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Effect of Drought on Outbreaks of Major Forest Pests, Pine Caterpillars (*Dendrolimus* spp.), in Shandong Province, China

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Abstract: As the main defoliators of coniferous forests in Shandong Province, China, pine caterpillars (including *Dendrolimus suffuscus suffuscus* Lajonquiere, *D. spectabilis* Butler, and *D. tabulaeformis* Tsai et Liu) have caused substantial forest damage, adverse economic impacts, and losses of ecosystem resources. Therefore, elucidating the effects of drought on the outbreak of these pests is important for promoting forestry production and ecological reconstruction. Accordingly, the aim of the present study was to analyse the spatiotemporal variation of drought in Shandong Province, using the Standard Precipitation Index, and to investigate the impact of drought on the outbreak of pine caterpillar infestations. Future trends in drought and pine caterpillar populations were then estimated using the Hurst exponent. The results showed that: (1) Drought decreased gradually and showed a wetting trend from 1981 to 2012, with frequency decreasing on a decadal scale as follows: 1980s > 1990s > 2000s > 2010s; (2) The total area of pine caterpillar occurrence decreased strongly from 1992 to 2012; (3) Long-term or prolonged drought had a greater positive impact on pine caterpillar outbreak than short-term drought; (4) In the future, a greater portion of the province's area will experience increased wetting conditions (57%) than increased drought (43%), and the area of pine caterpillar outbreak is estimated to decrease overall. These findings help elucidate the relationship between drought and pine caterpillar outbreak in Shandong Province and, hence, provide a basis for developing preventive measures and plans.

Keywords: drought; Standard Precipitation Index; forest pest; pine caterpillar; insect outbreak; Hurst exponent

1. Introduction

Insects play important roles in the maintenance of ecosystem structure, function, and biodiversity, but they also have the potential to threaten natural, biological, and social environments and even to cause disasters [1,2]. In the 1990s, for example, there was a severe and extensive outbreak of pine caterpillars (*Dendrolimus* spp.) that caused dramatic tree mortality and loss in Shandong Province, China. However, outbreaks of insect pests are not only affected by its own inherited characteristics but are also influenced by: (1) host tree abundance, (2) high insect population density, and (3) adaptive environmental characteristics, including forest structure, climate, and site conditions [3]. Indeed, climate and weather can influence insect outbreaks both directly or indirectly, by affecting insect growth, reproduction, spread, and hosts [4]. It is worth mentioning that the occurrence, development, and outbreaks of forest pests often co-occur with meteorological disasters, such as drought and heat waves [5]. In particular, increasing drought frequency has been identified as an important predisposing factor that can trigger insect outbreaks, directly by affecting insect population dynamics and indirectly by altering host plant growth and defence [6,7]. Furthermore, extensive research has demonstrated that severe or prolonged drought has adverse effects on tree growth and survival and that it can also trigger more frequent or severe outbreaks of forest pests [8].

Currently, pine caterpillars (*Dendrolimus suffuscus suffuscus* Lajonquiere, *D. spectabilis* Butler, and *D. tabulaeformis* Tsai et Liu) are the most serious defoliators of coniferous forests, which are dominated by members of the Pinaceae, Cupressaceae, or Taxodiaceae. These pests cause a wide range of hazards, and during recent decades, their outbreaks have caused huge economic losses in China by causing damage to trees, loss of amenity value from forests, and a variety of other direct and indirect impacts and costs [9]. Moreover, most of the existing forests in Shandong Province are monocultures, and the simple forest structure, poor site conditions, and weak resistance of host trees to biotic factors make the insect pests more likely to outbreak and create subsequent disasters [10]. Liu et al. (2018) reported that the frequency of drought events was relatively high in Shandong Province during the 1980s and that serious outbreaks of pine caterpillars occurred in the early 1990s [11]. This suggests that dry weather favours the spread and survival of pine caterpillars and that understanding the interactions between drought and caterpillar outbreaks will help elucidate the impact of future drought on forest ecosystems.

Drought is a period of below-average precipitation in a given region that results in prolonged shortages in the water supply [12]. Droughts can have high frequency and long duration and have wide influence and far-reaching impacts on forests, ecological environment, and social economic development [13,14]. In order to investigate the impacts of different drought types on terrestrial ecosystems, researchers have developed several drought indices, including the Palmer Drought Severity Index (PDSI), Rainfall Anomaly Index (RAI), Joint Deficit Index (JDI), Standardized Relative Humidity Index (SRHI), Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Soil Water Deficit Index (SWDI) [15–23]. Such indices have been used extensively in meteorology, hydrology, agriculture, and socio-economic studies. However, SPI is used widely, owing to its accuracy and simplicity, making droughts comparable in different regions or periods. It can be applied over multiple timescales such as 1, 3, 6, 9, 12, and 24 months, to describe short- and long-term drought [24]. As a result, SPI has been recommended as a standard drought indicator by the World Meteorological Organization (WMO) [25].

As a result of recent climate change, the effects of prolonged or worsening drought on pest damage is a major concern for forest ecosystems [26], and it is necessary to elucidate the impact of drought on pest performance, as well as on their damage to host trees. Accordingly, the aim of the present study was to analyse the characteristics of drought in Shandong Province and to investigate the impact of drought on the outbreak of pine caterpillars. More specifically, the study analysed: (1) variations in drought and pine caterpillar occurrence and severity, (2) the correlation of drought (or prolonged drought) and pine caterpillar outbreaks, (3) future trends in drought and pine caterpillar occurrence. This work will provide a meaningful basis for pest prevention and control in Shandong Province.

2. Materials and Methods

2.1. Study Area

Shandong Province, which is located along the eastern coast of China and the lower reaches of the Yellow River (34°22.9′ to 38°24.01′ N and 114°47.5′ to 122°42.3′ E), has a total area of 155,800 km^2 [27] and contains plains, hills, and mountains. The central region of the province is generally mountainous, whereas the other areas are covered by plain and hilly grassland. The elevation of the province decreases gradually from the centre of the province to the surrounding areas, and the average elevation is about 91 m (Figure 1a). In addition, coniferous forest (mainly *Pinus thunbergii* Parl., *Platycladus orientalis* (L.) Franco, and *Pinus densiflora* Sieb. et Zucc) is distributed in the mountainous areas of central and eastern Shandong, covering 5027 km^2, and the region is also susceptible to the occurrence and, sometimes, outbreak of pine caterpillars (including *Dendrolimus suffuscus suffuscus* Lajonquiere, *D. spectabilis* Butler, and *D. tabulaeformis* Tsai et Liu), owing to poor forest quality and higher proportions coniferous monocultures and less mixed forest (Figure 1b).

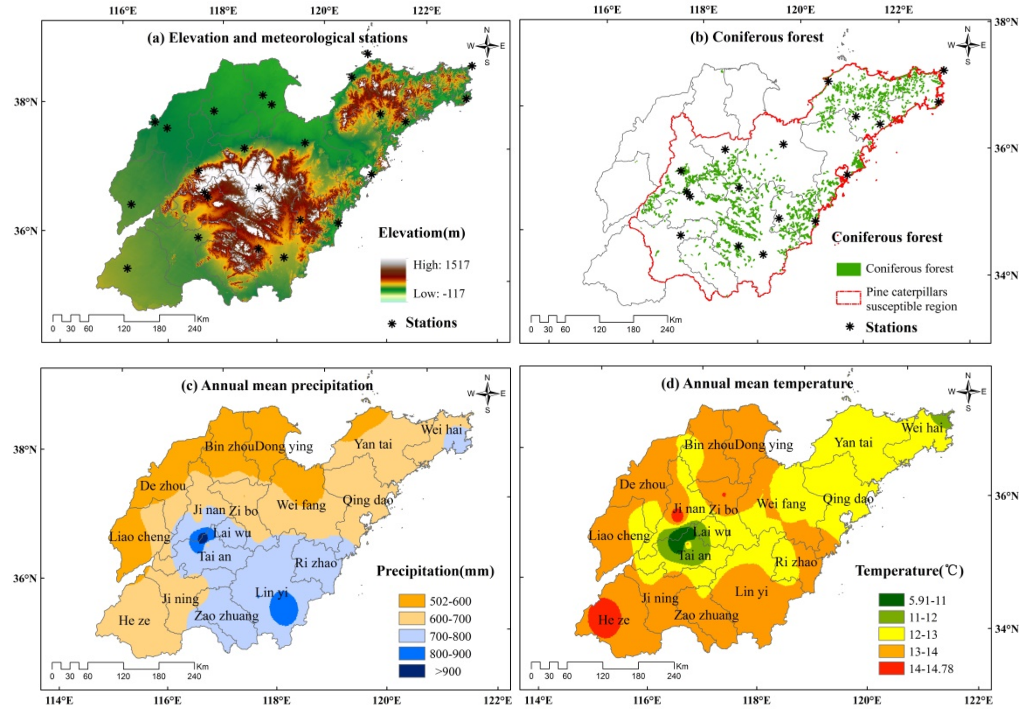

Figure 1. Basic characteristics of Shandong Province, China: Elevation (**a**), coniferous forest (**b**), annual mean precipitation from 1981 to 2012 (**c**), and annual mean temperature from 1981 to 2012 (**d**).

In regard to Shandong's climate, mean annual precipitation gradually decreases from the southeast (950 mm) to northwest (550 mm), and summer rainfall accounts for 60%–70% of annual precipitation, with drought occurring during late autumn, winter, and spring (Figure 1c). Meanwhile, the mean annual temperature of the province ranges from 5.93 to 14.78 °C (Figure 1d). Shandong Province possesses a warm temperate monsoon climate, being affected by a maritime monsoon climate during the summer and the East Asian winter monsoon (Mongolian high activity in winter), so that the region's climate is characterized by hot, rainy summers and cold, dry winters [28,29].

2.2. Data Sources

Monthly precipitation and temperature data for 25 meteorological stations during 1981–2012 were obtained from the China Meteorological Data Sharing Service System (http://data.cma.cn/) and used to calculate monthly Standardized Precipitation Index (SPI) values, which are correlated with the occurrence of drought, insect pests, and vegetation growth. Pine caterpillar occurrence data, including total area and the area of individual infestation categories (light, moderate, and severe), for Shandong Province during 1992–2012 were obtained from the China Forestry Statistical Yearbook. Meanwhile, elevation data and the distribution of coniferous forest were obtained from the Digital Elevation Database (http://srtm.csi.cgiar.org/) and Shandong Forestry Research Academy, respectively (Figure 1).

2.3. Calculations

2.3.1. Standard Precipitation Index

The Standard Precipitation Index (SPI) is a drought index that was proposed by McKee et al. (1993) to analyse the wetness and dryness of any area at multiple time scales using long-term (>30 years) precipitation data [30]. Bonaccorso et al. (2003) suggested that short- and medium-term (e.g., 1-, 3-, or 6-month) SPI values are appropriate for detecting drought events that affect agriculture, whereas long-term (e.g., 12- or 24-month) SPI values are more suitable for managing water resources [31]. In the present study, 1-, 3-, 6-, and 12-month SPI values were calculated from monthly precipitation data as described by Gidey et al. (2018). The calculation program was acquired from the National Drought Mitigation Center (https://drought.unl.edu/) [32]. The SPI values were classified into five classes [33] (Table 1).

Table 1. Classification used for the Standard Precipitation Index (SPI) and Hurst exponent (H).

SPI	Drought Class	H	Consistency
$0.5 < \text{SPI} \leq 1$	Moderate wet	$0.65 < \text{H} \leq 1$	Strong consistency
$0 < \text{SPI} \leq 0.5$	Normal	$0.5 < \text{H} \leq 0.65$	Weak consistency
$-0.5 < \text{SPI} \leq 0$	Light drought	$\text{H} = 0.5$	No relevance
$-1.0 < \text{SPI} \leq -0.5$	Moderate drought	$0.35 \leq \text{H} < 0.5$	Weak inconsistency
$\text{SPI} \leq -1.0$	Severe drought	$0 \leq \text{H} < 0.35$	Strong inconsistency

To further understand the impact of prolonged drought on pine caterpillars, mean SPI was calculated for the first n years (n = 1, 5, 10), with SPI10, SPI5, and SPI1 providing insight into the drought conditions of the first 10, 5, and 1 years, respectively. The indices were calculated as follows:

$$SPI10_{1992} = \sum_{1983}^{1992} (SPI_{1983} + SPI_{1984} + \ldots + SPI_{1992})/10 \quad (1)$$

$$SPI5_{1992} = \sum_{1988}^{1992} (SPI_{1988} + SPI_{1989} + \ldots + SPI_{1992})/5 \quad (2)$$

$$SPI1_{1992} = \sum_{1991}^{1992} (SPI_{1991} + SPI_{1992})/2 \quad (3)$$

Then, SPI10, SPI5, and SPI1 were obtained for 1992–2012, in order to calculate their correlation with pine caterpillars. SPI10, SPI5, and SPI1 values of less than −0.5 indicated prolonged drought for nearly 10, 5, and 2 years, respectively, and the index values were classified into five classes, as described above for SPI (Table 1).

2.3.2. Hurst Exponent and Rescaled Range Analysis

The Hurst exponent (H) was first proposed for the analysis of hydrological data from the Nile River (Hurst, 1951) and is now often used to analyse long-term time series correlations [34]. The principle of Rescaled Range (R/S) is briefly described as follows:

Consider a time series $\{\varepsilon\ (t)\}$, t = 1, 2,..., and for any positive integer $\tau > 1$, a time series is defined as:

$$< \varepsilon >_\tau = \frac{1}{\tau} \sum_{t=1}^{\tau} \varepsilon(t) \qquad t = 1, 2, 3 \ldots \quad (4)$$

The cumulative deviation is calculated as:

$$\mathrm{X}(t, \tau) = \sum_{u=1}^{\tau} (\varepsilon(u) - < \varepsilon >_\tau) \qquad 1 \leq t \leq \tau \quad (5)$$

The extreme deviation sequence is calculated as:

$$R(\tau) = \max_{1 \leq t \leq \tau} X(t,\tau) - \max_{1 \leq t \leq \tau} X(t,\tau) \qquad \tau = 1, 2, \ldots \tag{6}$$

The standard deviation sequence is calculated as:

$$S(\tau) = \left[\frac{1}{\tau} \sum_{t=1}^{\tau} (\varepsilon(u) - < \varepsilon >_{\tau})^2 \right]^{\frac{1}{2}} \qquad \tau = 1, 2, \ldots \tag{7}$$

Based on $R(\tau)$ and $S(\tau)$, R/S is calculated as:

$$R/S = R(\tau) \ / \ S(\tau) \tag{8}$$

It is assumed that:

$$R/S \propto \left(\frac{\tau}{2}\right)^H \tag{9}$$

The Hurst phenomenon exists in the time series, where H is the Hurst exponent with a range from 0 to 1, and the value of H reflects the strength of the consistency or inconsistency in the series (Table 1) [35]. When $H = 0.5$, there is no change in the data series. However, when $H > 0.5$, the sequence has a persistent trend and the future trend will be consistent with the past trend, and when $H < 0.5$, the future trend will be opposite that of the past. In the present study, H was calculated using *R/S* analysis to show whether the future trend would be consistent with the current state.

2.3.3. Correlation, Linear Regression Analysis

Because the data were normally distributed, correlations between pine caterpillar outbreak and SPI were calculated using Pearson's correlation coefficients, and to investigate the impact of prolonged drought on pine caterpillar outbreak, mean SPI (for season, growing season, and year) and the occurrence area of pine caterpillars were examined using correlation analysis. In addition, linear regression analysis was used to measure current trends in SPI and the occurrence area of pine caterpillars [36].

3. Results

3.1. Variations of Drought in Shandong Province

The annual mean moisture conditions as well as conditions in the growing season and in the four seasons between 1981 and 2012 were observed. SPI-1 provided insight into the rapid variability of drought at the monthly scale (Figure 2). Alternate dry/wet episodes occurred frequently, and a short-term drought was detected in 1992 and 1998–1999. A similar pattern of drought was indicated by SPI-3, which provides insight into both short-term drought and seasonal conditions. Severe and extreme drought was the most prevalent for SPI-3, of the four timescales. The responses of mean SPI values to short-term precipitation weakened with increasing time scale, although the drought variation was stable. However, the main and long-term dry/wet episodes occurred in SPI-12. Moreover, a significant period of drought was detected during the 1980s and 1999–2003, whereas major wet episodes occurred during the mid-1990s and after 2003. It should be noted that Shandong Province experienced a shift from wet to dry during 1991–1993, 1998–1999, and 2006–2007. The results suggest that SPI-12 intuitively reflects annual variations in drought and it is used in the following study.

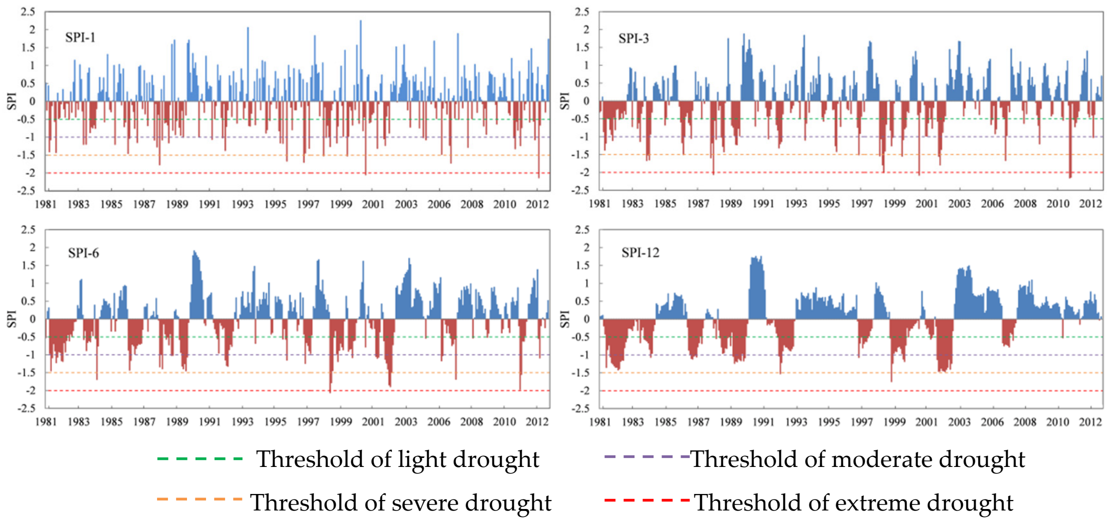

Figure 2. Standard Precipitation Index (SPI) at 1-, 3-, 6-, and 12-month scales during 1981–2012 in Shandong Province. Blue indicates wetness, and red indicates drought.

To further investigate the dry/wet conditions in detail, the temporal distribution of drought was summarized (Table 2). Generally speaking, light drought occurred more frequently than moderate drought, and both light and moderate drought were mainly prominent in the 1980s (except for 1985), 1990s (1992–1993 and 1997–1999), and the early 2000s (2000–2003), with few such droughts reported after 2010. On a decadal scale, drought frequency decreased in descending order (1980s > 1990s > 2000s > 2010s), thereby indicating that drought decreased gradually and showed a wetting trend during 1981–2012.

Table 2. Summary of drought events in Shandong Province from 1981 to 2012.

Drought Category	Years
Light	1983, 1984, 1986, 1987, 1988, 1993, 1997, 1999, 2001, 2003
Moderate	1981, 1982, 1989, 1992, 2000, 2002

Based on SPI-12, the dry/wet conditions for each decade were obtained and spatially interpolated (Figure 3). Obviously, the drought characteristics of the four decades were quite different and exhibited great inter-annual variation. In the 1980s, drought occurred in Shandong Province as a whole (60% light and 40% moderate), with moderate drought mainly distributed in the south eastern and northern parts, while light drought distributed in the remaining areas (Figure 3a). There was a shift from dry to normal in Shandong Province during the 1990s, and it was dominated by normal conditions, rather than light drought (Figure 3b). However, 4% moderate drought and 32% light drought was still monitored in the western and eastern regions. In the 2000s, Shandong Province was in a normal condition, other than light drought in the northern part, (Figure 3c). In the 2010s, moderately wet conditions increased significantly, whereas the percentage of light drought and normal conditions decreased (Figure 3d). That is, the 2010s were the wettest decade in Shandong Province during 1981–2012. In addition to the 1980s, Shandong Province has been dominated by normal conditions, whereas light and moderate drought has decreased, so that moderate drought has not been observed since the 2000s. With the moderate wet conditions of the 2010s, light drought fell to a minimum level. In general, extensive drought only occurred from the 1980s to the 1990s in Shandong Province.

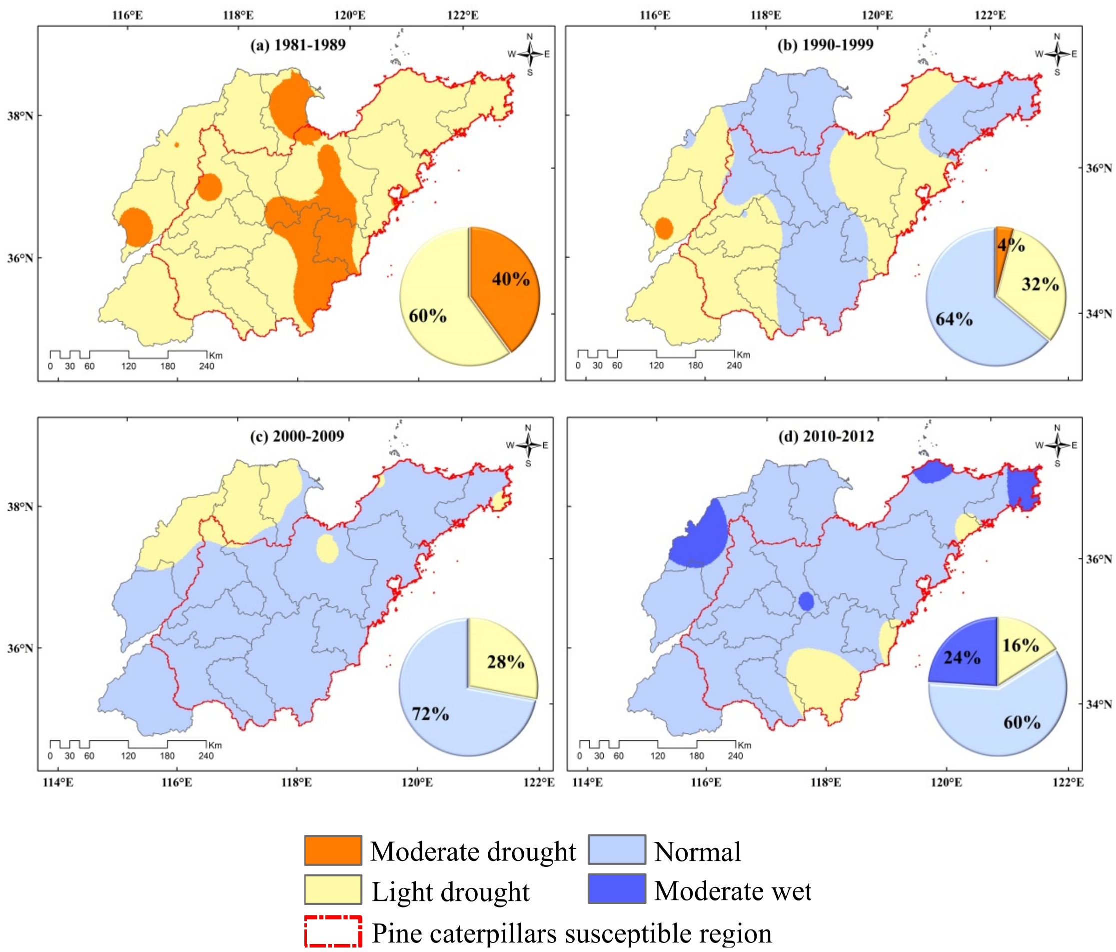

Figure 3. Spatial distribution of the SPI-12 during 1981–2012 in Shandong Province. 1980s (**a**), 1990s (**b**), 2000s (**c**), and 2010–2012 (**d**).

3.2. Variations of the Outbreak of Pine Caterpillars in Shandong Province

The total area of pine caterpillars decreased greatly from 1992 to 2012 (Figure 4a), with an average value of 574.18 km^2 and linear decrease of −52.89 km^2/year, possibly resulting from the increase in wetting trend in Shandong Province during the same period. The 1992–2012 period was divided into four parts: 1992–1997, 1998–2002, 2003–2007, and 2008–2012 (yellow lines, Figure 4a). The fluctuation of the total area curve (green line, Figure 4a) exhibited some regularity; although the total area of pine caterpillars decreased, in general, small peaks occurred every few years (e.g., 1992, 1999, 2004, and 2008). Furthermore, the area of pine caterpillar infestation categories (i.e., light, moderate, and severe) has been recorded since 1998. The areas of all three infestation categories decreased at −39.49, −14.58, and −6.06 km^2/year, respectively, and moderate infestation has almost disappeared since 2010, whereas severe infestation has not occurred since 2003. Therefore, after 2010, light infestation has made the greatest contribution to total pine caterpillar area.

On a decadal scale, the occurrence area of pine caterpillars decreased with time: 1990s > 2000s > 2010s, when drought occurred simultaneously. The maximum and minimum pine caterpillar area occurred in 1992 and 2012, respectively. To further investigate this trend, the inter-annual variation of SPI in 1992 and 2012 were compared (Figure 4c). The SPI values indicated a drought in 1992, especially during the growing season, whereas wet conditions were detected in 2012. Therefore, there was a certain correlation between drought and the outbreak of pine caterpillars.

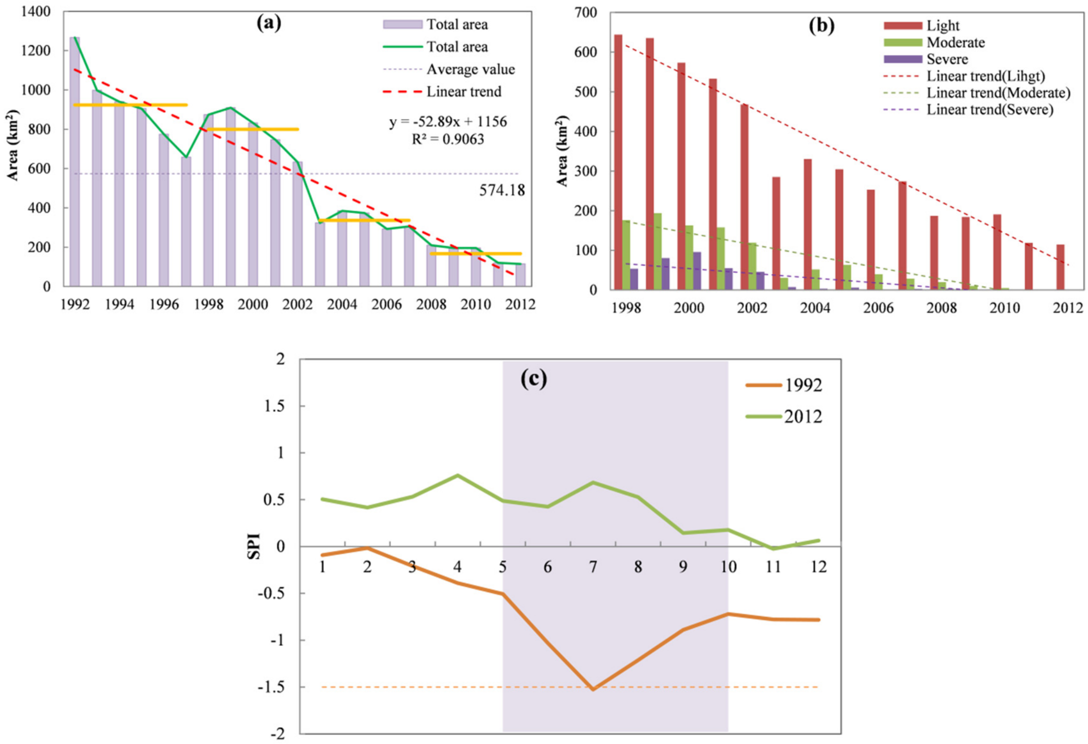

Figure 4. (**a**) Total area of pine caterpillars. Yellow lines indicate 1992–1997, 1998–2002, 2003–2007, and 2008–2012, respectively. (**b**) Distribution of pine caterpillar damage. (**c**) Inter-annual variation of SPI in 1992 and 2002. Dashed line represents the threshold of severe drought. Shaded region represents the growing season.

3.3. Drought Impacts on the Outbreak of Pine Caterpillars in Shandong Province

Spatiotemporal drought variability and evolution on the occurrence area of pine caterpillars in Shandong Province were analysed in the previous section. Given the relationship between drought and the outbreak of pine caterpillars, the correlation between SPI (meteorological stations in the susceptible region, as shown in Figure 1b) and the occurrence area of pine caterpillars were analysed. Significant differences in the responses of the pine caterpillars to different scales of SPI were identified. A negative correlation was observed when SPI conditions significantly influenced the outbreak of pine caterpillars, indicating that the year-to-year variations of pine caterpillars were related to the year-to-year variations in SPI. In other words, drought has a positive impact on pine caterpillar outbreak, that is, the drought could cause the increment of the outbreak of pine caterpillars.

The coefficients between pine caterpillar outbreak and SPI, SPI1, SPI5, and SPI10 at the year, growing season, and seasonal scales are presented in Figure 5. First, for the different time scales, the magnitude of the correlation between SPI and pine caterpillar outbreak from large to small was as follows: year > winter > growing season > autumn > summer > spring. The correlation between SPI and pine caterpillar outbreak is more significant at the year and winter time scales. Second, for the four different SPI scales, SPI10 was more strongly correlated with pine caterpillar outbreak than the other three (SPI10 > SPI5 > SPI1 > SPI). Therefore, the correlation between SPI and pine caterpillar outbreak was greatest at the year scale, and the insects were highly sensitivity to SPI10. Furthermore, the correlation coefficients for SPI10 and pine caterpillar outbreak, on a yearly basis, were consistently below −0.5, thereby indicating that pine caterpillar outbreak could be attributed to SPI10. Thus, long-term or prolonged drought has a greater impact on the outbreak of pine caterpillars than short-term drought.

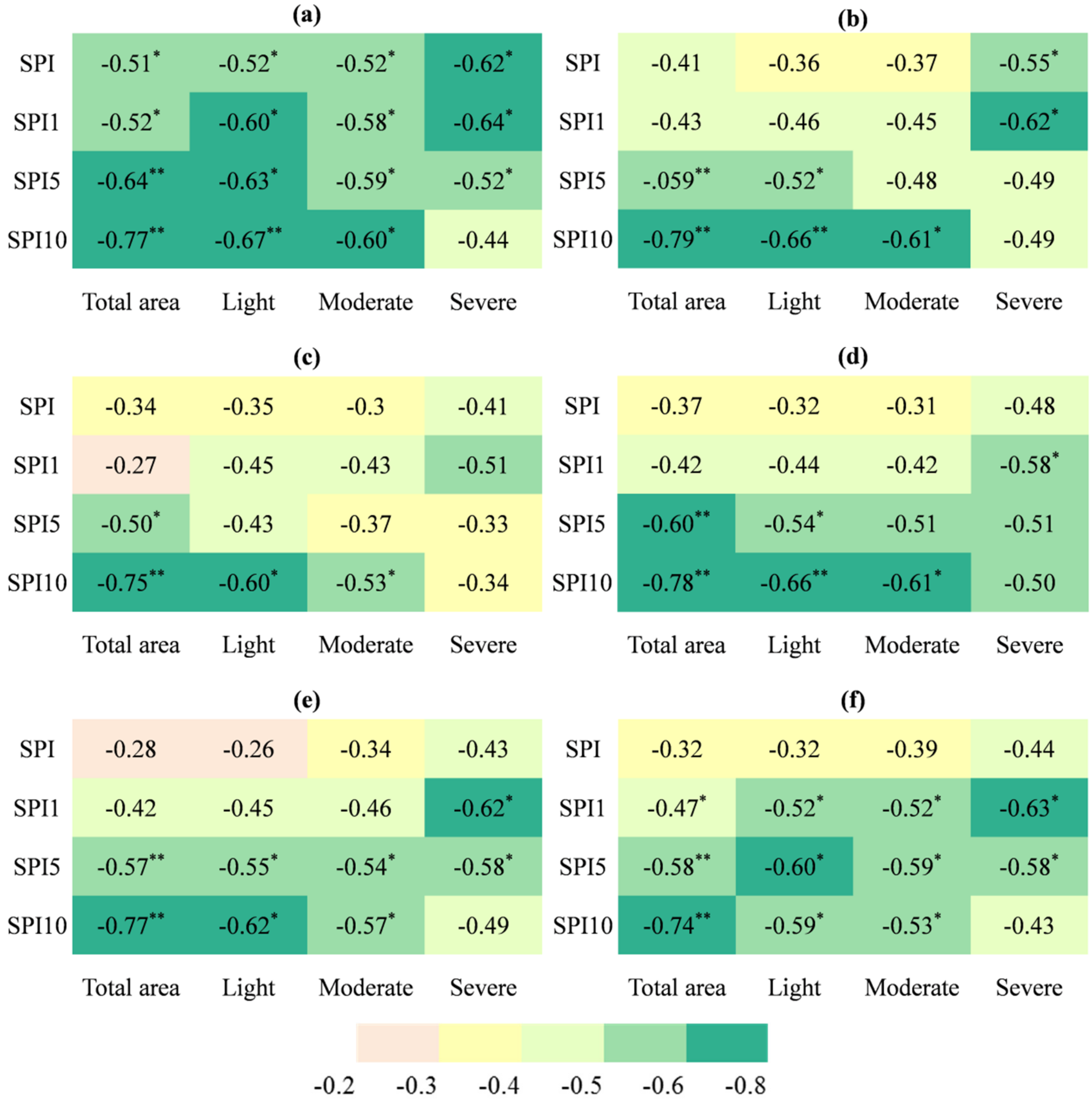

Figure 5. Effect of Standard Precipitation Index on pine caterpillar outbreak. Values are Pearson's correlation coefficients for the correlation of pine caterpillar outbreak and SPI, SPI10, SPI5, and SPI1 at year (**a**), growing season (**b**), spring (**c**), summer (**d**), autumn (**e**), and winter (**f**) scale for 1992–2012. ** and * indicate $p < 0.01$ and $p < 0.05$, respectively.

3.4. Future Trends in Drought and Pine Caterpillar Outbreaks in Shandong Province and the Consistency of Trends

To quantitatively analyse future trends in drought and the occurrence area of pine caterpillars, linear regression analysis was performed to reveal the current trend of drought and the occurrence area of pine caterpillars, and R/S analysis was performed to estimate whether the future trends will be consistent to the current state.

First, the current trend of SPI, which ranged from 0.006 to 0.047, indicated that SPI was increasing in Shandong Province, with seven stations exhibiting significant changes (Figure 6a). The region where the changes in SPI ranged from 0.02 to 0.03 accounted for 54% of the total area and was mainly distributed in the southern, northern, and central areas of the province. Meanwhile, the region where the changes in SPI ranged from 0.01 to 0.02 accounted for 25% of the total area and was mainly distributed in the western part of the province. In general, a weak wetting trend was detected in Shandong Province, and the wetting trend of southeast Shandong was the highest.

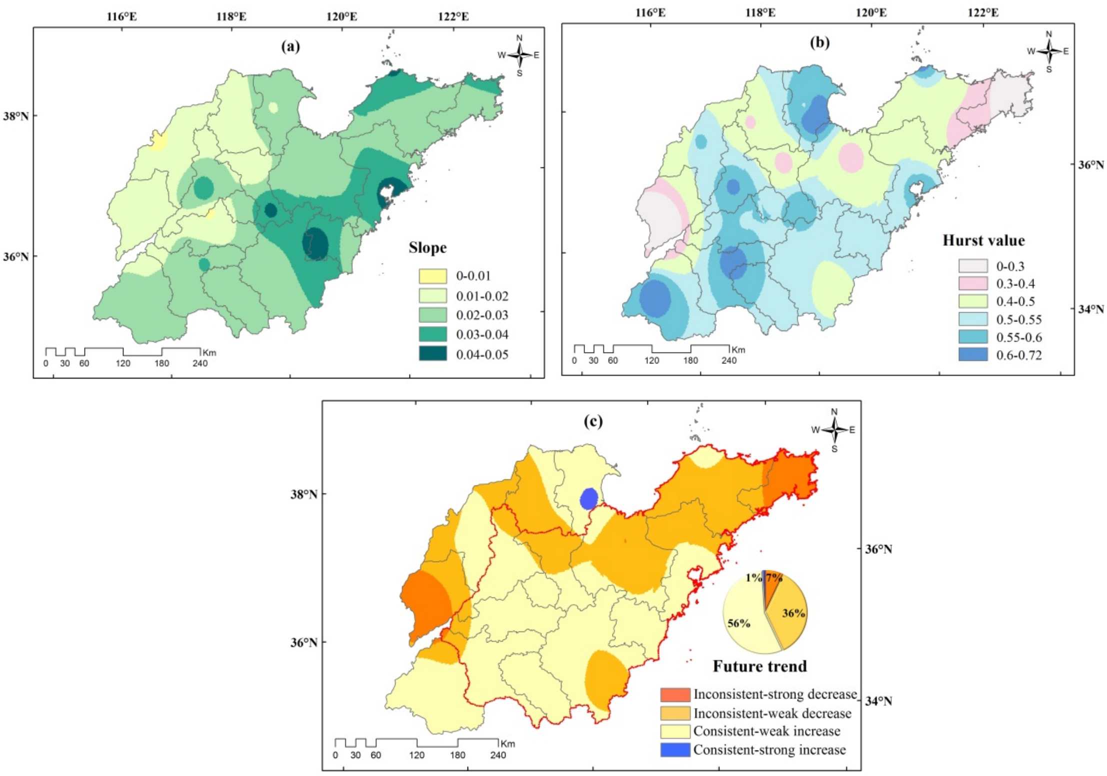

Figure 6. Spatial distribution of trends in variation (**a**), Hurst values (**b**) and future trend (**c**) of SPI in Shandong Province during the period 1981–2012.

Second, Figure 6b shows *H* exponent which was calculated by *R/S* analysis. The *H* values of SPI ranged from 0 to 0.717 and were divided into four types (Table 2). The future dry/wet trend exhibited obvious spatial heterogeneity, with weak consistency being most prevalent, followed by weak inconsistency, strong inconsistency, and strong consistency, respectively. In general, *H* values of 0.5 indicate that future dry/wet trends will remain consistent with current trend and those of <0.5 indicate that future trends will be opposite current trends. Overall, moisture trends that were consistent and inconsistent with the current state accounted for 57% and 43% of the entire province, respectively. Therefore, the future dry/wet patterns are approximately consistent with the current state. Regions with *H* values of >0.5 were mainly distributed in central, southwest, and northeast Shandong, whereas regions with *H* values of <0.5 were distributed in eastern and western Shandong.

Finally, we spatially overlaid the results of the linear regression and *R/S* analyses (Figure 6a,b) in order to predict the consistency of the trend on drought changes (Figure 6c). Future wetting trends for 57% of the province area will be the same as current trends and will, therefore, consistently increase, and these areas are mainly distributed in south eastern and northern Shandong, where strong and weak increases will account for 1% and 56%, respectively. However, future moisture trends for the remaining 43% of the province area will exhibit an opposite trend, decreasing strongly and weakly in 7% and 36% of the area, respectively. Overall, there will be a general increasing trend in moisture for 57% of Shandong, mainly in the central region, and increasing drought trend for the remaining 43% of Shandong, mainly in the eastern and western areas. In the region susceptible to pine caterpillar outbreaks (within the red line), regions with drought trends are more dominant and are mainly distributed in eastern Shandong.

Similarly, the current trend, *H* values, and future trend of the occurrence area of pine caterpillars were calculated using linear regression and *R/S* analyses. The total area and infestation category areas all exhibited significant decreasing trends (Table 3). In addition, the *H* values were all close to 0.9, which indicated strong consistency. Therefore, the future trend of the occurrence area of the pine caterpillars will be consistent with the current state, i.e., consistently decreasing.

Table 3. Trend, Hurst (*H*) values, and consistency of pine caterpillars in Shandong Province.

Pine Caterpillars	Linear Equation	R^2	Trend	*H* Value	Consistency
Total area	y = −52.98x + 1156	0.906	↓ **	0.923	Consistent and strong decrease
Light	y = −39.49x + 655	0.922	↓ **	0.937	Consistent and strong decrease
Moderate	y = −14.58x + 187	0.853	↓ **	0.935	Consistent and strong decrease
Severe	y = −6.06x + 72	0.664	↓ **	0.948	Consistent and strong decrease

** $p < 0.01$; ↓ decrease.

4. Discussion

According to the results of the present study, both drought and pine caterpillar outbreaks in Shandong Province exhibit pronounced variation. Moreover, the current findings confirm that drought promotes pine caterpillar outbreaks and that the effects of long-term or prolonged drought are greater than those of short-term drought, which is in line with the previous findings [37,38]. In other words, pine caterpillars and pine caterpillar outbreaks are more likely to develop and spread in dry areas, which, in the present study, was quantified using SPI.

4.1. Effects of Drought on the Pine Caterpillar Outbreak

The outbreak of pine caterpillars is the result of interactions between habitats, insect populations, and host trees, and the extent of such outbreaks is determined by the stability of habitats, insect populations, and the resistance of host trees. Among the influencing factors, habitat is the background condition that affects insect populations and trees [39]. Thus, drought is a habitat condition, and pine caterpillar outbreak can be considered a consequence of tree resistance and pine caterpillar population dynamics under drought conditions.

Indeed, drought affects the nutritional quality and metabolism of host trees of pests through changes in water metabolism, carbon cycling, and nitrogen content, all of which are involved in resistance to pest damage [40]. Currently, there are three hypotheses about drought and tree mortality (i.e., the effect of drought on trees), including the hydraulic failure, carbon starvation, and biotic attack hypotheses [41]. The hydraulic failure hypothesis suggests that drought conditions that result in cavitation embolism in the transporting tissues of the woody parts of trees limit the transport of water roots to leaves and, ultimately, contribute to the dehydration and drying of trees [42]. Meanwhile, the carbon starvation hypothesis suggests that long-term drought disrupts the balance between the carbon uptake and expenditure of trees, finally leading to carbon starvation [43]. Finally, the biotic attack hypothesis suggests that drought affects population dynamics by altering biological factors, such as insect growth rate, winter mortality, and geographical distribution [44]. According to these three hypotheses, drought stress greatly influences photosynthesis and, hence, the non-structural carbohydrates (NSCs) that provide carbon for plant respiration and growth and to plant-feeding insects. Non-structural carbohydrates (i.e., soluble sugars, like sucrose and fructose) and starch play important roles in pest and pathogen resistance, tree growth, and hydraulic properties. Terpenoids, phenolics, resins, tannins, and other pest- and pathogen-resistant substances in trees are all synthesized from NSCs [45]. Therefore, inadequate NSC levels will retard the growth rates of trees and reduce the ability of trees to resist pests and pathogens, and drought stress can also increase and reduce the sucrose and starch synthesis of leaves, respectively, thereby increasing the provision of food to pests [46].

These mechanisms may work alone or in interaction during drought. For example, hydraulic failure may affect carbon uptake through cavitation embolism, whereas carbon starvation may affect water transport and pathogen resistance, and biotic attack can initiate the negative effects of both hydraulic failure and carbon starvation, through the blockage of xylem by pests or pathogens or the depletion of carbon reserves by increased resin synthesis, respectively. In addition, both hydraulic failure and carbon starvation can also expand the role of biological attacks, for example, through reductions in the synthesis of carbon-based defence compounds (e.g., resins), increases in the production of volatile substances (e.g., ethanol) that attract pests, and changes in insect foods [47].

Furthermore, during drought events, reduced water content and protein hydrolysis contribute to the accumulation of nitrogen in tree organs [48]. Nitrogen, while an essential nutrient for plant growth and cellular growth, can also promote the growth and reproduction of phytophagous insects and even stimulate insect feeding [49].

More generally, host trees provide essential resources for the growth and reproduction of defoliating insects, such as pine caterpillars. However, drought stress disrupts the normal carbon metabolism pathway and sugar content of host trees, thereby affecting the development of insect populations. For example, the glucose, fructose, and sucrose content of pinus (*Pinus massoniana* Lamb) needles increases by 45.92%, 34.01%, and 138.32%, respectively, under drought stress, and increasing soluble sugar content in Eucalyptus (*Eucalyptus robusta Smith*) bark has been associated with increases in the body weight and decreases in the mortality of longhorn beetles (*Phoracantha semipunctata*) [50].

Importantly, drought also has direct and indirect effects on insect pests. First, drought stress affects the physiological characteristics of insects (e.g., water content and respiratory metabolic rate), as well as their growth, mating selection, and reproduction, possibly affecting the trends of pest populations, migration and diffusion, habitat selection, and other ecological characteristics [51]. Drought affects the reproduction of insects during the same year and, thereby, influences the base number and occurrence of larvae during the following year. Second, drought-mediated changes in the physical properties, nutritional status, and secondary metabolites of host trees affect the habitat and food acquisition of insects, thereby affecting the growth and population dynamics of their natural enemies [52]. Parasitic natural enemies are effective in controlling insect populations, even at low population levels. However, such enemies are generally susceptible to the adverse effects of drought, owing to their small size and specific diets or hosts [53], and levels of terpenoids, which are one of the most important volatile compounds in the plant arsenal to attract natural enemies, can be reduced by drought stress, so that drought has the potential to reduce the ability of plants to attract natural enemies.

It is certain that topography, forest structure, soil, and forest management measures also affect the breeding and reproduction of pine caterpillars [54,55]. For instance, the outbreak of pine caterpillars was lower at higher elevations, on north-facing sites, and in areas with poor soil or forest quality [56]. This does not contradict the conclusion that drought is closely related to pine caterpillar outbreaks. Indeed, higher SPI values are associated with less frequent pine caterpillar outbreaks. In fact, large-scale pine caterpillar outbreaks often occur during or after drought events, which suggests that drought has a lagging effect (Figure 7). The present study also demonstrated that SPI1 had a more significant impact on pine caterpillar outbreaks than the other SPI indices and that the SPI values of both the previous and current year play a role in determining the likelihood of pine caterpillar outbreaks (Figure 7). It can also be concluded that prolonged drought has a significant effect on pine caterpillar outbreaks.

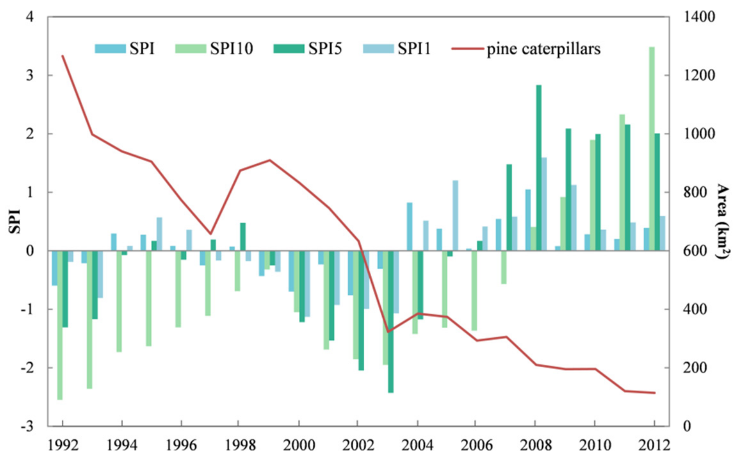

Figure 7. Standard Precipitation Index and pine caterpillar outbreaks in Shandong Province.

In fact, in the early 1990s, when the pine caterpillars broke out in Shandong Province, drought had occurred in most parts of China, including in North China, especially in the provinces of Shandong, Henan, and Hebei [57]. Meanwhile, an outbreak of second-generation cotton bollworm was extremely serious, with the pest's population exceeding the sum of the populations from the past 20 years [58]. In addition, from winter 1992 to spring 1993, the drought in Qinghai Province was relatively severe, and the grassland was seriously attacked by pests [59]. Losses of cotton to pest species in the United States were equally severe in 1992 [60]. Therefore, the association between drought and pest occurrence is widespread [61].

4.2. Future Trends, Consistency on Drought and Pine Caterpillar Outbreak

Both linear regression and *R/S* analysis indicated that future drought and pest outbreak trends would be consistent with current trends in Shandong Province. Although the occurrence of pine caterpillars has recently decreased, researchers should continue working toward a cure in its prevention and cure in arid forests. If there is a new, long-term drought cycle in the region, it is possible that pine caterpillars could break out again on a large scale [62–65]. Compared to previous studies of forest pests, the present study questions whether future pest trends will be consistent with the current state. However, the proposed *R/S* analysis, with the Hurst exponent, was unable to determine how long the anticipated trend would continue into the future. Thus, it is important for future research to focus on extending the time span for which future forest pest dynamics can be forecasted [66].

Because long-term, regional occurrence data of pine caterpillars are rather limited in China, one of the limitations of the present study is that it only applies to a single province. Nevertheless, the present study aimed to link a theoretical analysis of the impact of drought at different time scales on the pine caterpillar outbreaks. In general, drought had a positive effect on the outbreak of pine caterpillars in Shandong Province, especially prolonged or more severe drought events [36], and drought affected the area and extent of pine caterpillars by reducing the resistance of host trees and by increasing the population dynamics of pine caterpillars [67]. This is an important step toward improving the current understanding of the impact of drought on the biology of forest pests on a global scale. Future studies should focus on the combination of field investigations and remote sensing monitoring to achieve real-time monitoring and the issuance of early warning signals. The goals of such studies would be to reduce the frequency of natural disasters and to promote the healthy growth of trees.

5. Conclusions

The present study used correlation, linear regression, and *R/S* analyses to investigate the impacts of drought on pine caterpillar outbreaks, based on SPI data for 1981–2012 and pine caterpillar occurrence data for 1992–2012. The annual SPI exhibited an increasing trend, which indicated that there was a wetting trend in Shandong Province during 1981–2012. Moreover, a significant period of drought was detected during the 1980s and 1999–2003, whereas major wet periods occurred in the mid-1990s and after 2003. The total area of the pine caterpillars exhibited a strong decrease from 1992 to 2012, with a linear decrease of -52.89 km^2/year, possibly due to the concurrent wetting trend, and the pine caterpillar infestation categories (light, moderate, and severe), which had been recorded since 1998, also exhibited downward trends. These findings suggest that drought promotes pine caterpillar outbreaks and that long-term or prolonged drought events have greater impacts than short-term drought events. In the future, a greater portion of the province's area will continue experiencing increased moisture conditions (57%) than the portion that will experience increased drought (43%), and the area of pine caterpillar outbreak is estimated to remain consistent with the current state, i.e., to decrease consistently.

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