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Regime Shifts in the Hexi Oases over the Past Three Decades: The Case of the Linze Oasis in the Middle Reaches of the Heihe River

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Abstract: Oases regime shifts in the context of integrated water resource management have a significant impact on ecosystem functions and services and affect regional sustainable development and human wellbeing. Taking the Linze Oasis in the middle reaches of the Heihe River as a case study, we evaluated the regime shifts of the oases over the past 30 years from the two perspectives of scale and structure, considering the structural diversity index (*H*), water savings (C_n), productivity (WP), and other indicators. Furthermore, the driving factors of the socio-hydrological processes and the corresponding effects of the regime stages were discussed. The results indicate that the oases expanded concurrently with the increase in the regional water consumption from 1.09×10^8 m^3 to 1.93×10^8 m^3. The production of low-water-consumption and high-yield crops was found to be the main cause for the oases structure's adjustment. The regime shifts in the oases comprised three main stages from 1990 to 2020, based on the interaction of socio-ecological elements. Water management policies promoted the regime shift process, while economic factors determined the long-term shifts. The improvement in water-saving practices driven by economic benefits is an effective way to realize the sustainable development of the Hexi oases.

Keywords: oases economy; regime shifts; water management policies; water savings; water productivity

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1. Introduction

Regime shifts refer to significant and persistent changes in the structure and function of ecosystems or socio-ecological systems that substantially affect relevant ecosystem services. They are considered a critical perspective from which to examine and evaluate the evolution and elasticity of systems [1,2]. The risks faced by the oases water resources in the arid region of northwest China have increased with rising climate change and human activity, especially in the agricultural oases of the Hexi Corridor [3,4]. Since the implementation of integrated water resources management (IWRM) in 2000, the oases have had a significant impact on the regional social ecosystem [5,6]. Identifying the regime shifts, as well as their dominant drivers and specific effects, is of critical significance to the sustainable development of arid areas [7].

In general, regime shifts are cumulative changes caused by drivers within ecosystems or by human and natural disturbances [2,8,9]. Current studies on regime shifts are mainly focused on the identification and analysis of their driving mechanisms. Their influencing factors, cascades within and across scales, and the reciprocity of shifts have also attracted attention [2,10]. Climate change and agriculture-related activities have significant effects on a variety of regime shifts in integrated socio-ecological systems [1]. As for the oases dominated by agricultural irrigation in the middle reaches of the Heihe River, IWRM and the agricultural planting structure play a significant role in promoting the regional water resource balance [11]. Taking these factors into account can effectively strengthen the coupled human–water systems involved in sociohydrological processes [12].

The ecological and economic development of oases in northwest China is driven by the area's limited water resources [13,14]. The ecological constraints on economic development are enhanced with the expansion of oases and populations [13–15]. IWRM has been implemented to control the water system in order to reach the desired outcomes for society and the environment. It is of great significance to determine the appropriate hydrologic and ecological thresholds for the water security of river basins [16,17]. The '2000 water distribution' policy has had significant effects on the balance of the water resources in the Heihe River basin [18,19]. To facilitate the restoration of the ecological environment, the water distribution was supplemented with 10^9 m^3 from the Zhengyi Gorge in 2020, which increased the water stress in the middle reaches of the Heihe River. The regime shifts of the oases continue to adapt to the regional water distribution. The coordination of the water distribution is critical for the management of the oases in the middle reaches [20].

Moreover, the efficient utilization of water resources is significant for the stability of the oases in the middle reaches [21] and could alleviate a series of social and environmental challenges caused by water shortages [22,23]. The quantitative description of the state of water systems is part of the research in the field of socio-hydrology [24]. Agriculture accounts for more than 80% of the water consumption in the oases in the middle reaches of the Heihe River basin [25], and crops are considered a measure of both economic benefits and water constraints [11]. Meanwhile, assessing the effects of water savings and productivity is critical to the evaluation of water policies [26]. Many water efficiency studies at different scales have indicated that evapotranspiration (ET) is an effective supplement to traditional water resource management [20,27,28] and provides a basis for improving the WUE [29]. Although macroscale estimates based on remote sensing [21,30] are not sufficient to estimate the water consumption of the highly spatially heterogeneous crop structures in the Hexi oases [31], crop statistics based on the ET within a reasonable irrigation system are an effective method for calculating the total water consumption [32]. Consequently, water resource management and its economic benefits, as well as other feedback, mutually depend on the socio-ecological systems of the oases in the middle reaches to generate a balance. The systematic establishment of oasis regimes is vital to the realization of the sustainable development of the oases.

Accordingly, we selected the Linze Oasis, a typical middle reaches Oases in the Heihe River basin, as the research area in this study. We investigated the quantitative relationship between the ecosystem and society from a sociohydrological perspective [33], as well as the impact of water resource utilization on agricultural development. Furthermore, we conducted these investigations in terms of scale and structure for the years 1990 to 2020 (i.e., before and after the implementation of water distribution policies in the Heihe River basin) to reveal the regime shifts and cascading effects in the oases associated with policy, economic, and other factors. This study aimed to provide a scientific basis for decision making regarding the sustainable development of oases in arid regions, as well as to enhance our ability to address climate change and other systematic risks.

2. Material and Methods

2.1. Study Region

The Linze Oasis is located in the desert oases transition zone (100°06′04″~100°09′53″ E, 39°19′07″~39°24′40″ N) in the middle part of the Hexi Corridor of northwest China, representing a major part of the middle reaches oases (Ganzhou, Linze, and Gaotai) (Figure 1). The Linze Oasis serves as a critical area in the Hexi Corridor for agricultural production, with its favorable water and heat conditions. It is in a typical zone of the arid subtype of a temperate continental climate, and its potential evapotranspiration ranges from 1900 to 2088 mm, far exceeding its average annual precipitation of 124 mm [34,35].

Agricultural irrigation accounts for over 95% of its total water use [25], to which surface water contributes the majority, and groundwater contributes the rest. The Heihe River and one of its immediate tributaries, the Liyuan River, have been confirmed as the main water source for irrigation. The Hexi Corridor has the most competitive seed production in China, with its advantageous location and natural conditions. Since 2005, the proportion of corn seed production areas has been stable, at above 70% [11].

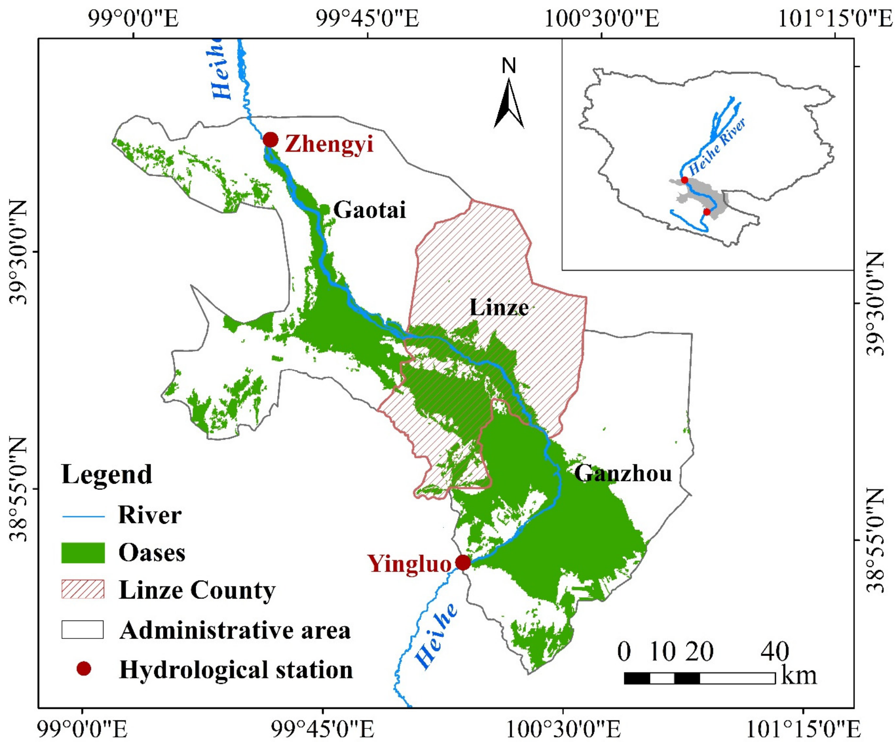

Figure 1. Distribution range of oases in the middle reaches of the Heihe River.

2.2. Data and Data Processing

The data of the structure and output of the crops in Linze Oasis from 1990 to 2020 were taken from the County Statistical Yearbook, and we followed the classification of the statistics. The food crops primarily comprised wheat, corn, etc., and the cash crops largely included vegetables, beet, cotton, oils, chrysanthemum (stevia), etc. Moreover, its fruits (e.g., jujubes and fruiters) were classified into the forestry rather than the planting category, and these did not have a large impact on the regional water resource. The price of the main crops was defined by the price-guaranteed contracts and the purchase prices that were uniformly converted into 1990 prices. The information on the water distribution and corresponding irrigated area in Linze Oasis came from the Water Authority and its divisional water management offices. The water consumption in the middle reaches for the field measurement of crops in the growing season was obtained from the National Field Scientific Observation and Research Station for the Linze Farm Ecosystem of the Chinese Academy of Sciences (Table 1), which was consistent with the water requirements at sufficient irrigation conditions [36]. The details are listed in Table 1.

Table 1. The water consumption of the crops in the Hexi oases.

Crops	Food Crops			Cash Crops				
	Wheat ①	**Field Corn** ①	**Seed Corn** ②	**Vegetables** ②	**Oil Crops** ②	**Beet** ①	**Cotton** ①	**Stevia** *
ET (mm)	435	656	671.2	674	377.3	677	675.5	589.5

Note: The water consumption of regional crops ① (Cheng et al., 2014) [26] ② (Ji et al., 2005) [37]. * The water consumption of stevia within the growth period is 10% less than that of corn seed.

2.3. Methods

An interpretive framework based on the interaction between social and ecological elements is a specific evaluation system for the research on regime shifts [1,38]. There are two aspects within this that determine whether or not a regime shift has taken place: one is the relationship between the social and ecological systems, and the other is the degree of influence of each component of society and ecology [7]. The identification of the transitions depend on the statistical analysis of long-term sequences [39]. In this study, the mentioned framework was established for the scale (crop area and water consumption) and the structure (crop structural diversity, water savings, and productivity) to identify the regime shifts in oases, as well as the intervals between the shifts with different dominant drivers in accordance with the changes in the interaction between these social and ecological elements.

2.3.1. Water Consumption of Crop Farming

There is critical significance for the increase in WUE for irrigation with crop requirements [32]. Based on the long-term stability of cultivation and field management, the water consumption of crops during the growing season remains stable, consistent with the crops' water requirements [36]. The equation is written as follows:

$$W_n = \sum_{i=1}^{m} ET_i \cdot S_n \tag{1}$$

where ET_i denotes the water use of the crop ith during the growing season; W_n represents the total WU in the nth year (m^3); and S_n expresses the sown area of the crop in that year (hm^2).

2.3.2. Analysis of Crop Farming Restructuring

The diversity index (H) indicates the diversity of the regional ecological structures primarily through the energy (resources) flows [40,41]. The diversity of the systematic structures of ecosystems can be set with the proportion of the actual water consumption of each crop. The equation is expressed as follows [42]:

$$H = \sum_{i} [P_i \cdot \ln P_i] \tag{2}$$

where P_i denotes the proportion of the water consumption of the crop ith to the total. The larger the H, the more diversified the crops will be, and the more even the WD will be and vice versa.

2.3.3. Effects of Crop Farming Restructuring on Water Savings

It is practical to evaluate the WUE of agricultural water in consideration of the recycling of the irrigation return flow [20]. The changes in water consumption, ΔW_n, are useful to compare the crop restructuring to regional water savings in different years [43,44]. The equation is written as follows:

$$\Delta W_n = W_n - W'_n \tag{3}$$

where W_n and W'_n express the total and unadjusted water consumption of crops in the nth year, respectively. To remove the effect of area changes, W'_n is obtained as follows:

$$W'_n = \sum_{i=1}^{m} (ET_i \cdot S_n \cdot P'_i) \tag{4}$$

where S_n represents the area of the crop in the nth year (hm^2); and P'_i expresses the proportion of the area of the crop i in the reference year (1990). When the changes in the water consumption $\Delta W_n = 0$, this means that the regional water savings are not affected by the crop restructuring; $\Delta W_n < 0$ represents that the crop restructuring is positive for water savings and vice versa.

2.3.4. Effects of Crop Farming Restructuring on Water Productivity

The evaluation of water efficiency has shifted from a single indicator to an integrated evaluation characterized by the combination of efficiency and profit [45]. Water productivity (*WP*) is the ratio of the net benefits from agricultural systems to the amount of water used to produce those benefits [46], characterizing the relationship between output (material and economic output) and water usage (volume, value) [47,48]. The equation is expressed as follows:

$$WP = \frac{Y}{WU} \tag{5}$$

where *WU* represents the water consumption of the crop (m^3); *Y* represents the yield of the crop (e.g., physical yield and economic yield). The physical *WP* is defined as the ratio of the agricultural output to the amount of water consumed, and the economic *WP* is defined as the value derived per unit of water used in agriculture for nutrition, welfare, and the environment [46]. It is more convenient to use the economic yield as the benchmark for the comparison of the *WP* among crops.

3. Results

3.1. Regimes at the Oases Scale

For the middle reaches dominated by irrigated agriculture, the crop area and the water consumed are effective in indicating the changes in the scale of the oases as shown in Figure 2. The area of crops increased from 1.71×10^4 hm^2 in 1990 to 1.98×10^4 hm^2 in 2010 and further increased by 88.90% to 3.23×10^4 hm^2 in 2020; the water consumed increased from 1.09×10^8 m^3 to 1.93×10^8 m^3, correspondingly. Specifically, the water consumed by food and cash crops increased from 0.89×10^8 m^3 and 0.20×10^8 m^3 in 1990 to 1.65×10^8 m^3 and 0.28×10^8 m^3 in 2020, respectively. In addition to the increased fluctuation at the beginning of the implementation of the water distribution policies in 2000, the proportion of the water consumption of food crops has stabilized at more than 70%.

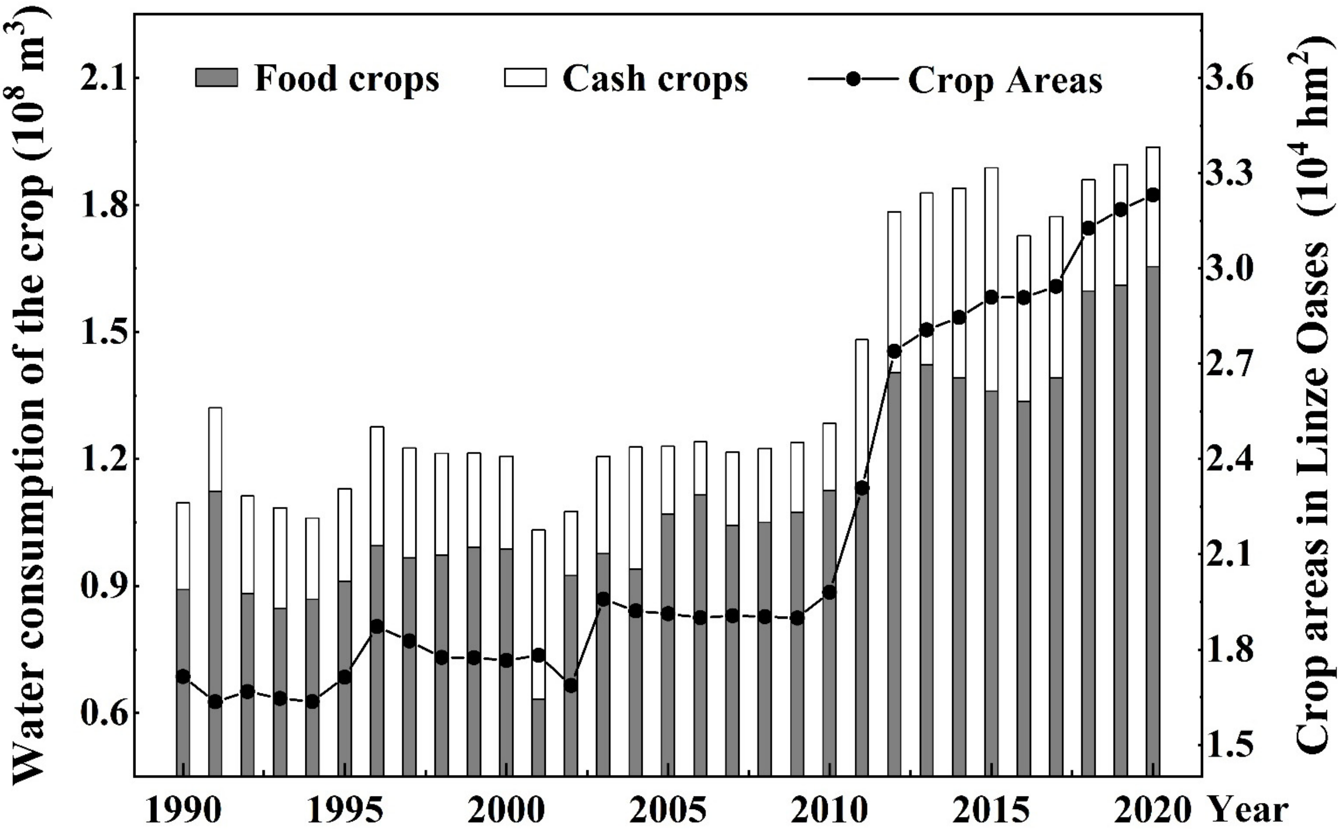

Figure 2. The scale and water consumption of the crops in Linze Oasis.

3.2. Regimes in the Structures of the Oases

Structural optimization within the water constraints is vital for regime shifts in oases. For the middle reaches, with agricultural water accounting for over 95%, the regime shifts can be analyzed based on the structural diversity of crops and its effect on the regional water savings and productivity.

3.2.1. Structural Diversity of Crops

The crop structures between 1990 and 2020 are characterized as shown in Figure 3. Before the implementation of the water distribution policy in 2000, the overall structural diversity of crops increased from 0.69 in 1990 to 0.89 in 2001, where the food crops showed a slight increase from 0.42 to 0.57. After that, the area of crops rapidly increased from 0.34×10^4 hm^2 in 2001 to 1.46×10^4 hm^2 in 2009. Meanwhile, the overall H significantly decreased from 0.89 to 0.35; in particular, that of the food crops decreased from 0.37 to 0.16. Furthermore, the overall structural diversity rose to 0.55 in 2020 with the structural optimization of the crop, to a certain extent. The cash crops have shifted from being diversified, with the H decreasing from 0.73 to 0.21 in 2020, in which vegetables and chrysanthemum crops accounted for 80% and 15% of the total in 2015, respectively.

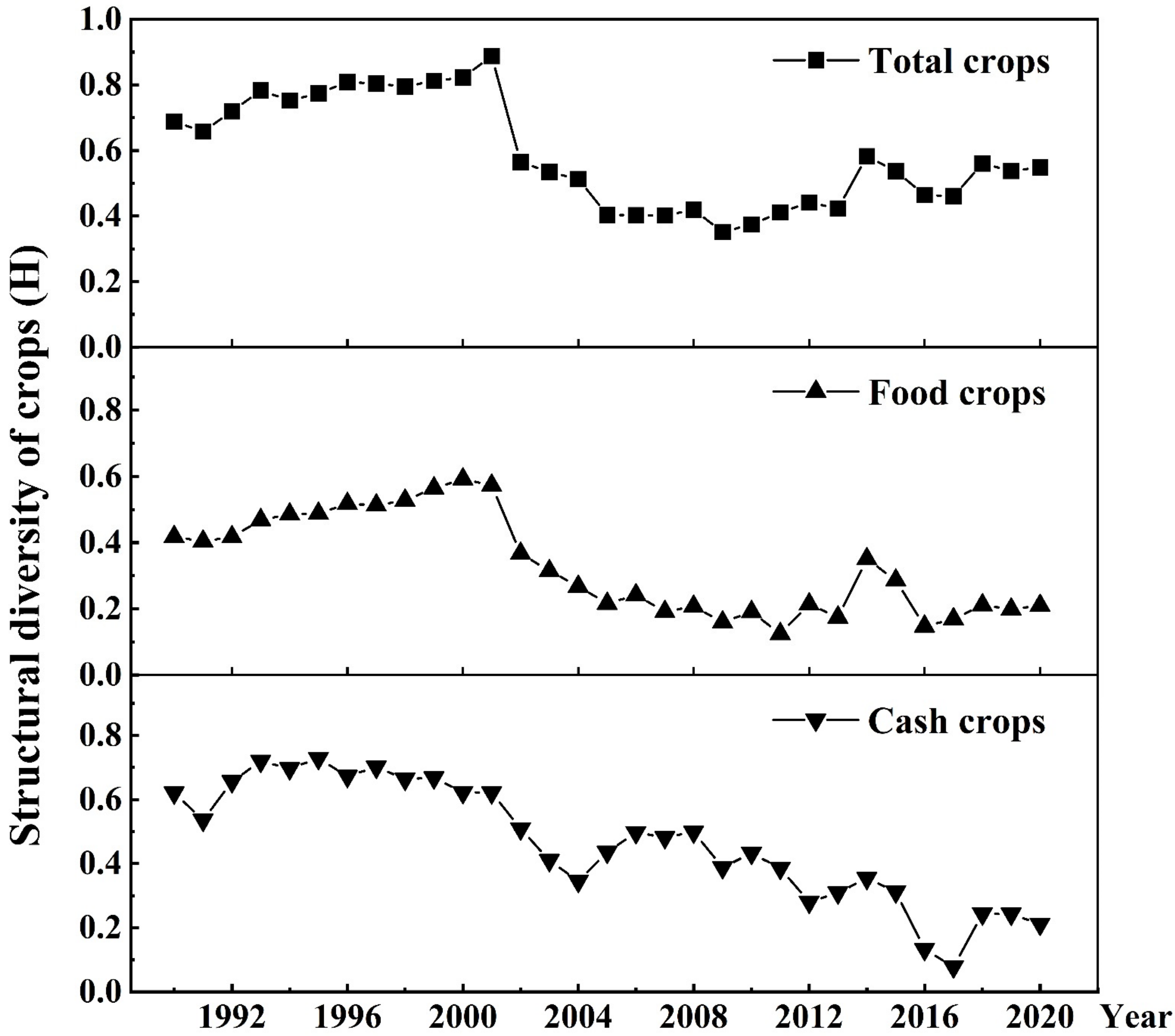

Figure 3. Structural diversity of the crops in Linze Oasis.

3.2.2. Changes in Water Savings

Taking 1990 as the reference year, the crop restructuring between 1990 and 2020 caused characteristic changes in the total ΔWn, following a "rapidly rising–relatively stable–rapidly rising" pattern (Figure 4). Before 2000, $\Delta W_n > 0$ and reached 0.076×10^8 m^3 from 1990 to 2020. In this period, the conventional mode of high WU cultivation, which was dominated by corn with banding, showed a negative effect on water savings. After 2000, $\Delta W_n < 0$ between 2001 and 2015, which indicates that the crop restructuring had a significant positive effect on water savings. During the initial implementation of the policy between 2000 and 2003, ΔW_n decreased to 0.25×10^8 m^3, accounting for 20% of the total water consumption in 2000. However, there was an opposite effect on water savings compared with the structure of crop farming after 2015.

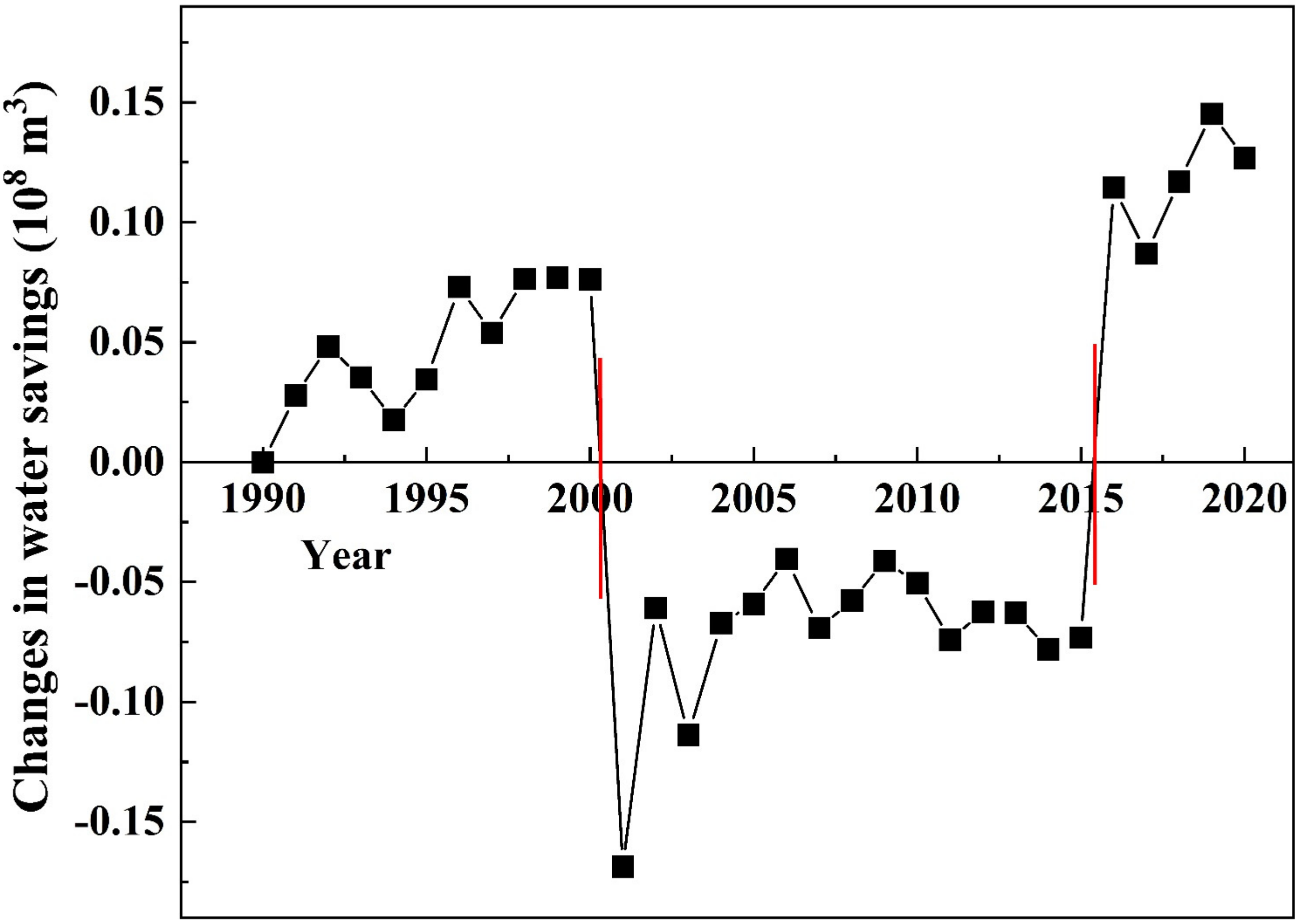

Figure 4. Effects of the changes in the crop restructuring on water savings in Linze Oasis.

3.2.3. Changes in Water Productivity

The prices in this section were uniformly converted into the fixed prices from 1990 to eliminate the effects of inflation and fluctuation. The outputs of the total crops increased from RMB 0.88×10^8 to 4.33×10^8 in the period 1990–2020, and the unit of water productivity increased from 0.94 to 2.10 RMB/m^3 correspondingly. The water productivity steadily increased to 1.32 RMB/m^3 before 2000. Notably, the water productivity during the crop restructuring experienced a "rapidly rising–fluctuating" effect (Figure 5), which significantly increased after the 2000 policy implementation. The water productivity between 2000 and 2007 had a rapid increase of 86% from 1.32 to 2.45 RMB/m^3 and a further decrease to 1.96 RMB/m^3 in 2013. It is noteworthy that the water productivity during the crop restructuring kept fluctuating between 2.00 and 2.45 RMB/m^3 after 2014.

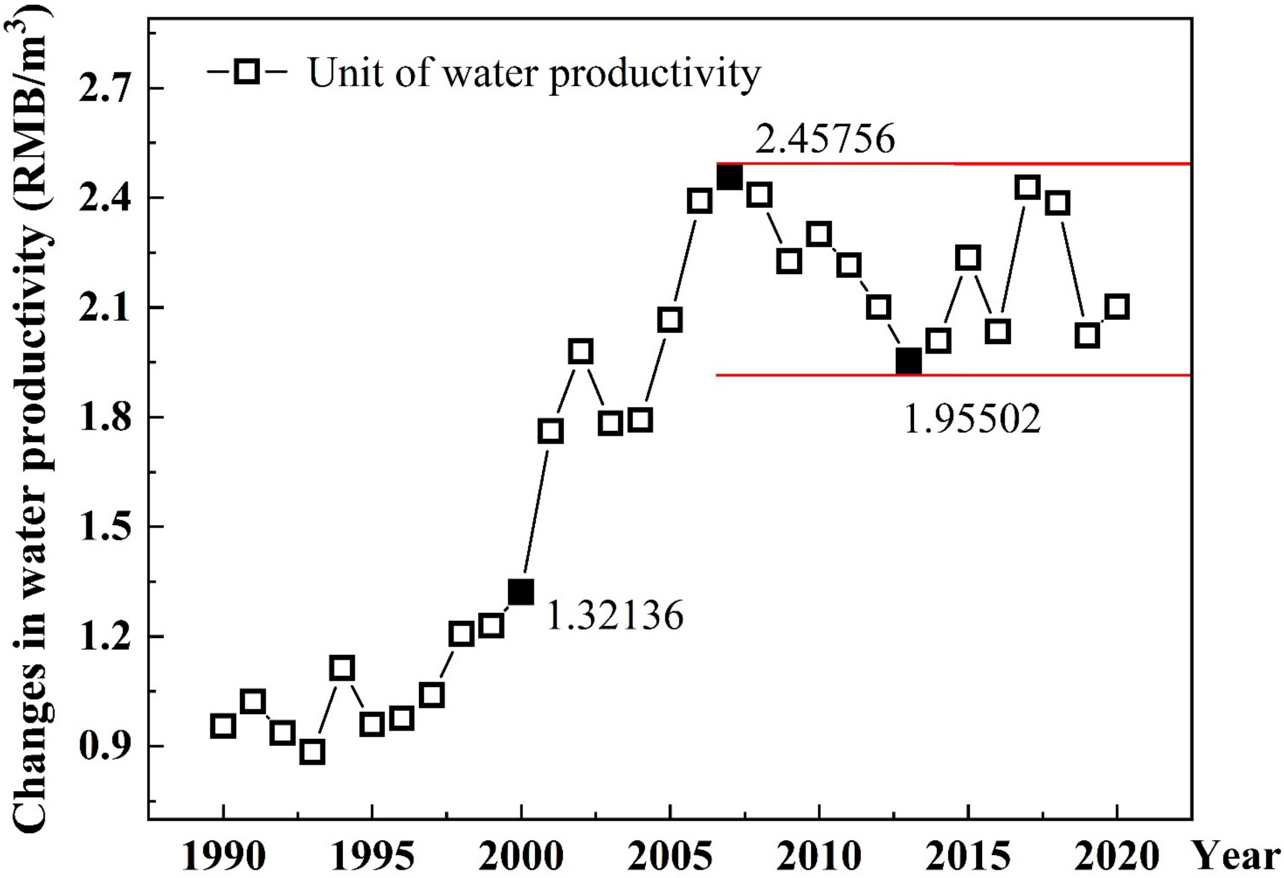

Figure 5. Effects of the changes in the crop restructuring on the water productivity in Linze Oasis.

4. Discussion

Water policies and economic factors commonly expedited the regime shifts in the Hexi oases. The shifts and their dominant drivers are further discussed and incorporated with the interactions among the socio-ecological elements.

4.1. Regime Shifts in Oases and their Dominant Drivers

The Linze Oasis has experienced three regimes from 1990 to 2020 based on the interaction between the social and ecological elements. Before the implementation of the 2000 water policy, crops with high water consumption were planted under the conditions of adequate irrigation. The scale and structure of the oases were relatively stable in this period (Figure 6, Regime 1). The pressure on ecological protection has increased with the continuous increase in the production of water [23,49]. It is of great significance for water security to identify the reasonable threshold of the watershed hydrology and ecosystem within the river basin [16,17]. On the one hand, the crop areas of the oases decreased by 0.19×10^4 hm^2, and the water consumption correspondingly decreased from 5.45×10^8 m^3 to 4.55×10^8 m^3. On the other hand, the conventional structure of "wheat–field corn" was replaced by a seed corn structure with corresponding changes in arable land, crop rotation, market, etc. The water policy was the dominant driver of the rapid regime changes in the scale and structure of the oases between 2000 and 2002. It was effective in alleviating the seasonal insufficiency of irrigation through reasonable crop restructuring and the temporal coupling of regional water demands and different crops [50].

Crop restructuring can be recognized as feedback to the pursuit of economic benefits within the water resource constraints [11]. Different crops significantly impact the hydrology and water balances, especially the WUE, due to their significant differences in field management, planting patterns, irrigation, and so on [51]. The Linze Oasis maintained a stable period of adjustment between 2003 and 2010 after the implementation of the water distribution policy in 2000 (Figure 6, Regime 2). Not only the water savings but also the positive profits in the water-saving process are matters for water resource management [52]. The effect of crop restructuring on the regional ecology based on its comparative advantages and market demand has gradually been emphasized. Meanwhile, farmers have a weak resistance to market risks and choose crops with relatively high yields and low risks [53]. Low-water-consumption and high-yield crops are the main causes of structural change. Additionally, a series of policies, such as irrigation management, land standardization, water rights and price reforms, and ecological compensation [54], have encouraged the concentration of regionally advantageous crops. As a result, the seed corn rapidly increased to 1.46×10^4 hm^2, accounting for 75% of the total area in 2009. The structure dominated by seed corn has effectively promoted water savings and productivity simultaneously and eliminated the negative effects of the implementation of rigorous water resource management.

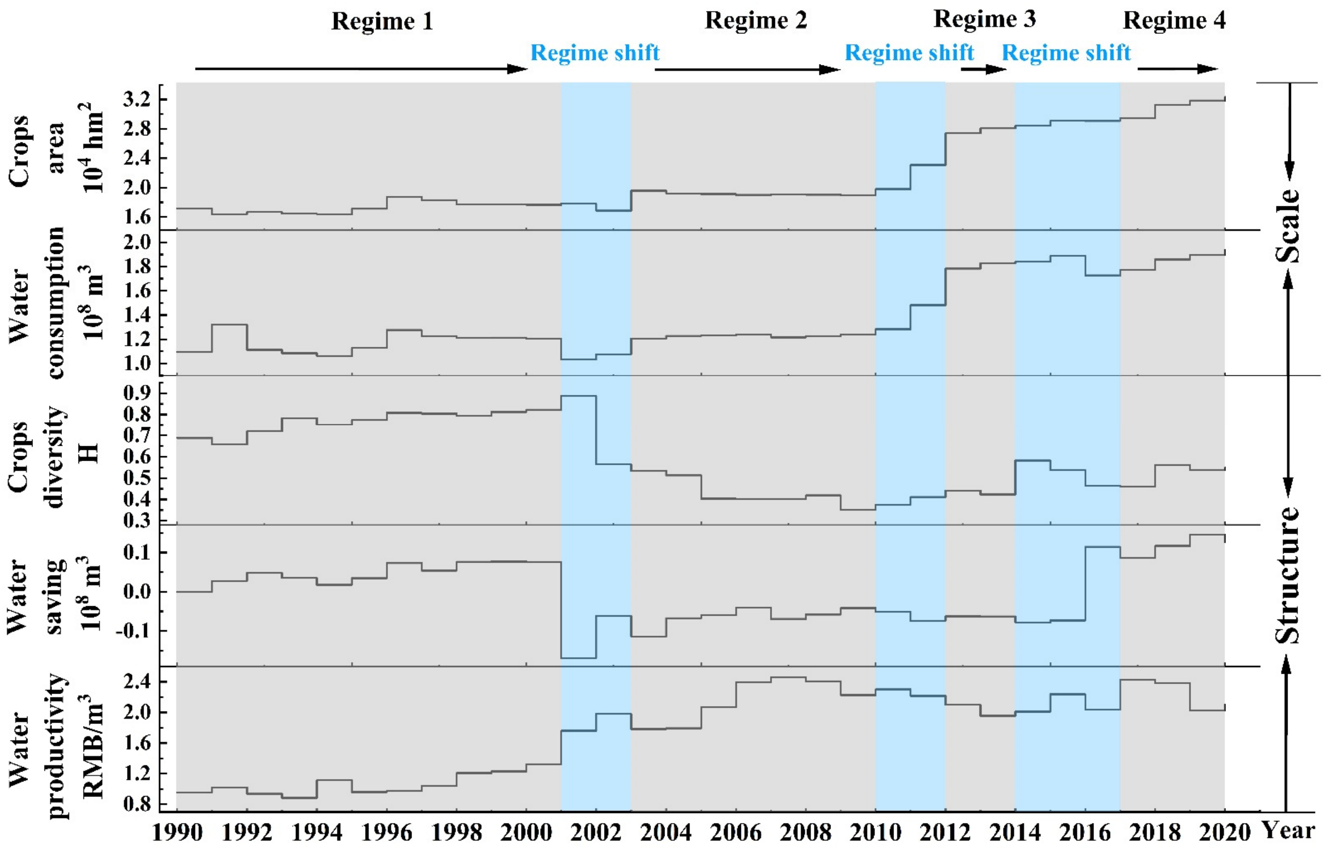

Figure 6. Regime shifts with the interaction of the socio-ecological elements in Linze Oasis.

Generally, the transformation of institutions and policies had significant effects in a certain period. The homogenization of crops reduced the ability to resist the influence of market saturation and increased the potential risk, resulting in a continuous decline of agricultural water productivity in the oases after 2007. Therefore, two main shifts were obvious to reverse the tendency after 2010. Firstly, enlarging the crop areas was a priority to increase income, since the water productivity decreased. The scale of the oases had a significant expansion in the period 2010–2012. In addition, the saved water resources with the increased WUE were further returned to agriculture to support the oases' expansion in the Hexi Corridor [5]. Considering that the water resources are the main limits for regional oases, an appropriate scale of oases is essential to maintain the sustainable development of the regional ecological economy [55]. However, the expansion of the oases scale did not effectively reverse the decline in water productivity in this process (Figure 6, Regime 3). The adjustments in the structure were the cause of the regime shifts from 2014 to 2017, especially the economic crops (e.g., vegetables, stevia, etc.), which were introduced to mitigate the risk of the monotony, resulting in significant fluctuations in water efficiency and a significant increase in water consumption. The scale (2010–2012) or structural (2014–2017) shifts, with an obvious bouncing back of the total water consumption and water savings in succession, further show that economic factors have significantly driven the regime shifts in the oases after 2010 within the context of water resource management. It should be emphasized that cash crops, mainly vegetables, are greatly affected by the market, and their water consumption increased during the same periods, resulting in significant fluctuations in water productivity in 2018–2020 (Figure 6, Regime 4).

4.2. Effects of Policies and Economic Factors on Oases Regimes

The oases regime shifts had no significant effect on water savings during 2000–2020, and the fluctuation in the water productivity corresponded to the adjustment in the structure, which indicates that economic factors, rather than policies, were the dominant factors for the regime shifts in the long-term development of the oases. Improving economic benefits associated with water savings is the basis of oasis sustainability [22] and can alleviate a series of social and environmental issues within the constraints of water resources [23]. Productivity on the basis of water savings is a priority to retain agricultural oases on a larger scale [52].

In addition, integrated water resource management aims to increase the WUE, including the transmission and terminal-field water efficiency [45]. Specifically, the "integrated regulation and discharge" policy has increased the efficiency of the water distribution, and the infrastructure construction has increased the transmission efficiency [56]. Consequently, the terminal water consumption in Linze Oasis remained stable at 2.5×10^8 m^3, while the irrigation water decreased from 5.45 to 4.55×10^8 m^3 during the same time. The overall and terminal-field efficiency increased from 50 to 58% and 78%, respectively. Moreover, the saved water resources with the increased WUE were further returned to the agricultural system [5], which were effective to reduce the fluctuation in the cascading effects on the social ecosystem. Nonetheless, considering the frequent transformation between the surface and groundwater in the middle reaches of the Heihe River basin [57,58], the water-saving measures will increase the complexity of the regional hydrologic processes [59] and further affect the regime shifts of the Heihe oases to a certain extent.

5. Conclusions

The middle reaches of the Heihe oases have experienced a long-term dynamic process over the past 30 years. The expansion of crop areas has significantly increased the water consumption during the shift periods. Reducing the high-water-consumption areas moderately at the edge of the oases is of great significance to the sustainable development of agricultural oases. Moreover, the adjustment in the structure of crops was the main cause of the regime shifts for the agricultural oases, which significantly affected the regional water savings and productivity.

The regime shifts in the middle reaches of the Heihe oases were recognized as a factual response to the water policies and economic benefits. The integrated water management expedited the regime shifts in the oases, while the economic factors dominated the shifts over the long term. Specifically, the water policy in 2000 effectively promoted the regime shifts of the whole oases. The shifts in scale (2010–2012) and structure (2014–2017) were temporary adjustments of the sustainable development with multiple drivers.

To summarize, the water-saving effect driven by the improvement of economic benefits is of great significance to the sustainable development of the middle reaches oases. Improving water productivity is the dominant direction of the sustainable development of oases under climate change. Moreover, the water consumption of the main crops varies in different years with climate change, which will have a potential impact on the regional water balance in the long term.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142316309/s1.

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