreased by 1.9 hm²/person. In the case of the ecological deficit, fossil energy land and forest were the dominant land types in controlling the ecological footprint and ecological capacity; (2) EPI and EFG decreased by 6.6381 hm²/person and 2.2462 hm²/person, respectively, and ESI and ECI increased by 0.3436 hm²/person and 0.2897 hm²/person, respectively. These indices also reflect that the utilization rate of natural resources in Panzhihua City has been improved, with enhanced sustainability, as well as a decline in ecological pressure. This ecological footprint-based framework could work as a template for evaluating the sustainability of resource-based cities from positive and negative ecological footprint indices.

Keywords: sustainable development; ecological footprint (EF); NPP; resource-based cities; Panzhihua Prefecture-level city

1. Introduction

During the last thirty years, China has experienced rapid growth in its population and urbanization, which have directly or indirectly worsened human consumption of natural resources, even causing various ecological and environmental disasters that severely affect human well-being [1,2]. Thus, sustainable development has become a societal consensus attempting to address various resource and environmental issues, such as air pollution, resource depletion, and global warming [3,4]. A regionally sustainable ecological status is crucial for lessening competition among population, economy, and natural resources in
a sensible manner [5,6]. However, gaps in the modeling methodology and evaluation for regional sustainability exist.

In terms of the method, the ecological footprint (EF) is an easy-to-calculate model for assessing the impact of human activities on the natural ecosystem and the environment [7]. The EF value can reflect the volume of natural resources required by human activities at the regional scale. A higher value indicates the ecological environment is more affected by human activities. In the early 1990s, Rees [8] firstly applied the ecological footprint to depict the impact of human activities on the Earth’s environmental changes, which was called the traditional ecological footprint model. Then Wackernagel [9] defined the ecological footprint from different perspectives and pointed out that an ecological footprint can reflect the relationship between human demand and ecological availability. Subsequently, researchers combined the ecological footprint with other domains and proposed improved ecological footprint models, such as NPP-based EF models (EF-NPP) [10], energy-based EF models (EF-E) [11], and a three-dimensional ecological footprint model (3D-EF) [12]. The EF-E and EF-NPP models can obtain more accurate equivalence factors (EQF) and yield factors (YF) [13–15]. To create a three-dimensional ecological footprint model, the concept of the footprint depth and footprint width is involved in the traditional ecological footprint model [16,17].

Subsequent studies revealed that ecological footprint models were closely related to the spatial range and could be modified on various spatial scales, from national hectares [18,19], provincial hectares [20,21], to municipal hectares [22,23]. Essentially, the ecological footprint model is critical, and it must be improved to better reflect the ecological status of the target area. In fact, the EF model has been widely utilized to evaluate regional sustainable development. Some industrial cities in China (e.g., Shanghai [24] and Suzhou [25]) have shown an improvement in the ecological environment according to the assessment of the ecological footprint model.

Our study focuses on Panzhihua City, a typical resource-based city in southwest China, which was mainly developed by coal industries in the early days. After years of intensive development, the problem of overcapacity in the coal industry has occurred, and the pressure to remove and adjust the production capacity is increasing. Panzhihua City has achieved sustainable economic, social, and environmental development through an innovative approach to development. Panzhihua City has transformed from the former “Western Steel City” to the current “Vanadium and Titanium Capital of China” and “Excellent Tourism City of China”. However, the achievement of this transformation of sustainable development should be assessed.

Based on the above analysis, this paper aims to build an ecological footprint-based framework to assess the sustainability of Panzhihua city from 2000–2020, with a model of the ecological footprint based on a provincial hectare. We applied remote-sensing-derived net primary productivity (NPP) and various social statistical data to construct this framework and explore the spatial and temporal variations of the ecological footprints. Finally, the regional capacity of the sustainable development of Panzhihua City was estimated using various ecological footprint indices.

2. Materials and Methods
2.1. Study Area and Datasets

Panzhihua Prefecture-level city (hereafter Panzhihua City) is located in the southwestern Sichuan-Yunnan border area (26°05′ N–27°21′ N, 101°08′ E–102°15′ E), where the Jinsha and Yalong rivers meet in Sichuan Province (Figure 1). Panzhihua City consists of three districts and two counties, with a total area of 7440 square kilometers.
Panzhihua City has a mixed climate of the south subtropical and north temperate zones, with dry and hot valley climates on both sides of the river valley. There are four seasons, which could be divided into dry and wet seasons, with an annual average rainfall of 800–850 mm. The general relative altitude difference in the city is 1500–2000 m. The terrain slopes from northwest to southeast, and the vegetation distribution falls into clear vertical zones.

The model of this study mainly uses MODIS Net Primary Productivity, GlobeLand30, and Social statistical data. MODIS NPP (MOD17A3HGF) data were obtained from NASA Earthdata (https://earthdata.nasa.gov/) (accessed on 1 August 2021) [26]. The net primary productivity product (MOD17A3) defines the rate of net useful chemical fossil energy production by all plants in the ecosystem. The MODIS NPP’s spatial resolution is 1 km × 1 km and is obtained from the Terra satellite. GlobeLand 30 data (http://www.globallandcover.com) (accessed on 1 August 2021), 30 m global land cover data released by the National Basic Geographic Information Center (NGCC), mainly distributed 10 coverage types in the study area, namely cultivated land, forest, grassland, shrubland, wetland, water bodies, tundra, artificial surface, bare ground, glaciers, and permanent snow and ice.

Social statistical data were obtained from the Sichuan Statistical Yearbook, Panzhihua Statistical Yearbook, Panzhihua Yearbook, and government websites. Social factors include
the area, population, consumption, and production of biologically productive land in Panzhihua City, as well as in Sichuan Province.

After that, we preprocessed the data. Firstly, MOD17A3HGF data were reprojected to Albers using MODIS projection tool (MRT) software and vector cropped MOD17A3HGF data from Panzhihua City as well as Sichuan Province to obtain NPP data for 2000, 2010, and 2020. Secondly, GlobeLand30 products were recorded and classified into five categories of sensing parameters, including cultivated land, forest, grassland, water bodies, and construction land. Finally, all data were resampled to 500 m, and Albers was selected for the projection.

2.2. Methods

In order to make a breakthrough in the domain of ecological footprint for geographic spatial analysis of city development, this study constructed an ecological footprint-based framework. We applied this framework to explore the spatial and temporal variations of the ecological footprints in the study area. Then, two negative indicators (EPI and EFG) and two positive indicators (ESI and ECI) were selected as the proxy of sustainable development capability. The outputs of this model could provide reference information to policymakers on sustainable development and ecological civilization construction in Panzhihua City. A flowchart of the provincial hectare ecological footprint study is displayed in Figure 2.

Figure 2. Flowchart of provincial hectare ecological footprint study.

2.2.1. Ecological Footprint Model

The ecological footprint model is composed of the ecological footprint, ecological capacity [27], and regional ecological footprint equation as shown below.

\[
EF = N \times ef = N \times r_j \times \sum_{j=1}^{n} \left( \frac{c_j}{NPP_j} \right)
\] (1)

where \(EF\) is the ecological footprint of the study region, \(N\) is the total population (people) in the region, \(ef\) is the ecological footprint per capita, \(r_j\) is the equivalence factor, \(c_j\) is the \(j\) per capita consumption (kg/person) of the land type, \(NPP_j\) denotes the regional \(j\) type of land unit area, the average NPP (kg/(m\(^2\)*a)), \(j\) is the land type, and \(n\) is the number of land types in the study area.
The regional ecological capacity is calculated as:

$$EC = N \times ec = N \times \sum_{j=1}^{n} a_j \times r_j \times y_j$$  \hspace{1cm} (2)$$

where $EC$ is the regional ecological capacity ($\text{hm}^2$), $N$ is the realistic population of the region (million people), $ec$ is the per capita capacity ($\text{hm}^2$/person), $a_j$ is the area of biologically productive land of category $j$ per capita ($\text{hm}^2$), and $y_j$ denotes the yield factor. To protect biodiversity, the final ecological capacity should be reduced by 12% to balance the ecological capacity base.

Based on the production and data availability in the study area, the consumption items are classified as shown in Table 1.

**Table 1.** Consumption items of the province hectare ecological footprint model.

| Type of Land Use      | Type of Consumption                     |
|----------------------|----------------------------------------|
| Cultivated land      | food, vegetables, oilseeds, pork, poultry, and eggs |
| Forest               | fruit, tea                              |
| Grassland            | beef, lamb, poultry, milk, honey, cocoons |
| Water bodies         | aquatic product                         |
| Built-up land        | electrical power                        |
| Fossil energy land   | raw coal, coke, crude oil, gasoline, diesel, kerosene, natural gas |

When calculating the ecological footprint of all accounts in this document, account consumption data are used instead of production data to calculate the corresponding footprint.

2.2.2. Equivalence Factors and Yield Factors

The equivalence factors (EQF) refer to the coefficient obtained after equalizing the area of biologically productive land such as cultivated land, forest, grassland, and water bodies [28]. Most of the construction land is reflected through the area of cultivated land and fossil fuels are reflected by the area of forest. Therefore, the equivalence factor of cultivated land is consistent, and the equivalence factor of fossil energy land is equivalent to the forest. The yield factor (YF) [29] is a coefficient describing the yield difference of biologically productive land between the study area and Sichuan Province. In the process of calculating the fossil energy land yield factor, the ecological footprint generated by the consumption of fossil energy is reflected by the area of forest that can absorb CO$_2$, and it can be concluded that the yield factor of fossil energy land can be taken as zero. Although the built-up land can capture part of the NPP, the yield factor for the building still uses the yield factor of cultivated land. According to previous studies, the formulas of the equivalence factor and the yield factor are as follows [28,29]:

$$r_j = \frac{NPP_j}{\overline{NPP}}$$  \hspace{1cm} (3)$$

where $r_j$ is the equivalence factor, $NPP_j$ is the average NPP of $j$-th bio-productive land in the study region, and $\overline{NPP}$ is the annual average NPP (g/(m$^2$*a)) for all types of bio-productive land in the study region, and

$$y_j = \frac{\overline{NPP}_j}{\overline{NPP}_j'}$$  \hspace{1cm} (4)$$

where $y_j$ is the yield factor, $\overline{NPP}_j$ is the regional average NPP (g/(m$^2$*a)) of $j$-th bio-productive land type, and $\overline{NPP}_j'$ is the average NPP (g/(m$^2$*a)) of $j$-th bio-productive in Sichuan Province.

2.2.3. Ecological Deficit/Surplus Model

The ecological deficit/surplus refers to the value obtained after the difference between the ecological capacity and ecological footprint is calculated, which is used to determine
whether the human activities in a region are within the tolerable range of the region. If the value of the ecological footprint exceeds the value of the ecological capacity, there will be an ecological deficit, indicating that with the current technology and productivity, the area of biologically productive land cannot support human livelihood. Otherwise, when there is an ecological surplus, this means that the area of biologically productive land can adequately support human life. The formula for calculating the ecological deficit/surplus is

\[ ES = EC - EF \]  

(5)

where \( ES \) is the regional ecological surplus/deficit (hm\(^2\)), \( EC \) is the regional ecological capacity, and \( EF \) is the regional ecological footprint. The per capita ecological deficit/surplus model can be derived from Equation (5). The calculation formula is

\[ es = ec - ef \]  

(6)

where \( es \) is the per capita ecological surplus/deficit (hm\(^2\)), \( ec \) is the ecological capacity per capita, and \( ef \) is the ecological footprint per capita.

2.2.4. Sustainable Development Evaluation Indicators

The following ecological indicators were applied to evaluate the sustainable development capability of Panzhihua City.

(1) Ecological Pressure Index (EPI). The ecological pressure index is an indicator to characterize the state of regional ecological security (see Table 2 for specific divisions). The calculation formula is as follows [30,31]:

\[ ESI = \frac{ef}{ec} \]  

(7)

where \( ESI \) represents the ecological pressure index, \( ef \) is the ecological footprint per capita in Equation (1), and \( ec \) is the ecological capacity per capita in Equation (2).

Table 2. Ecological Pressure Index.

| Level | Ecological Pressure Index | Characterization Status |
|-------|---------------------------|-------------------------|
| 1     | <0.5                      | Extremely safe          |
| 2     | <0.8                      | Safe                    |
| 3     | <1.0                      | Relatively safe         |
| 4     | <1.5                      | Relatively unsafe       |
| 5     | <2.0                      | Unsafe                  |
| 6     | >2.0                      | Extremely unsafe        |

(2) Ecological footprint per ten thousand GDP (EFG). The ecological footprint per ten thousand GDP reflects the relationship between regional socio-economic development and resource utilization [32]. The calculation formula is:

\[ EFG = \frac{EF}{GDP} \]  

(8)

where \( EFG \) is the ecological footprint per ten thousand GDP. \( EF \) is the ecological footprint of the total regional population. \( GDP \) is the regional gross domestic product. The value of EFG represents the efficiency of resource use in the region, and a high value indicates the more efficient use of resources in the region.

(3) Ecological Sustainability Index (ESI). The ecological sustainability index indicates the state in which the ecological environment of an area meets the needs of human ecology [33]. The formula is:

\[ ESI = \frac{ec}{(ec + ef)} \]  

(9)

where \( ESI \) is the ecological sustainability index. \( ef \) is ecological footprint per capita. \( ec \) is the ecological capacity per capita. ESI has a value from 0 to 1. The larger the value, the
higher the degree of ecological sustainability, and vice versa, the weaker the degree of ecological sustainability (see Table 3 for specific divisions).

### Table 3. Ecological Sustainability Index.

| Level | Ecological Sustainability Index | Characterization Status              |
|-------|--------------------------------|--------------------------------------|
| 1     | >0.80                          | Strong sustainability                |
| 2     | <0.80                          | Medium sustainable                   |
| 3     | <0.65                          | Weakly sustainable                   |
| 4     | <0.50                          | Weakness is not sustainable          |
| 5     | <0.35                          | Moderately unsustainable             |
| 6     | <0.20                          | Strong but unsustainable              |

(4) Ecological Coordination Index (ECI). The ecological coordination indicates the degree of coordination between the economic and social development situation in the region and the regional ecological environment [34]. The calculation formula is:

\[
ECI = \frac{ec + ef}{\sqrt{ec^2 + ef^2}}
\]  

(10)

where ECI is the ecological coordination index, ef is the ecological footprint per capita, and ec is the ecological capacity per capitate value of ECI ranges from 1 to 1.44, where the greater the value of ECI, the better the degree of coordination between economic and social development and ecology in the study area, and vice versa. Generally, 1.2 can be the demarcation line of ecological coordination in the study area.

### 3. Results

#### 3.1. Temporal Dynamics of Ecological Footprint

The ecological footprint, ecological capacity, and ecological deficit of Panzhihua City in 2000, 2010, and 2020 were calculated according to Equations (1), (2), (5), and (6). The statistical results are shown below (Figure 3).

In order to accurately analyze the changes over time of Panzhihua City’s ecological footprint, we studied the composition of the ecological footprint, ecological capacity, and ecological deficit during the study period. The ecological footprint of fossil energy and land contributed the most, which dropped from 91% to 26% (Figure 3a). The ecological capacity changed from 80% of cultivated land in 2000 to 66% of forest land in 2020 (Figure 3b). Fossil energy land accounted for the largest share of the ecological deficit, which fell from 94% to 54%, while the grassland ecological surplus rose from 2% to 31% (Figure 3c). The ecological footprint, ecological capacity, and ecological deficit of the water bodies did not change much, indicating that the human impact on water bodies is relatively small.

Figure 3. Cont.
Figure 3. Composition of (a) the ecological footprint, (b) the ecological capacity, and (c) the ecological deficit in Panzhihua City from 2005 to 2014.

3.2. Spatial Pattern of the Ecological Footprint

The spatial patterns of the ecological footprint, ecological capacity, and ecological deficit in Panzhihua City during the research period are shown in Figures 4 and 5.

![Maps of ecological footprint per capita.](image)

Figure 4. Maps of ecological footprint per capita.

![Maps of ecological capacity per capita.](image)

Figure 5. Maps of ecological capacity per capita.

The spatial pattern of the ecological footprint per capita did not change much during the study period (Figure 4). Red indicates a high ecological footprint per capita and pink indicates a low ecological footprint per capita (the fossil energy ecological footprint was not included). The low values of per capita ecological footprint are mainly concentrated in the central part of the study area and the location of rivers, while the high values are not included. The low values of per capita ecological footprint are mainly concentrated.
in the central part of the study area and the location of rivers, while the high values are mainly distributed to the left and right of Panzhihua City.

Likewise, there are scarce changes for the spatial pattern of ecological capacity per capita from 2000 to 2020 (Figure 5). Red and pink colors indicate the high and low ecological capacity of the region, respectively. The area with a low ecological capacity is mainly distributed in rivers and the central location in the study area. The areas with high ecological capacity in the study area are located on both sides and distributed in a block. The low ecological capacity of the central region is due to frequent human activities in the central city, which has a greater impact on the ecology and low ecological capacity.

3.3. Sustainable Development Evaluation

3.3.1. Dynamics of Ecological Pressure Index and Ecological Footprint per Ten Thousand GDP

The ecological pressure index and ecological footprint per ten thousand GDP of Panzhihua City in 2000, 2010, and 2020 were calculated based on Equations (7) and (8). The results are as follows.

The change of the ecological pressure index from 2000 to 2020 showed that ecological pressure first increased and then decreased sharply, from 7.8428 to 11.8119, and finally dropped rapidly to 1.2047 (Figure 6). This situation may be attributed to the stable ecological capacity of Panzhihua City in the period 2000–2020, but the ecological footprint increased significantly from 2000 to 2010 and decreased greatly during 2010 to 2020, resulting in the overall increase and then decrease in EPI. According to the classification table in Table 2, the ecological pressure status of the study area was in a very insecure state in 2000 and 2010, while it was relatively unsafe in 2020. Generally speaking, the EPI of the study area fell by 85% from 2000 to 2020, indicating that the ecological stress of the study area increased and then decreased sharply from 2000 to 2020, and the ecological environment is good.

The ecological footprint per ten thousand GDP in Panzhihua City decreased rapidly and linearly from 2000 to 2020 ($R^2$ was 0.99), with a value of 2.3288 in 2000 and 0.0826 in 2020, showing a decrease of 96% (Figure 6). This indicates that the study area has rapidly improved the efficiency of resource utilization. The mode of production has changed from
the previous unsustainable crude type to the intensive type of sustainable development, and the city’s development has moved in the direction of resource recycling.

3.3.2. Changes in the Ecological Sustainability Index and the Ecological Coordination Index

According to Equations (9) and (10), the ecological sustainability index and the ecological coordination index of Panzhihua City in the three periods of 2000, 2010, and 2020 are calculated, and the results are shown below.

The ecological sustainability index shows an overall increasing trend. The ESI increased from 0.1131 to 0.4536, with a turning point in 2010 (Figure 7). The ecological sustainability index level changed from strongly unsustainable development to weakly unsustainable development but is still in an unsustainable state. The ecological coordination index is similar, which usually used 1.2 as the dividing line between good and bad. The ECI increased from 1.1185 to 1.4082, an increase of 0.2897, and experienced a shift from decreasing to increasing in 2010 (Figure 7). The ecological coordination development capacity of the study area changed from poor to better coordination, and the ecological coordination development capacity increased. The two positive assessment measures, the ecological sustainability index and the ecological coordination index, revealed that the ecological environment of the study area deteriorated in general in the first decade, whereas the ecological environment improved rapidly in the second decade. Overall, Panzhihua City’s capacity for sustainable development as well as coordinated development has generally improved.

4. Discussion

4.1. EF-NPP and Traditional Ecological Footprint Analysis

Traditional ecological footprint analysis is improved by EF-NPP. The key distinction is in how the equivalence (EQF) and yield factors (YF) are calculated. The traditional ecological footprint calculates the elements based on the consumption and yield of bio-productive land, whereas the EF-NPP calculates the factors based on the NPP of different types of land. Aside from that, EF-NPP may calculate built-up land factors to better convey productivity [28,29].
Compared to the ecological footprint determined by EF-NPP for all of China [28,29], we found that cultivated land, built-up land, and fossil energy land in Panzhihua City have lower equivalency factors and yield factors than the national average, implying that the NPP of these biologically productive lands in the study area is lower than the national average (Figure 8). Furthermore, the equivalency factors and yield factors of grassland and water bodies are greater than the national average, implying that the NPP of these bioproduction land is comparable to the national average value (Figure 8).

![Figure 8. The comparison of average EQF and YF with Liu's and Yang's studies.](image)

4.2. Ecological Footprint Spatial Pattern and Sustainable Development Evaluation

This research’s ecological footprint and ecological capacity figures are lower than those of the previous study, which also focused on Panzhihua City’s ecological footprint (Figure 9). Both results show that the study area’s ecological footprint increased during the study period. The proposed methodology of this study for studying the sustainable development capability is advantageous when compared to the study published in 2017 [35]. First, the two studies used different equivalence factors and yield factors. The equivalence factors used in Liu’s article are from Wackernagel [36] and the yield factors are from the Food and Agriculture Organization’s yield factors (FAO) [37]. Meanwhile, the approach used in this research estimates the NPP of various vegetation types and categorizes them into land-use groups (Cultivated land, Forest, Water bodies, Grassland, and Built-up land) based on their direct human use relevance to obtain more reasonable equivalence factors and yield factors (Figure 8). Secondly, the previous work used national equilibrium and production factor data. This study is calculated by the provincial hectare model, which better matches small and medium scales.
There are still limitations in this study. Since there is no unified and standardized accounting system for ecological footprint accounting, and due to the limited available knowledge, different researchers may adopt different parameter criteria for ecological footprint studies in the same region. Those issues result in certain shortcomings in the reliability and consistency of ecological footprint models in terms of calculation results. Because there are few ecological footprint documents in this area, we take Sichuan Province as an example for comparison. According to the study by Xu et al. [38], the per capita ecological footprint of Sichuan Province in 1999 was $0.951 \text{hm}^2/\text{person}$, while the ecological capacity per capita of Sichuan Province in 1999 was $0.385 \text{hm}^2/\text{person}$. Their direct results are different. Different results may limit the usefulness of the ecological footprint as a tool for assessing sustainable development capacity. In the future, ecological footprint research still needs to continuously improve the ecological footprint accounting method and propose a framework for the standardized calculation of key parameters.

5. Conclusions

It is critical to examine the influence of human activities on the ecosystem in the region during a period of rapid population increase and urbanization and maintain sustainable development. In this paper, we built a framework of the provincial hectare ecological footprint model (EF-NPP) to study the sustainable development capacity of Panzhihua City. The main conclusions of this paper include three points. Firstly, the temporal changes in the ecological footprint of our study area were measured quantitatively and the ecologically vulnerable areas were spatially located. The results show that the ecological environment of Panzhihua City was extremely unsafe from 2000 to 2010, and in the period of 2010–2020, the ecological environment improved rapidly. The spatial pattern shows that the downtown area of the study area and the built-up area are ecologically fragile areas with low ecological capacity and greater ecological pressure. Third, this research shows that human impacts on ecosystems are more fully reflected by using two negative indicators (EPI and EFG) and two positive indicators (ESI and ECI). The study area still needs to continue to optimize the industrial structure, change the method of resource utilization, and build an ecologically civilized city.
Author Contributions: Conceptualization, S.Z., F.L. and Y.Z. (Yali Zhang); formal analysis, S.Z., F.L. and Y.Z. (Yali Zhang); funding acquisition, F.L. and Y.Z. (Yuke Zhou); methodology, S.Z., F.L. and Y.Z. (Yuke Zhou); data curation, R.Z., X.X. and Y.Z. (Yali Zhang); writing—original draft preparation, F.L. and Y.Z. (Yuke Zhou); writing—review and editing, F.L., Z.H. and Y.Z. (Yuke Zhou) All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program (Grant No. 2021xjkk0303 and 2018YFB0505301).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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