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New Perspectives on the Impact of Human Activities on Natural Resources in Oasis Areas: A Case Study of Oasis in Wuwei, China

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Abstract: An accurate analysis of the relationship between humans and the land in oasis areas is essential for the formulation of policies for differentiated oasis urban development and resource management measures. Therefore, researchers have conducted numerous studies based on the linear relationship between "people and land" in oasis areas. To address this gap, this paper takes the Wuwei oasis as an example and re-examines the impact of human activities on the sustainability of natural capital from a new research perspective (nonlinear perspective). The study selected four variables, namely planted forests, scientific R&D investment, urbanization, and population density, as the main human activities affecting the Wuwei oasis area. The NARDL model, the nonlinear Granger causality test, is employed to investigate the interactions between the variables and the oasis natural capital in both the short and long term. The results indicate the following: (1) During the study period, the consumption of natural capital in the Wuwei oasis has been increasing annually and has long exceeded the local ecological carrying capacity. (2) In the short term, planting forests is the most beneficial human activity. The most beneficial human activity is the planting of trees, while in the long term, scientific R&D investment has the most positive effect on enhancing the oasis' resource reserves. (3) Urbanization, population density, and planted forest land all have a direct effect on the sustainable development of natural resources in the oasis. The findings of the study indicate that the application of scientific and technological innovation to promote the sustainable development of resources and the environment is a more reliable approach for oasis cities with a high degree of industrialization.

Keywords: natural capital; nonlinear relationship; human activities; oasis city; sustainable development

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1. Introduction

The world's deserts currently cover 36 million square kilometers, representing one-quarter of the world's land area [1]. Oases, which are important to human life in desert areas, account for only a few hundredths of a percent of the land area. However, 10 percent of the world's population lives in oases. In addition, oases are shrinking every year, and desertification is expanding [2]. The 2023 UN report states that between 2015 and 2019, land desertification resulted in the loss of at least 100 million hectares of healthy and productive land annually, affecting global food and water security [3,4]. If land degradation continues at a similar rate, then desertification of an additional 1.5 billion hectares of land by 2030 will be imminent. Due to increasing global desertification, desertification control has been listed as one of the top 10 global environmental issues [5,6]. Likewise, many countries and regions have proposed solutions to this international priority issue [7,8], and an increasing number of scholars believe that oasis ecological protection and ecosystem stabilization are important ways to hinder the fight against desertification [9–11].

China is home to one of the largest numbers of oases globally, with the majority situated in the northwestern region [12]. These oases are largely dependent on the abundant water resources of the mountainous areas, which gives them a unique ecological function and productivity. Moreover, they have become the sole ecosystem capable of effectively counteracting the arid climate [13–15]. Oases are typically characterized by their small size, dense population, and ecological sensitivity and fragility. Consequently, numerous scholars have researched the sustainable development of oasis regions [16–20]. This research has focused on two main areas: protecting oasis ecosystems and enhancing their ecological carrying capacity. Previous studies aim to maintain sustainable regional development by constructing an oasis ecological security pattern. However, the sustainable development of oasis cities requires a series of optimal trade-offs between different economic, social, and ecological interests [21–23]. In other words, dealing with the relationship between human activities and environmental changes is crucial to realizing the sustainable development of oasis systems. Therefore, this study takes the people–land relationship in oasis cities as a starting point to explore the potential for sustainable development in Chinese oasis areas.

The developmental relationship between human activities and oasis natural resources can be divided into two stages. In the initial stage, human beings are deepening the utilization of natural resources. Promoting national strategies such as the "Belt and Road" initiative and the development of the western region have led to an increase in the population of arid regions along the Silk Road in China [24]. This has resulted in the deterioration of the ecology of the oases due to the accumulation of human impacts. Concurrently, as many individuals relocate from rural to urban areas, there is a paucity of available space for expanding land resources, particularly arable land, in oasis cities [25,26]. Consequently, the substantial expansion of urban construction land presents significant obstacles to the protection of oasis ecosystems and the assurance of food security [27,28]. With time, urban managers have gradually realized the encroachment of human activities on oasis resources, and the people–land relationship has begun to move toward the optimization stage. For example, to mitigate the negative impacts of land desertification and soil erosion, the Chinese government has initiated a series of projects to return farmland to forest and grassland [29]. These initiatives will undoubtedly enhance the region's biodiversity and planted forests. Furthermore, with technological advances and the increased demand for human well-being, the oasis region's unique light and wind advantages will be fully utilized [30], will continue to impede the extraction of non-renewable resources, and will promote the sustainable development of regional ecology.

The impact of human activities on the natural resource environment of Chinese oasis cities is a complex phenomenon. However, previous studies have usually used linear regression models or correlation analysis to clarify the relationship between the two [25–30]. This is at odds with the evolutionary model (inverted U-shape) of the 'people–land' relationship [31]. In addition, the impact of human activities on natural resources should not be defined in general terms as positive or negative. Therefore, there is an urgent need for a novel and objective coupling model to guide the future sustainable development of the region in the study of the "people–land" relationship in oasis cities. This study first used a nonlinear autoregressive distributional lag (NARDL) model. Compared to other nonlinear models, this model shows superior statistical performance in small samples and can effectively represent the asymmetric relationship between human activities and natural resources [32–34]. At the same time, this approach can also consider both short-term and long-term development, thus strongly avoiding the subjective research caused by "preconceived ideas". Secondly, this study incorporates a nonlinear Granger causality test into the "people–land" relationship. This is because the NARDL model can only reveal the extent of human activities' impact on oasis resources rather than the direction of causality. The inclusion of causality tests can help distinguish the indirect/direct impacts of human activities on resource depletion and also help

clarify the constraints of natural resource changes on human activities [35]. Hence, this study makes two significant contributions to the existing literature. First, it adopts a more developmentally realistic approach to identifying the linkages between human activities and natural resources. It can address the shortcomings of previous studies on the 'people–land' relationship in oases. Second, this study innovatively applies the Granger causality test to studying the human–land relationship in oasis cities. In order to ensure the unity of research perspectives, the causality test also follows the principle of nonlinearity, which can find a more accurate path for the sustainable development of natural resources in oases.

To make the study's results meaningful, a typical oasis city in western China, Wuwei Oasis, was chosen for this study. The Wuwei Oasis is a typical area of complex human–land relations in China [36], and the results of the sixth survey on desertification and sanding in China in 2019 clearly show that the area around the Hexi Corridor in China is home to some of the most severe desertification and sanding in the country [37]. There are 20,800 square kilometers of decertified land and 15,100 square kilometers of non-decertified land in Wuwei, accounting for 64.4% and 46.7% of Wuwei's land area, respectively [38]. In addition, Wuwei is an important energy corridor for transporting clean energy from Northwest China to the Middle East [39]. It is currently undergoing a period of rapid economic development. It is, therefore, important to assess the current ecological status of the Wuwei Oasis and the impact of human activities on its natural resources. Based on this, this study takes Wuwei Oasis as the study area, starts from the development law of the "people–land" relationship, takes nonlinear change as the research perspective, and deeply explores the relationship between human activities and natural capital. This study aims to answer the following questions:

- What is the current change in natural resources in the Wuwei Oasis?
- Is the relationship between human activities and natural resources in oasis cities harmonious in the long term?
- Which human activities will have a direct impact on the sustainable development of oasis resources?

2. Materials and Methods

2.1. Study Area

The Wuwei Oasis in China is located in the temperate arid zone with a typical continental climate, living inland, an arid climate, scarce precipitation, and strong evaporation; however, it features long sunshine hours and abundant heat (Figure 1). The Tengger Desert in the eastern part of the study area is 122 km long from east to west and 90 km wide from north to south, with a total area of 5080.97 km^2. The central part of the area is flat and has fertile soil, which is one of the most concentrated areas for high-quality agricultural products in China. The unique natural conditions have enabled Wuwei to form the largest oasis area at the eastern end of the Hexi Corridor in China. To control the desertification of the land in the Wuwei Oasis, the local government has constructed a 30 km windbreak and sand-fixing forest belt through a series of ecological management strategies, such as artificial afforestation and conversion of farmland to forests, which have significantly increased the vegetation coverage rate.

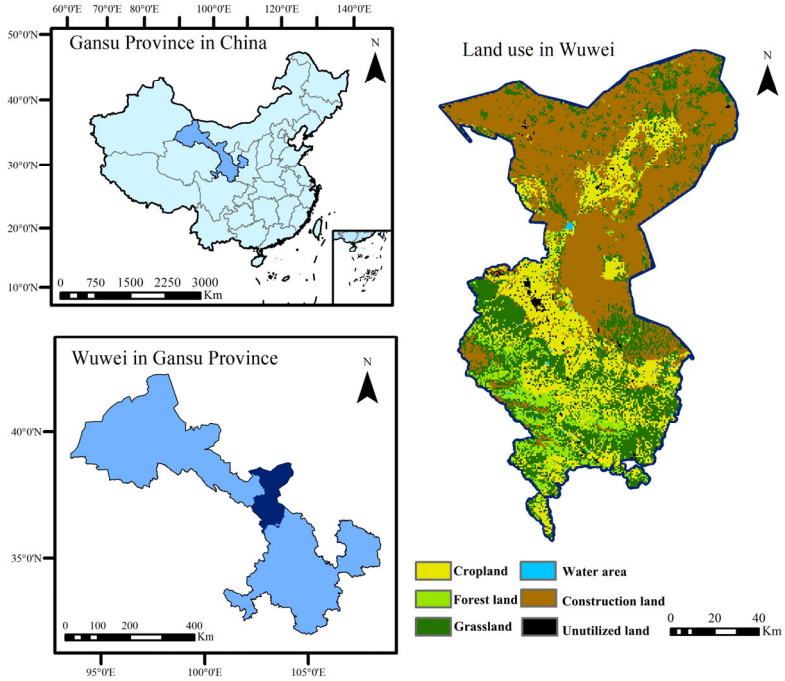

Figure 1. Study area.

2.2. Data Source

In this study, we mainly used socioeconomic data from 2000 to 2020. In order to calculate the natural capital consumption, 22 bio-resource items, such as wheat, corn, and oilseeds, and 4 energy consumption items, such as raw coal, oil, natural gas, and electricity, were selected to analyze the biological and energy resource consumption. The data were obtained from the Gansu Provincial Statistical Yearbook, China Regional Economic Statistical Yearbook, and China Urban Statistical Yearbook. The four indicators of planted forests, scientific R&D investment, population density, and urbanization are from the Gansu Provincial Statistical Yearbook.

2.3. Methods

Rapidly urbanizing regions exhibit economic, social, and urban population growth and agglomeration. Both per capita demand and total consumption increase the consumption and occupation of natural capital, resulting in insufficient supply and severe ecological deficits. However, regional economic development provides opportunities to improve resource utilization efficiency. Accordingly, in the context of the natural capital sustainability objective and in conjunction with the team's existing work, indicators representing human activities were selected in terms of UR (urbanization), PD (population density), PF (plantation forestry), and SR&D (scientific research and development inputs). In this manner, the asymmetric and symmetric impacts of human activities on natural capital sustainability are analyzed. PF indicates artificially restoring severely damaged ecosystems and protecting and rationalizing limited natural and ecological space utilization [40]. Therefore, in this study, we considered plantation forestry an essential symbol of human participation in ecological reconstruction. Secondly, the process of urbanization and the concentration of population often result in significant alterations to the structure of oasis ecosystems [41,42], which can also influence how people utilize the land. Furthermore, these alterations can have profound implications for the trajectory of social development. Finally, SR&D represents a crucial means of achieving a harmonious relationship between economic growth and environmental protection [43]. The level of government investment in scientific research and development in oasis areas will profoundly impact the sustainability of natural resource utilization.

Many studies have indicated that the three-dimensional ecological footprint can be used to measure the sustainability of natural capital [44,45]. The depth of the footprint represents the degree of depletion of the natural capital stock [46–48], and the regional sustainable development status is judged based on the degree of reduction in the capital stock. Based on this, we used ecological footprint depth (EFD) as a dependent variable to indicate the sustainability of natural capital in the study area. To ensure that the EFD closely follows the actual situation in the study area, available global-scale data were not used in this study. The specific reprocessing method is described in detail in Section 2.3.1.

2.3.1. Natural Capital Accounting

Because the biological production capacity per unit area of cropland, unutilized land, grassland, forest land, and water area varies considerably, it is necessary to multiply the production of each organism by an equivalence factor in order to convert the results of the calculations into comparable standards. Similarly, since the productivity of different organisms varies considerably from country to country and region to region, it is necessary to multiply each organism by a yield coefficient to convert it into a bio-productive area. Considering the actual cultivation in the study area, yields were calculated as follows (Table 1): Cropland was calculated using the yields of three crops: cereals, oilseeds, and vegetables (wheat, corn, potatoes, cotton, oilseeds, vegetables, herbs). Grassland was calculated using the yield of livestock and its by-products. Forest land was calculated from the yield of fruit trees by area. The consumption of each energy source was converted to standard coal consumption, and secondary energy conversion was excluded from the calculation. Based on the results of previous studies [49] and the carbon cycle, the ecologically productive land occupied by unutilized land and construction land was corrected to forest land and grassland, respectively. The average yield of primary products was calculated based on the agricultural production in Gansu Province from 2000 to 2020. The equivalence coefficient and production coefficient were taken from Guo [50].

Table 1. Classification of production products.

Consumption Entries	Producing Products	Land Type
Consumption of biological resources	Wheat, corn, potatoes, cotton, oilseeds, vegetables, herbs	Cropland
	Apples, pears, dates, persimmons, apricots, peaches	Forest land
	Pork, beef, lamb, wool, milk, eggs	Grassland
	fishery product	Water area
Fossil energy consumption	Coal, oil, natural gas	Unutilized land
	Electricity	Construction land

Footprint depth indicates the degree of natural capital stock overdraft when the consumption of natural capital exceeds its flow; that is, the accumulation of human resources in time beyond the ecological carrying capacity part has a temporal property. It can be understood as the number of years required by ecological land production of an area to completely overdraw the natural capital stock of that area; it is calculated as follows:

$$EFD = 1 + \frac{\sum_{i=1}^{n} max(EF_i - EC_i)}{\sum_{i-1}^{n} EC_i} \quad (1)$$

where EFD represents the footprint depth, EF_i is the ecological footprint of the type i productive land, and EC_i is the ecological carrying capacity of the type i productive land.

$$EF = N \times \sum_{i=1}^{n} \frac{C_i}{Y_i} \times r_j \quad (2)$$

$$EC = \frac{1}{N} \times \sum_{i=1}^{n} A_i \times r_j \times y_i \quad (3)$$

where EF is the ecological footprint, n is the total number of biological resource types, i is the ith biological resource, C_i is the per capita consumption of i biological resource, Y_i is the average production of the ith biological resource in the study area, N is the number of populations, EC is the per capita ecological carrying capacity, A_i is the biologically productive area of different land types, r_j is the equilibrium factor, and y_i is the yield factor.

2.3.2. NARDL Model

We explored the relationships among the variables using the NARDL model developed by Shin et al. [51] in 2014. The NARDL model does not require same-order cointegration and only needs to satisfy the time series variables at I(0) or I(1) [52], which undoubtedly expands the applicability of the model in the empirical study of different issues and has a particularly obvious advantage in testing the long-run relationship [53]. Furthermore, the model is capable of distinguishing between the short-term and long-term impacts of regression variables, as well as considering the positive and negative shocks of explanatory variables [54]. This enables the differentiation between the positive and negative shocks of different variables on the sustainable development of oasis cities. We examined the effect of the decomposition of the explanatory variables into positive and negative changes on the explanatory variables and provided reliable results. First, we used footprint depth as the dependent variable and described the indicator as a function of UR, PD, PF, and SR&D accumulation as follows:

$$EFD = \int (UR, PD, PF, SR\&D) \quad (4)$$

This equation can be further established as:

$$EFD = \beta_0 + \beta_1(PF) + \beta_2(UR) + \beta_3(SR\&D) + \beta_4(PD) + u_t. \quad (5)$$

where β_0–β_4 are the coefficients of each variable in the model, and u_t is the error term at time t.

Then, unlike other models, the order of integration of the time series is considered the same in the NARDL model, which accepts I(0) and I(1) orders of integration or a mixed model. The model can be used to evaluate the nonlinear asymmetries and covariates present in small samples in a single equation. This step allows the examination of the effects on the explanatory variables when they are decomposed into positive and negative changes and provides reliable results [55].

$$y_t = \beta^+ X_t^+ + \beta^- X_t^- + u_t. \quad (6)$$

where y_t is the explanatory variable; X_t is the vector of explanatory variables; X_t^+ and X_t^- are the positive and negative cumulative increments for X_t, respectively; $X_t^+ = \sum_{j=1}^{t} \max(\Delta X_j, 0)$, $X_t^- = \sum_{j=1}^{t} \max(\Delta X_j, 0)$. Further, $X_t = X_0 + X_t^+ + X_t^+$; β^+ and β^- are long-term asymmetric parameter vectors, respectively, which indicate the positive and negative shocks of X_t to y_t in the long run, respectively. Based on this analysis, the variables can be combined and rewritten as:

$$\begin{aligned} EFD = \alpha_0 + \alpha_1(UR^-) + \alpha_2(UR^+) + \alpha_3(PD^-) + \alpha_4(PD^+) + \alpha_5(PF^-) \\ + \alpha_6(PF^+) + \alpha_7(SR\&D^-) + \alpha_8(SR\&D^+) \end{aligned} \quad (7)$$

where α_0–α_8 are the coefficients of each variable in the model.

2.3.3. Nonlinear Granger Causality Test

The Granger causality test, the most widely used causality test, is applied to unit root processes with smooth series or in cointegration [56,57]. Moreover, it can only be used to

test smooth series. The causality obtained is not a cause–effect relationship in the usual sense [40]. Granger defines causality in terms of prediction: X is a Granger cause of Y, if X helps to predict Y; that is, the inclusion of past X in the information set can improve the prediction accuracy of Y. The test method is as follows:

$$Y = \lambda + \sum_{i=1}^{\rho} a_i Y_i + \sum_{i=1}^{\rho} \beta_i Y_i + \nu \quad (8)$$

$$X = \lambda + \sum_{j=1}^{\rho} a_i X_i + \sum_{j=1}^{\rho} \beta_i X_i + \nu \quad (9)$$

where λ is the constant term; α and β are the corresponding regression coefficients; i and j are the lag orders; ρ is the maximum lag order; and υ is the residual.

However, the prediction accuracy of this traditional test is insufficient for revealing the nonlinear relationships among the variables; this shortcoming can be remedied by combining it with the HJ test proposed by Hiemstra and Jones. The HJ test is a nonparametric causality test applied to a smooth series after removing the linear components [58–60]. The original hypothesis of the HJ test, "X is not the Granger cause of Y", can be expressed by a probability density function in the following form:

$$\frac{C1(m + Lx, Ly, e)}{C2(Lx, Ly, e)} = \frac{C3(m + Lx, e)}{C4(Lx, e)} \quad (10)$$

where C_i, $i = 1, 2, 3, 4$ are the estimates of the association integrals. Lx, Ly lagged independent and dependent variables. The null hypothesis for $e > 0$ and $m > 0$ is as follows: X is not a Granger causality of Y.

3. Results

3.1. Natural Resource Utilization

Overall, the average value of footprint depth from 2000 to 2020 is 55.610, indicating that the resource demand for social development in Wuwei has long exceeded the carrying capacity of the local natural resources. Figure 2 demonstrates that the EFD from 2000 to 2020 in the study area shows a fluctuating upward trend. Before 2005, the footprint depth in the study area showed a downward trend, with the value decreasing from 50.61 to 39.280, indicating that the ecological pressure caused by the consumption demand of the residents continues to decrease. From 2005, the footprint depth shows a gradual upward trend, with an increase of only 3.56 in 2012. China's key ecological reconstruction projects, such as the Three North Protective Forests and Sand Control Program, effectively controlled the problem of insufficient natural capital stock in the study area during this period. However, after 2012, the EFD rapidly increased, reaching 74.901 in 2020. From 2012 to 2020, the footprint depth changed by 28.790%, with an average increase of 3.600%, which indicates excessive depletion of the natural capital stock. This result implies that nearly 75 times the natural capital stock is required to meet the current resource consumption needs of the residents in the study area.

A comprehensive analysis of the different land categories (Figure 3) indicates that the waters EFD rose from 0.390 to 1.780 with an average annual growth rate of 6.950%, showing a general upward trend over the study period. However, the water EFD only exceeded 1 in 2017, indicating that the consumption of aquatic products was largely self-sufficient until 2017. Forest land EFD was basically maintained between 1 and 2, with a maximum of 2.960 in 2019. Cropland EFD briefly declined during the study period but increased by an average of 19.530% annually from 2000 to 2020, with a maximum of 5.090 in 2018. This result indicated that the cropland in the study area entered into a deficit state and was insufficient to support the expanding consumption demand; thus, the capital of cropland stock must be overdrawn to maintain the consumption rate, and the cropland in the districts and counties was under great pressure. Notably, the energy EFD of the research Wuwei Oasis is continuously increasing from 2000 to 2020, and the rate of increase is fast. The average annual rate is 93.810%, rising from 6.210 to 24.980, peaking in 2020. Construction

land EFD is rising the fastest, with an average annual rate of 111.340%. From 2000 to 2003, the encroachment of natural resources by construction land basically remained at 1. From 2004 to 2009, natural capital showed a high rate of depletion, soaring from 2.478 to 9.786. After 2010, the EFD of construction land increased steadily, with a peak in 2020 at 22.661. This indicated that the expansion of the scope and area of construction land for improving the construction of urban infrastructure and public service facilities, as well as for attracting industrial agglomeration and development, led to accelerated natural capital depletion. Grassland EFD was the highest during the study period, requiring nearly 39 times the amount of grassland resources in 2020 to meet the demand for livelihood development in the region. This result could be attributed to the mismatch between the consumption demand for meat agricultural products and the spatial distribution of grassland resource supply; this mismatch caused the study area to overdraw the grassland capital stock to fulfill the livestock-product demands of the urban and rural residents.

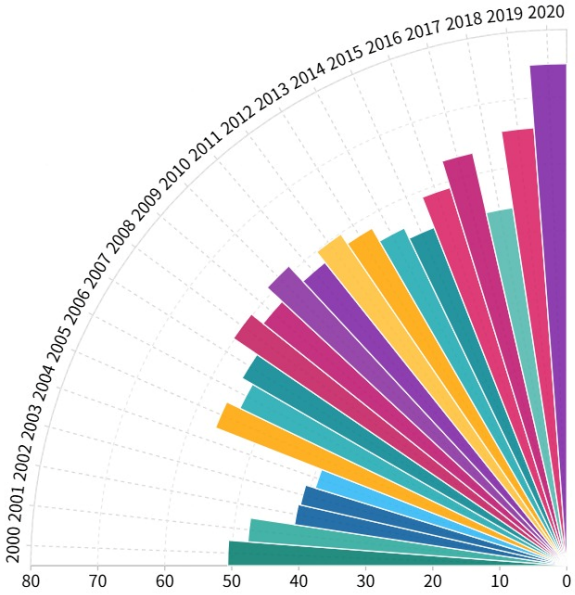

Figure 2. Consumption of natural capital in 2000–2020.

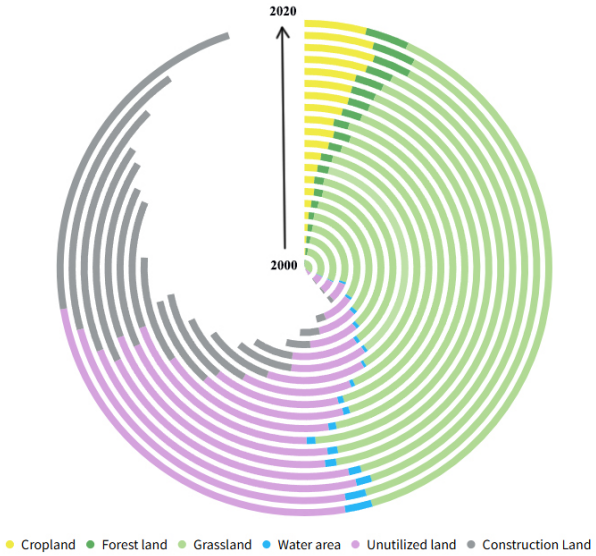

Figure 3. Extent of natural capital depletion for different land types.

3.2. Analysis of NARDL Results

Table 2 elucidates the descriptive survey of the NARDL model, which describes the mean values of the selected variables as positive. The natural capital stock occupancy varies between 39.297 and 84.895 during the period of 2000–2020, with a mean and standard deviation of 56.088 and 56.323, respectively. The scientific R&D shows a considerable variation as it increases from 600.000 to 37,677.000 with a mean value of 15,487.570 and a standard deviation of 11,453.900. Similarly, PF shows considerable variation, increasing from 473.000 to 36,693.000 with a mean value of 15,220.000. Population Density fluctuates slightly during the period of study from 192.520 to 203.800 with a mean value of 197.237. Urbanization shows the least variation, with a minimum value of 19.600 and a maximum value of 43.220. In addition, this study borrowed the Jarque–Bera statistic (JB) to check the normality of the data. The value of the JB statistic elucidates the significant value of the selected variable, which confers nonnormality in the data.

Table 2. Descriptive statistics.

	UR	PD	PF	SR&D	EFD
Mean	29.554	197.237	15,220.000	15,487.570	56.088
Median	26.860	196.700	12,828.000	11,098.000	56.323
Maximum	43.220	203.800	36,693.000	37,677.000	84.896
Minimum	19.600	192.520	473.000	600.000	39.297
Std. Dev.	7.827	3.167	11,519.260	11,453.900	9.739
Skewness	0.550	0.502	0.41534	0.464	0.717
Kurtosis	1.837	2.256	2.222	2.112	5.201
Jarque-Bera	2.243	1.366	1.133	1.444	6.037
Probability	0.326	0.505	0.568	0.486	0.049

Before evaluating the NARDL results, Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests are performed to assess the smoothness of all the variables. Because the critical values for detecting cointegration between the variables are different when the variables are I(0) or I(1), unit root tests are performed for all the time series variables. The time series of all the variables in Table 3 exhibit first-order unit roots. Therefore, the data of the four variables selected in this study can support the NARDL model in the I(1) case.

Table 3. Unit root test results.

Variables	I(0)		I(I)	
Empty Cell	**C**	**C&T**	**C**	**C&T**
Dickey-Fuller (1979) unit root tests				
EFD	−0.607	−2.399 *	−3.579 **	−3.806 **
UR	0.676	−2.342 **	−3.749 **	−4.848 ***
PD	−1.763 *	−1.785 *	−4.662 ***	−4.915 ***
SR&D	−1.773 *	−3.899 **	−5.093 ***	−5.185 ***
PF	−1.836 *	−3.450 **	−5.034 ***	5.201 ***
Phillips and Perron unit root test				
EFD	0.122 *	−2.045	−3.194 **	−3.454 **
UR	1.271	−2.726	−5.189 ***	−5.821 ***
PD	−1.817	−1.557	−4.624 **	−4.697 **
SR&D	−1.796	−3.632 *	−10.823 ***	−11.352 ***
PF	−1.892	−2.909	−8.506 ***	−9.153 ***

*** Statistical significance at the 1% level. ** Statistical significance at the 5% level. * Statistical significance at the 10% level.

Next, in this study, we used the NARDL model to investigate the long-run asymmetric dynamic equilibrium relationship as well as the short-run asymmetric dynamic correction

relationship between the explanatory and explained variables. The optimal lag in the model is based on the Akaike information criterion (AIC); AIC is a measure of the goodness of fit of a statistical model. After setting the lag period, the insignificant variables are eliminated, and the model is tested. The results of the NARDL model are shown in Table 4.

Table 4. Analysis of the NARDL model results.

Short Run Coefficients				
Variable	**Coefficient**	**Std. Error**	**t−Statistic**	**Prob.**
D(PF_POS)	0.071 **	0.001	−1.397	0.040
D(PF_NEG)	−0.013 **	0.001	−4.794	0.031
D(PD_POS)	0.059 *	0.570	2.796	0.219
D(PD_NEG)	−1.333 **	1.564	−0.852	0.056
D(SR&D_POS)	0.071 ***	0.006	2.406	0.003
D(SR&D_NEG)	0.002 **	0.001	3.280	0.019
D(UR_POS)	0.067 *	1.844	0.363	0.078
D(UR_NEG)	−1.193 ***	0.001	−1.397	0.007
ECM(-1)	−0.382 ***	0.241	−5.743	0.000
Long Run Coefficients				
PF_POS	0.003 **	0.002	−1.357	0.040
PF_NEG	−0.105 **	0.003	−1.675	0.034
PD_POS	0.004 **	0.558	1.863	0.031
PD_NEG	−1.831 **	4.534	1.286	0.042
SR&D_POS	0.162 **	0.002	1.307	0.042
SR&D_NEG	0.006 *	0.003	1.356	0.094
UR_POS	0.064 **	3.393	0.778	0.058
UR_NEG	−2.003 **	8.025	−1.371	0.014
C	−1.167 ***	32.628	−0.036	0.010

***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

Error correction models (ECM) are used to model short-term dynamics and to compensate for the shortcomings of long-run static models. Through the error correction model, it is possible to determine the extent to which the variables deviate from their long-run equilibrium relationship in short-term fluctuations [61]. The estimated results of the NARDL model show that the ECM(-1) coefficient is negative and statistically significant at the 1% significance level (the variables have a long-term stable relationship with each other, which means that they are covariant). This result implies that the 38.210% imbalance in the level of depletion of natural capital stock in the short run can be remedied in the long term owing to the presence of the independent variables.

In Table 4, under the positive shock, every 1% increase in the plantation area reduces natural capital consumption by 7.087% in the short term, whereas the positive effect of the plantation area on natural capital decreases to 0.309% under long-term development. This result mainly indicates that the planted forests in the Wuwei Oasis, as an oasis city, effectively conserve the natural capital stock in the short term. In the short term, although it can increase the forest stock, with the annually increasing forest cover, more dangers hidden behind artificial forestation are gradually revealed. In particular, the study area gradually fails to supply the amount of water required for the growth of large vegetation. Under the negative impact, every 1% increase in the area of planted forests land in the study area resulted in an average decrease of 1.301% in the stock of natural capital in the short term, and an average deterioration of 10.465% in the long term, which is seven times more than that detected in the short term. This result implies that large-scale planted forests shrink the space for food production and affect food security, further reducing the stock of natural capital.

The population density and natural capital sustainability in the Wuwei Oasis are strongly correlated (Table 4). Under positive shocks, every 1% increase in the population density will lead to a 5.928% and 0.392% increase in the stock of natural capital in the short and long terms, respectively. Under negative shocks, a 1% increase in the population density, both in the short and long runs, reduces natural capital by 133.358% and 183.053%, respectively. The results show that the negative shock of population density on natural capital stock is significantly higher than the positive shock. This observation is in line with the actual development situation of the study area, where the limited land resources of oasis cities lead to a positive low per capita land use, and the demand for natural capital exceeds the carrying capacity of the regional resources and environment, resulting in a continuous decline in the stock of natural capital in the region.

The positive and negative shocks of urbanization on natural capital are consistent with the trend of population density, and the magnitude of the negative shocks on natural capital is greater than that of the positive shocks for both variables (Table 4). In terms of negative shocks, every 1% increase in the urbanization rate will lead to a 119.287% and 200.285% decrease in the stock of natural capital in short and long time periods, respectively. The positive impact (positive shock) from the urbanization rate in any period is almost negligible and is less than 7%. This implies that because urbanization and economic growth in the Wuwei Oasis are in the stage of high-speed development, the continuous occupation and consumption of peri-urban cropland and garden resources, as well as the expansion of the scope and area of construction land, will eventually lead to excessive depletion of natural capital in the whole study area.

The results of the impact of science and R&D inputs on natural capital are consistent under positive and negative shocks, implying that both increasing and decreasing the science and R&D inputs will decelerate the depletion of the natural capital stock to varying degrees. Specifically, under positive shocks, every 1% increase in science R&D investment will reduce the level of short-term and long-term natural capital stock depletion by 7.143% and 16.158%, respectively. In contrast, under negative shocks, science R&D investment is also guaranteed to impede the depletion of resources by at least 0.213%. This result suggests that scientific and technological inputs can only indirectly improve the stock of natural capital and can help in enhancing the long-term value of natural capital. For example, by improving the structure of energy consumption and using more clean energy, we can reduce the consumption of mineral resources, shrink the ecological deficit, and reduce the degree of depletion of the natural capital stock.

The result of the JB test was 5.2, which verified the model's goodness of fit. The greater the variance inflation factor VIF, the greater the likelihood of covariance (a high degree of correlation between variables) between the independent variables. The VIF values in this study were 2.3–3.8, which is less than 5, indicating the absence of multicollinearity in the research model. By contrast, CUSUM and CUSUMSQ endorsed the model stability (reliable), and statistically significant values for all variables in the model are stable.

3.3. Causal Analysis Results

The NARDL model results indicate that urbanization, population density, plantation forestry, and SR&D exhibit both long- and short-term impacts on the sustainability of natural capital in oasis cities. However, whether this response relationship constitutes a causal relationship has not yet been verified. Therefore, a nonlinear Granger causality test was conducted to evaluate the causal relationship between the variables. The results provided in Table 5 show the existence of a single causal relationship between planted forests, population density, scientific R&D inputs, and natural capital. In addition, a causal relationship between plantation forestry and urbanization, as well as one between urbanization and population density, is evident.

Table 5. Nonlinear Granger causality test.

Null Hypothesis	F-Statistic	Prob.
EFD ≠> PF	2.647	0.741
PF ≠> EFD	0.749	0.022
EFD ≠> PD	0.735	0.767
PD ≠> EFD	1.756	0.022
EFD ≠> SR&D	2.378	0.035
SR&D ≠> EFD	1.009	0.103
EFD ≠> UR	3.231	0.591
UR ≠> EFD	1.986	0.007
PF ≠> UR	0.986	0.068
EFD ≠> UR	0.778	0.049
UR ≠> PF	0.511	0.031
PD ≠> UR	0.386	0.648
UR ≠> PD	1.662	0.042
SR&D ≠> UR	0.696	0.084
UR ≠> SR&D	1.879	0.030
PF ≠> SR&D	1.432	0.917
PF ≠> PD	2.647	0.741
PD ≠> SR&D	0.749	0.522

≠> describes the "absence of Granger's causality".

In addition, there is a two-way Granger test for EFD and UR. This implies that the process of urbanization is also the process of urban occupation of resources outside the district. The study area is a typical resource-consuming city and a comprehensive industrial city dominated by industry, which has led to huge resource consumption with economic development, continuous urbanization, and reduced energy use efficiency. However, with the limitation of natural resource development, cities relying on traditional mineral resources will also enter the late stage of industrialization while slowing down the development of urbanization. In addition, there are two groups that pass the causality test between the independent variables: urbanization and science R&D investment and urbanization and population. This further proves that urbanization drives human capital and science and technology investment.

4. Discussion

4.1. Human Activities and Government Policies

As the level of urbanization in oasis cities continues to increase, the oasis region is witnessing a gradual shift toward an increasingly urbanized landscape. A growing body of research has highlighted the impact of industrialization and urbanization on oasis ecosystems, which have led to changes in the structure and service functions of these ecosystems [62,63]. The most evident consequence is the emergence of a high concentration of urban population, industry, and urbanization, which has resulted in a series of resource, environmental, and ecological challenges [64]. As a result, areas with high human activity intensity gradually become areas with high ecological vulnerability and key management areas. This viewpoint has been discussed in depth by numerous scholars. For instance, Ding et al. [65] conducted a study utilizing the oasis in the Tarim Basin of China as the study area, and the results indicated that human activities (population density and GDP) are the most significant factors contributing to land degradation. Their study concluded that human activities have a significant impact on the ecological sustainability of the oasis. It found that population growth and urbanization will lead to an increase in the ecological deficit of the oasis by 1.17 and 1.15 times, respectively. In addition to Chinese scholars, many scholars from Arab countries have found that population growth and urban expansion will negatively impact the loss of natural resources in the region. For example, Chouari argues that population growth and the expansion of urban built-up areas will significantly negatively impact the Al-Ahsa oasis, especially in terms of exacerbating the loss of vegetation resources and reducing biodiversity [66]. In this regard, these

studies are comparable to the findings of this study. The impact of the population density and urbanization rate on the sustainable development of oasis resources is indeed more detrimental than beneficial. In particular, this effect will be exacerbated over time. In the long run, the population density and urbanization rate lead to a depletion of natural resources by a factor of 1.83 and 2, respectively.

However, it is important to note that human activities closely related to oasis ecology are not limited to urbanization, economic development, and population growth. Ecological reconstruction, scientific and technological innovation, and agricultural modernization can all be considered characteristics of human activities [67]. However, these factors are often overlooked. To address this gap, this study incorporates the levels of artificial forestation and scientific R&D into the analysis of human activities and quantifies their role in the sustainable development of oasis resources. One of the most significant factors influencing human activities that impact the environment is scientific research and development (R&D) investment [68]. The strength of scientific R&D investment can facilitate the green development of industry and reduce resource loss, thereby creating a more exquisite, healthy, and safe oasis city. Saber et al. argue that increased investment in water-saving technologies can help protect groundwater in the Kharga Oasis [69]. Khatib et al. suggest that tapping into the potential of solar energy and increasing corporate investment in photovoltaic technology is the leading way to restore the ecosystems of Mauritania's Oases [70]. Of course, as numerous studies conducted both domestically and internationally have demonstrated, there is a notable lag in scientific and technological R&D investment [71,72]. In particular, Yue et al., through a horizontal comparison of several cities in the Yellow River Basin [73], demonstrated that scientific R&D investment could gradually enhance the utilization efficiency of resources in Wuwei City. This corroborates the findings of this study, which state that the positive effect of scientific R&D investment on natural capital is considerably higher in the long term than in the short term (9% higher).

In addition, ecological reconstruction is often mentioned as a means for humans to increase the abundance of natural resources in oases. However, only some studies have quantified its contribution; most define it as a policy tool or management approach [74]. Consequently, the contribution of ecological reconstruction to the ecologically stable development of oases remains unclear. It is important to note that the results of this study diverge from the prevailing impression. The positive impact of plantation forestry on the natural capital of oasis cities is only evident in the short term. In the short term, planted forests can effectively mitigate the depletion of natural resources, reducing it by 7.09%. This finding is consistent with the majority of previous studies. For instance, Tian et al. demonstrated that planted forests contribute to expanding forest areas and enhancing the carbon storage capacity in the Zhangye Oasis [75]. Similarly, Li et al. elucidated how planted forests facilitate the development and utilization of forest land in the Qaidam Oasis [76]. Furthermore, Xue et al. demonstrated that planted forests have a beneficial impact on the prevention of desertification. Of particular significance is the role of planted forests in safeguarding farmland from the detrimental effects of dust storms and strong winds [77]. However, in the long term, it appears that the negative impacts of planted forests on the sustainable development of natural capital will outweigh the positive impacts. This is in stark contrast to the long-term development of afforestation and the mitigation of the natural resource-carrying capacity, which numerous studies encourage. In particular, numerous scholars have advocated for expanding plantation areas to the greatest extent possible. This approach will not only increase vegetation cover but also facilitate income generation for rural residents. This can be achieved through the cultivation of raw materials in forests and the development of a forest economy [78]. This approach is commendable and has indeed become an important source of income for residents in Southern China, particularly in Guangxi Province [79]. However, it does not apply to oasis cities. This is because such development plans fail to acknowledge the significant role of plantation forests in oases. The majority of planted forests in oasis areas are cropland protection forests, which represent a transitional zone between oasis and desert. Cropland protection

forests in oases serve as an effective means of protecting cultivated oasis land from wind and sand, thereby ensuring the stability of oasis agricultural production [80]. However, the shading of the cropland protection forest belt and the depletion of water and nutrients by the hardiest trees can also cause a reduction in crop production on both sides of the forest edge [81]. However, some studies in the Sahara region and the Arabian Desert have pointed out that unquestioningly more than expanding the planted woodland area is needed for the sustainable development of oasis cities [82]. Among them, the study of Moumane et al. pointed out that although expanding the area of palm tree plantations will increase the green area, in the long run, it will not only break the balance of resources in the Ternata Oasis but also lead to fires and bring unnecessary natural disasters [83]. This further elucidates the impracticability of the unstructured expansion of plantation forest areas in oasis cities over time.

4.2. Oasis Area Management Development

The results of this study, based on the nonlinear Granger causality test, indicate the necessity of implementing various management measures to regulate the relationship between human activities and the development of natural oasis resources.

(1) Given the bilateral causal relationship between scientific R&D investment and the resource environment, it is recommended that government departments continue to increase investment in science and technology in order to sustain the generation of new development momentum for enterprises through technological innovation. The proposal of carbon peak and carbon neutral targets by China and numerous other countries and regions has elevated the green economy to a dominant position in global industrial competition [84]. The arid regions are particularly susceptible to desertification, which is influenced by several factors, including strong sunlight, high winds, and low precipitation [85]. The "Shago Wilderness" region, a wind- and solar-energy resource-rich region in China, is particularly vulnerable to desertification. Consequently, oasis cities, particularly the Wuwei Oasis, can continue to rely on the Gobi Desert; the development of wind power, photovoltaic, new energy equipment; and a series of new industries. Promoting the clean and efficient use of traditional energy sources and improving the thermal efficiency of coal combustion can be further encouraged. The development of agriculture, forestry, grassland, and other resources can be further reduced in order to stabilize the current ecological environment.

(2) There is a direct causal relationship between urbanization and population density and resource consumption in oasis cities. For oasis cities, areas with high urbanization lead to population concentration, rising population density, and accelerated natural resource utilization. Therefore, limiting the rise of population size in oasis cities results from considerations based on food security, ecological protection, and other relevant factors [86]. Consequently, it is necessary to determine the direction and scale of urban development in the near and distant future. This should be performed in a way that incorporates the concept of an eco-city, which involves dividing different spatial control zones and arranging the layout of urban land in an integrated manner, preventing the expansion of urban land use as a result of population explosion. In addition, city administrators can gradually improve their urban development concepts to guide the future urban population towards unutilized land with relatively flat terrain and low construction costs and to protect the limited cropland resources and other ecological land in arid oasis zones.

(3) The financial outlay required to plant a tree in an oasis is considerably greater than in other areas [87]. In 2021, China issued the "Guidelines on Scientific Greening", which has led to the realization that not all "deserts" require "greening" [88]. Therefore, afforestation and greening of the Wuwei Oasis can involve planting mixed forests (planted forests supplementing natural forests) to improve forest quality and realize forest ecological restoration through the restoration and replanting of degraded forests. Furthermore, restoring degraded forests and replanting can enhance the efficacy of afforestation and greening. It is no longer necessary to pursue area expansion; rather, by adjusting the afforestation structure, greening transformation from "quantitative coverage" to "qualitative improve-

ment" can be promoted, and the development of natural resources can be encouraged in a more scientific and sustainable direction.

4.3. Limitations and Future Work

This study examines the relationship between human activities and the sustainable development of oasis resources, with oasis cities as the object of study. Although the results can provide useful guidance for preventing the continuous loss of natural resources and ecological conservation, there are still some limitations.

Firstly, as previously stated, agricultural modernization is closely related to the sustainable development of oasis urban resources. Oasis agriculture represents a distinctive form of agricultural development in oasis cities [86]. Traditional oasis agriculture is distinguished by high yields of single-season crops, high fertilizer application and irrigation, and an excessive demand for water resources, which has led to a soil–water imbalance [87]. In recent years, there has been a significant improvement in agricultural labor productivity due to the optimization and improvement in water-saving equipment, fertilizers and pesticides, and agricultural implements. Oasis agriculture is gradually evolving toward agricultural modernization to alleviate the pressure on resources and the environment. However, this study does not include it in the indicators characterizing human activities for two reasons. On the one hand, the Wuwei Oasis is a typical industrial city with a relatively small share of agriculture. On the other hand, Wuwei has a low level of agricultural modernization. The Qaidam Basin Oasis or other representative agricultural oases could be selected for better research on the interaction between agricultural mechanization and natural capital utilization.

Secondly, this study failed to demonstrate the mobility of natural capital. Our study fully demonstrated the trend of natural resources in time series, but it lacked evidence of the transfer between natural resources. For instance, it did not account for the number of deserts that changed into forest and grass resources during the study period. This is because our study was based on resource production, not resource areas. Resource transformation requires the existence of distinct boundaries [86]. In other words, the yield of a given resource is contingent upon several factors, including the price, market conditions, and seasonality [88]. However, the total area of a given resource within a given range remains constant regardless of these fluctuations. Consequently, it is impossible to demonstrate internal variation in the current data context. However, in the future, it is possible to alter the research perspective to that of ecological landscapes. This would enable the analysis of changes in natural resource categories using remote sensing images and machine learning. Furthermore, it would permit the exploration of the development path of future oasis cities based on resource flow laws.

Finally, although we confirmed the reliability of the results of this study by comparing previous studies, this study fails to propose guidelines with generalizability for oasis cities around the world. The reason for the lack of universal policy recommendations is due to the differences in the approaches to oasis city management in different countries [89]. As mentioned in the NASA study, "42% of China's oasis expansion comes from afforestation, while more than 80% of India's greening growth comes from agricultural land [90]". In future research, by expanding the scale of the study to a global scale and comparing the oasis urban development process in different countries and regions horizontally, it may be possible to find more generalized guidelines for ecologically sustainable development.

5. Conclusions

In this study, we adopted the NARDL method and annual data from 2000 to 2020 for the oasis city of Wuwei, China, and investigated the nonlinear relationship of natural capital sustainability with planted forests, scientific R&D investment, population density, and urbanization. The conclusions of the research are as follows:

(1) From 2000 to 2020, the natural capital of Wuwei Oasis is in an overloaded state, and the unsustainability of natural resources is increasing year by year. By land resource

types, grassland and over-consumption of unused land are the main land types that lose natural resources.

(2) Over time, the negative impact of population density and urbanization on natural capital stock will increase, leading to 130% and 200% depletion of natural resources, respectively. Similarly, planted forests will lead to a 10% depletion of natural resources in the long run. The only thing that has not caused damage to the stock of natural resources is investment in science and technology R&D.

(3) Using Granger causality, it was shown that three variables, urbanization, afforestation, and population density, passed the 5% significance test, which means that they have a direct impact on the sustainability of natural resources.

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