climate

MDPI

Concept Paper

Climate Variability Shifting Immigrated Rice Planthoppers in Taiwan

Shou-Horng Huang [1], Pau-Yu Lai [1], Shaw-Yhi Hwang [2,3,4,*], Krishna Borhara [5], Wan-Ru Huang [6] and Shih-Yu Wang [5]

[1] Department of Plant Protection, Taiwan Agricultural Research Institute, Chiayi 60044, Taiwan; shhuang@tari.gov.tw (S.-H.H.); tukust94413@dns.caes.gov.tw (P.-Y.L.)
[2] Department of Entomology, National Chung Hsing University, Taichung 40227, Taiwan
[3] International Bachelor Program of Agribusiness, College of Agriculture and Natural Resources, National Chung Hsing University, Taichung 40227, Taiwan
[4] Master Program for Plant Medicine and Good Agriculture Practice, College of Agriculture and Natural Resources, National Chung Hsing University, Taichung 40227, Taiwan
[5] Department of Plants, Soils and Climate, Utah State University, Logan, UT 84322, USA; krishna.borhara@aggiemail.usu.edu (K.B.); simon.wang@usu.edu (S.-Y.W.)
[6] Department of Earth Sciences, National Taiwan Normal University, Taipei 11677, Taiwan; wrhuang@ntnu.edu.tw
* Correspondence: oleander@dragon.nchu.edu.tw

Abstract: Rice planthoppers are common insect pests in Taiwan, and they have caused significant damage in the past. The majority of rice planthoppers have seen a drastic decline in their population since the mid-2000s, a trend that has anecdotally attributed to widespread and better pest control, as well as improved rice cultivation management. By analyzing 40 years of the airborne net trap data of rice planthoppers collected in Southwest Taiwan, it was found that the pests' yearly population, computed with a logarithmic transformation, resembles a signature climate pattern in the global oceans with a robust multi-decadal variability. An ocean temperature-based index derived from the patterns of multi-decadal variability shows a marked resemblance with the population change of common rice planthoppers, with overlapping peaks during the 1990–2010 period. The climate dynamics associated with the regional weather pattern in the vicinity of Taiwan are discussed. Phase reversal of this multi-decadal climate variability in the future may produce favorable climatic conditions for the rice planthopper population to increase back to its historical levels.

Keywords: rice planthoppers; climate change; multidecadal variation; Taiwan pests

check for updates

Citation: Huang, S.-H.; Lai, P.-Y.; Hwang, S.-Y.; Borhara, K.; Huang, W.-R.; Wang, S.-Y. Climate Variability Shifting Immigrated Rice Planthoppers in Taiwan. *Climate* **2022**, *10*, 71. https://doi.org/10.3390/cli10050071

Academic Editor: Tongli Wang

Received: 30 March 2022
Accepted: 14 May 2022
Published: 19 May 2022

1. Introduction

Taiwan, a topographically diverse island located in the subtropics, is known for its high-quality rice production that is widely distributed in its western lowlands (Figure 1). Consequently, rice planthoppers have been a severe issue for as long as rice production has existed. There are three major types of rice planthoppers in Taiwan: Nilaparvata lugens (Stål), Sogatella furcifera (Horváth), and Laodelphax striatellus (Fallén), better known by their common names as brown, white-back, and small brown planthoppers, respectively. These rice planthoppers can be both local and immigrated, and they exhibit a distinct seasonality. Past research has found that rice planthoppers can migrate to Taiwan from South China, Japan, Vietnam, and the Philippines under certain weather conditions, such as typhoons [1–4]. There is also a noticeable long-term trend in that the dominant species appeared to shift from brown planthoppers to white-back planthoppers around 1995 [5]. However, more recent records show that the number increased again throughout the 2000s before decreasing after 2015 (shown later).

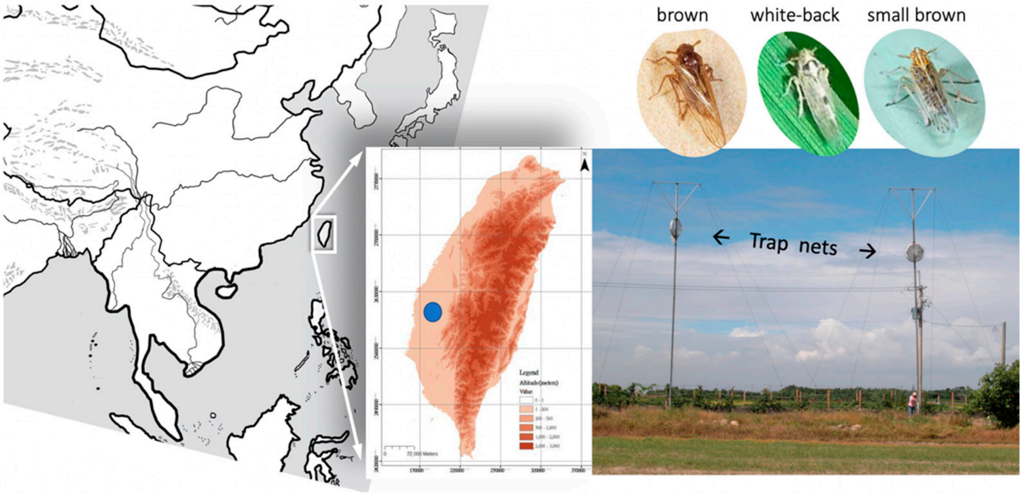

Figure 1. Map of Taiwan, its topography, and the location of the tow-net traps in Southwest Taiwan (blue dot). Pictures of the two tow-net traps and the three species of rice planthoppers are shown on the right.

One essential requirement for determining the population dynamics of pest species under climate change is having access to long-term data [6]. We recently obtained a long-term record of airborne net trap data from a fixed location in Chiayi, Taiwan (Figure 1). A tow-net traps tower of 10 m was established in 1981 and had been collecting data ever since, accumulating 40 years of consistent insect pest data with daily counts. The reason for setting up a tall tower that traps insect pests is to understand the immigrated population concerning weather conditions, such as the changes in the southwesterly monsoon flow and the northeasterly winter winds. While previous studies have analyzed the day-to-day, seasonal, and interannual variations of the trapped insect pests (e.g., [2,3]), as well as predicting the weekly or seasonal changes using statistical models [7], there has not been a systematic analysis of the impact of climate variability/change on immigrated rice planthoppers. This trap data not only provides the means for a robust analysis of the pest population dynamics but also establishes predictive models [8,9]. The predictions will be helpful in mitigating the adverse effects of climate anomalies on crop production [10].

In this study, we explored the possibility of large-scale climate variability in affecting the long-term population fluctuation and migration property of common rice planthoppers in Taiwan. This is the first study since [3] to analyze trap net pest data over the long term. The paper is arranged with an introduction to the modern climate data used in Section 2, the methodology and ensuing analysis presented in Section 3, and some concluding remarks offered in Section 4.

2. Materials and Methods

The insect data in this study was obtained from the Sikou Experimental Farm of the Chiayo Agricultural Station in Sikou Township, Chiayi Country, in Southwestern Taiwan (Figure 1). The setup consists of two tow-net traps placed at latitude 23.58° north and longitude 120.40° east. Each tow-net trap has a 1-m-diameter ring with a 1.5-m-deep tow net mounted at the top of each pole 10 m above the ground. The catch in each trap is collected every morning at 8:00 am (local time), and the species are identified according to their classification scheme and counted. The trap catch data from 1981 to 2020 were used for our analysis. The numbers from each net were averaged to form a daily count. While light trap data is also available at the site, we only analyzed the trap net data to focus on immigrated pests.

The climatic data sets used here include the "Kaplan" sea surface temperature (SST) anomalies data mapped on a 5° × 5° grid mesh [11], the European Centre for Medium-Range Weather Forecasts Reanalysis 5-th generation (ERA5) atmospheric data, including the wind field at 1° resolution [12], and the Global Historical Climatic Data (GHCN) version 3 gridded land air temperature data derived from surface stations [13].

3. Results

3.1. Pest Population Change

The long-term seasonality and year-to-year variation of each rice planthopper species are shown in Figure 2. All three species have two peaks in their population during the year, one in the summer around July and the other in the late fall and early winter. These two peaks coincide with the harvesting phase of the two cropping seasons in May to early June and mid-October to late November. The late fall peak of the pest population is more prominent. It results from the higher temperature in the early stage of rice growth during the second cropping season, with a possible increase of immigrants invading paddy fields, especially the brown rice planthoppers (Figure 2a). Consequently, the damages caused by rice planthoppers in the last season (winter) were more severe [5,7].

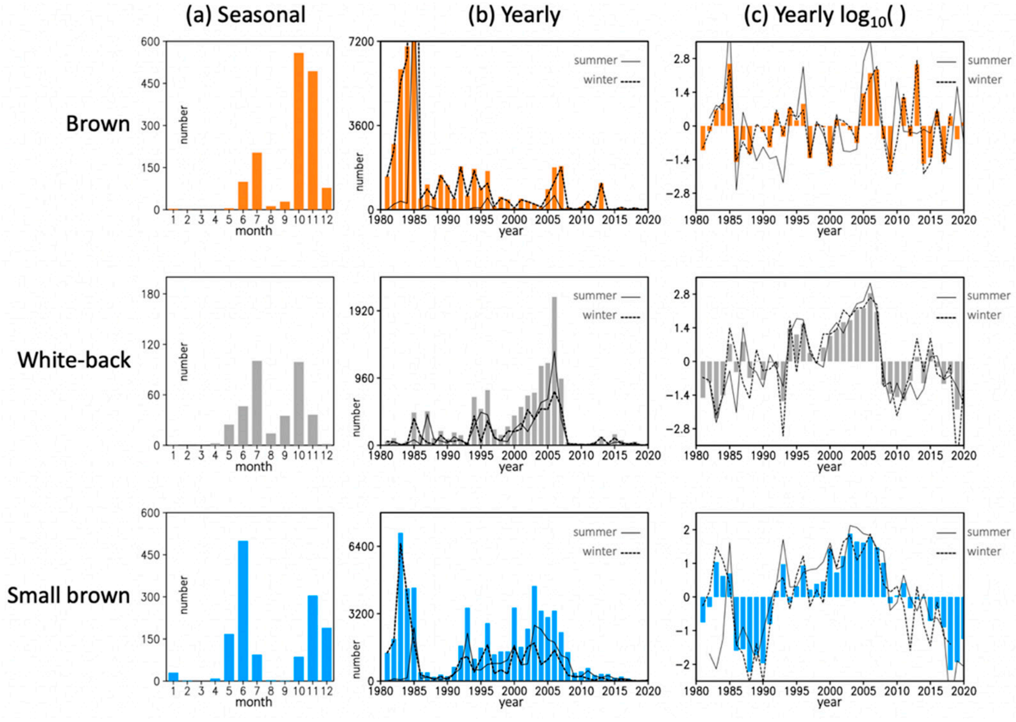

Figure 2. Numbers of pest counts for (**a**) long-term seasonal distribution, (**b**) yearly accumulations, and (**c**) same as (**b**) after the logarithmic transformation Log10 for (top to bottom) brown, white-back, and small brown rice planthoppers from the trap nets.

To investigate the effect of long-term climate variability on the evolution of the life cycle of rice planthoppers, we plot the annual counts in Figure 2b. There was a sharp increase in brown planthoppers during the early 1980s, followed by a sharp decrease and a further reduction after the late 1990s, consistent with findings from previous studies [5]. The fall harvest seasons of 1960 to the 1980s experienced a loss in the agricultural economy of over USD 9 million [14]. A similar increase in the population was observed in small brown planthoppers, although the sharp decrease was not as extreme. Afterward, all three species went through a gradual increase in population throughout the late 1990s and most of the 2000s, peaking in 2005, followed by yet another sudden reduction in 2008. The cause of this most recent decrease in pest counts is unknown.

The seasonal populations of the summer (May–August) and winter (September–December), arising during the two rice planting periods in Taiwan, are overlaid in Figure 2b as solid and dashed lines, respectively. Except for brown planthoppers, these pests exhibit a similar interannual variation with each other throughout the year, regardless of the seasons.

While treating different species of the pest as a whole population may seem unorthodox to the entomological community, it is arguably valid in terms of climate variability since the trap nets mostly catch immigrated planthoppers aided by winds.

In view of the significant contrast of pest numbers from year to year, we further plotted the logarithm (log base 10) of the pest populations and detrended the time series. This eliminates any spurious statistical signals in the regressive or correlative analysis and helps highlight the year-to-year variability that may be masked by the large numbers of certain years (since the population growth of these pests is nonlinear). As shown in Figure 2c, all species exhibit a marked interannual variability, while the brown and small brown planthoppers show a clear "multi-decadal" signal. There was an overall decrease in the population (or flattening) during the 1980s, followed by an elevated population during the 2000s, and another period again of a flattened or decreasing curve after 2010. The thin and dashed lines of different seasons in Figure 2c indicate that this multi-decadal variability is consistent throughout the year, i.e., they are intercorrelated.

We accumulated the populations of all three species into one annual, logarithmic population time series, hereafter the "Pest Index", which is shown in Figure 3a (bar). A smoother multi-decadal variation is readily visible. A slow-changing pattern like this signals the phase change of the widely reported climate "regime shift" that is either driven by or covarying with the world's oceanic variations. Well-known examples of such climate patterns include the Pacific Decadal Oscillation (e.g., [15]) and the Atlantic Multi-decadal Oscillation (e.g., [16]), both of which feature a phase reversal every few decades. Next, we derived a few oceanic indices from the SST data, and these indeed show an apparent correspondence with the Pest Index, which is explained next.

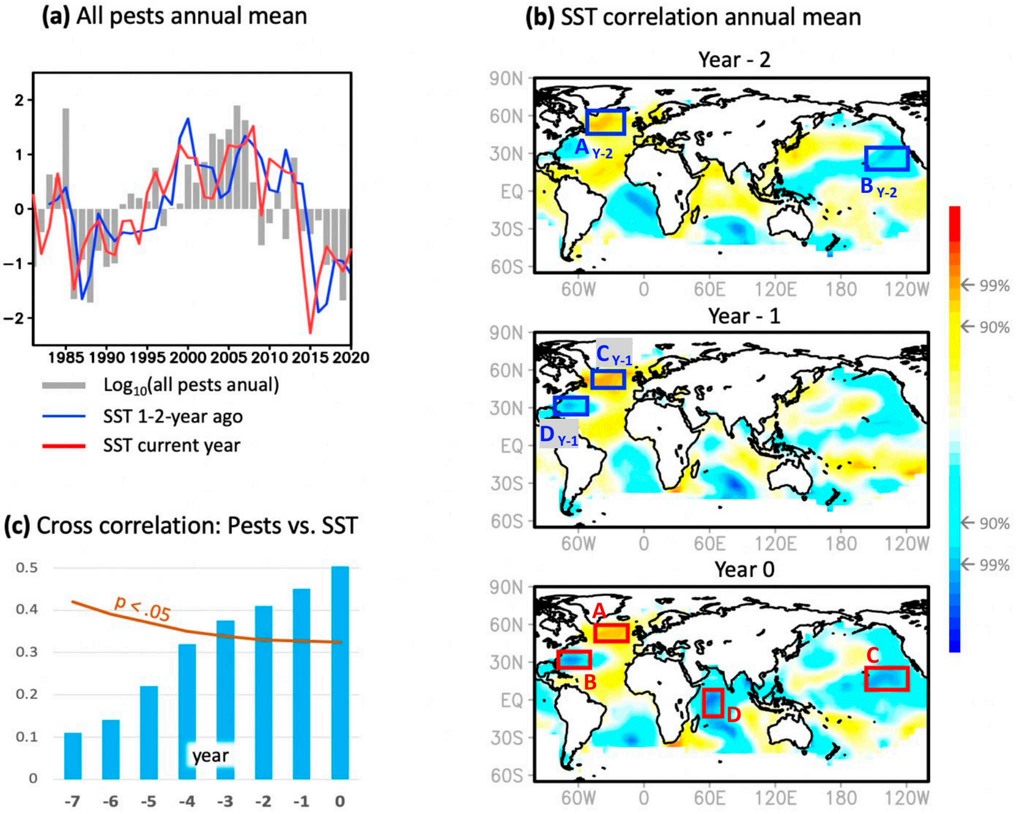

Figure 3. (**a**) Annual mean pest counts of all species from the logarithmic transformed (gray bars) superimposed with the SST indices (color lines; see text). (**b**) One-point correlation maps of the SST with the Pest Index at various time lags, as indicated at the top of each panel, where the boxes are domains used for extracting the SST values (see text), while the color bar indicates the significance levels. (**c**) Cross-correlation between the Pest Index and SST Index of various lag times in years (x-axis); red line indicates 95% confidence interval at each time lag.

3.2. Climate Variability Connection

By calculating the one-point correlation map of the SST, in which the annual mean SST at each grid point on the globe is correlated with the Pest Index, we plotted the correlation coefficients on the map as shaded contours. The bottom of Figure 3b shows the same year correlation map of the annual SST everywhere with the Pest Index, with the more significant correlation coefficients indicated by darker colors (positive correlation is red; negative correlation is blue). The areas marked by red boxes are where the significant ($p < 0.05$) correlations of the SST are found. The SST correlation patterns in the North Atlantic (Figure 3b) resemble the SST dipole associated with the prominent North Atlantic Oscillation (NAO; see Supplementary Figure S1a) that features a multi-decadal variability [17]. In the North Pacific, the SST correlation pattern resembles the well-known Pacific Decadal Oscillation (PDO; see Supplementary Figure S1b). The PDO has a predominant frequency of 20–30 years [18], similar to what we observe in the Pest Index (Figure 3a).

Next, we adopted a multivariate regression based on the four areas of significant SST signals for the Pest Index (domain given in Figure 3b "Year 0" as red boxes), to construct an "SST Index". The regression of this SST Index is shown in Equation (1), with the linear trends of the SST values removed to eliminate the climate warming signal (since we are looking at the internal variability rather than the warming trend). Referring to the annotation of the SST domains in Figure 3b, a proxy to the Pest Index can be derived with

$$\text{SST current year} = 0.347 \times (\text{A} - \text{B}) - 0.451 \times \text{C} - 0.202 \times \text{D} + 0.023 \tag{1}$$

This SST Index is plotted in Figure 3a as the red line. It has a significant correlation coefficient of 0.504 ($p < 0.01$) with the Pest Index, apparently capturing the major phase reversals during the past 40 years. Given the dominant multi-decadal variability, it is arguable that the oceanic variation is beyond the interannual scale. Therefore, the SST influences on the Pest Index should last beyond the current year.

Therefore, we further computed the multivariate regression using SST values extracted from the previous two years within the four domains, as indicated by the blue boxes (two in Year 1 and two in Year 2; Figure 3b). A new SST Index was constructed through the following equation:

$$\text{SST 1-2-year ago} = 0.435 \times (\text{A}_{\text{Y-2}} - \text{B}_{\text{Y-2}}) + 0.565 \times (\text{C}_{\text{Y-1}} - \text{D}_{\text{Y-1}}) + 0.082, \tag{2}$$

based on the areal averages, as indicated in Figure 3b. This "1 to 2 year ago" SST Index is plotted in Figure 3a as the blue line, and it also has a significant correlation coefficient with the Pest Index (0.45, $p < 0.01$). This result suggests potential predictability for the Pest Index at least one year in advance. Next, by deriving the SST time series based on Equation (2) from a different number of years in the past (Y-2, Y-3, Y-4, etc.) and computing a cross-correlation with the Pest Index (Figure 3c), it is found that the significant correlation coefficients can last for up to three years prior to the current year, with a marginally significant correlation four years ago. This result further indicates that using the historical SST anomalies can reasonably anticipate the change in the annual counts of all three rice planthopper species three years in advance.

The rice pest research community has explored statistical modeling to anticipate the pest population (e.g., [3]). One of the common approaches is the autoregressive (AR) model. To provide a baseline for the climate-driven modeling, we built an AR model using the Pest Index values of the previous three years (t-1, t-2, and t-3). The result indicates a significant autoregressive pattern at t-1 and t-2 (data shown to the reviewers), consistent with what one reviewer called the "memory effect" of the rice planthoppers in Asia. Such an autoregressive feature is expected, however, because both brown and white-backed planthoppers in the first and second cropping rice may breed themselves for three to four generations. The pest community has already used AR models to predict rice planthopper populations, so we did not investigate it further. Nevertheless, the SST-predicted result presented here adds insight as to why it worked.

The climate connection revealed in Figure 3 is intriguing because previous studies (e.g., [7]) indicated that rice planthoppers in Taiwan do not significantly correlate with local precipitation or temperature variations. This raises the question of how the SST anomalies that affect the regional climate in and around Taiwan may affect the overall population change in rice planthoppers. To address this question, we plotted in Figure 4 the similar correlation maps of 2-m air temperatures for years zero through two with the Pest Index and separated them into two seasons: summer (May–August) and winter (September–December). There were several places that showed persistent and significant correlations in the air temperature during the summer (Figure 4a), including parts of the Indochina Peninsula and the Philippines. Particularly for the Southern Philippines, cooler air temperature during the summer is persistent up to two years prior to an increase in the Pest Index. Since one of the known immigrant sources of rice planthoppers is the Luzon, and because typhoons can transport insect pests to Taiwan [3,4], it is arguable that persistently cooler summers and the fact that this time of the year is also the typhoon season contributes to the insect pests captured in Taiwan.

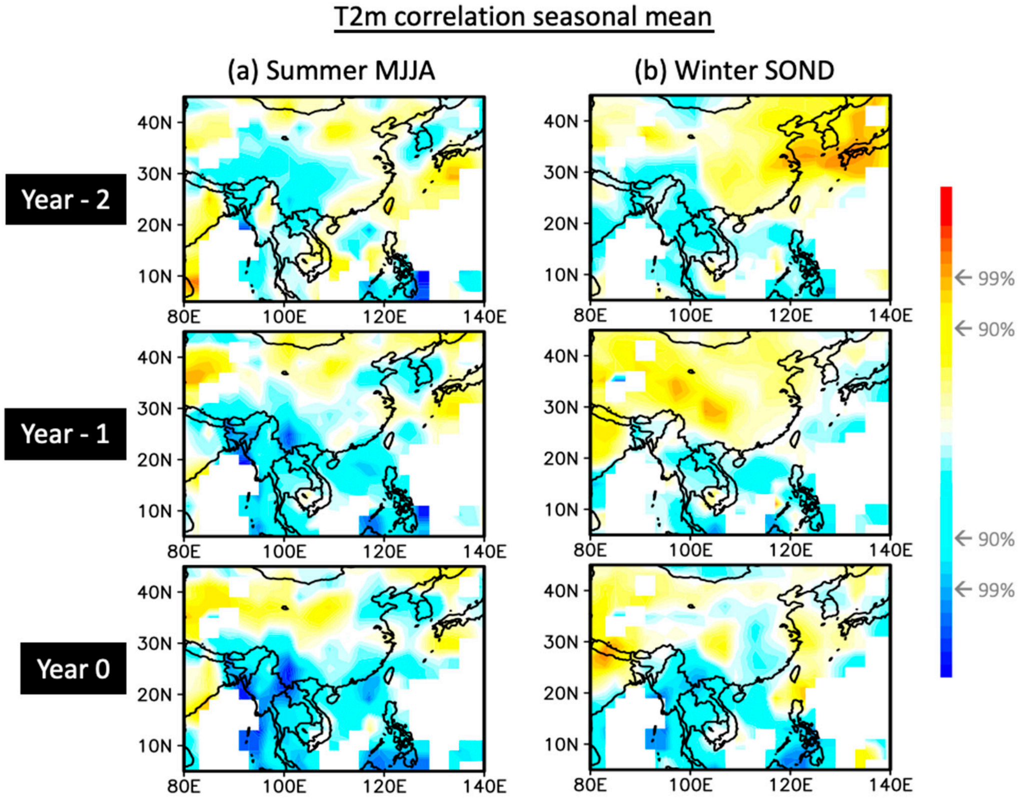

Figure 4. One-point correlation maps of the 2-m air temperature with the Pest Index for the (**a**) summer (May–August) and (**b**) winter (September–December), with the air temperature shifted from (top to down) two years ago to the current year. The color bar indicates the significance levels.

In the winter, the Indochina temperature variation during the years leading up to the current year is not as consistent as in the summer. Still, the Philippines remain cooler during the high-pest years, suggesting an enhanced monsoon system in either season [19]. There was a significant positive correlation over Southern Japan in Year 2, but its connection with Taiwan's immigrated rice planthoppers is unclear. We also observed that, in year 0 around Taiwan, the negative correlations in the summer and positive correlations in the winter seemed to suggest that milder seasons (not so hot of summer plus not so cold of a winter combined) may contribute to increases in rice planthoppers. Even though the correlations are only marginally significant, this observation echoes previous findings by [20] that milder summers and winters can promote the growth of rice pests. Only with summer air temperatures greater than 40 °C would they harm the development of rice planthoppers, predominantly brown planthoppers.

To examine the role of transportation by the wind field for the possibility of emigrated rice planthoppers, we conducted a regression analysis of the Pest Index with 925-hPa winds (around 600 m above the sea level). We displayed the regressed wind pattern in Figure 5, computed from the zonal/u-wind and meridional/v-wind regressed with the Pest Index. We only show the same year regression maps for the wind vectors for brevity. The southerly wind anomalies around Taiwan in the summer (Figure 5a) suggest that the prevailing winds, which correspond to the southwesterly monsoon flows, are generally more substantial when the Pest Index increases. Since the regression is linear, it also means that the summers with fewer rice planthoppers are characterized by a northerly wind anomaly or a weaker monsoonal flow. This result echoes the previous finding [2,3] that insect pests can be transported from the Philippines by riding enhanced southerly winds, as indicated by the schematic drawing of the near-surface winds in Taiwan (bottom of Figure 5a).

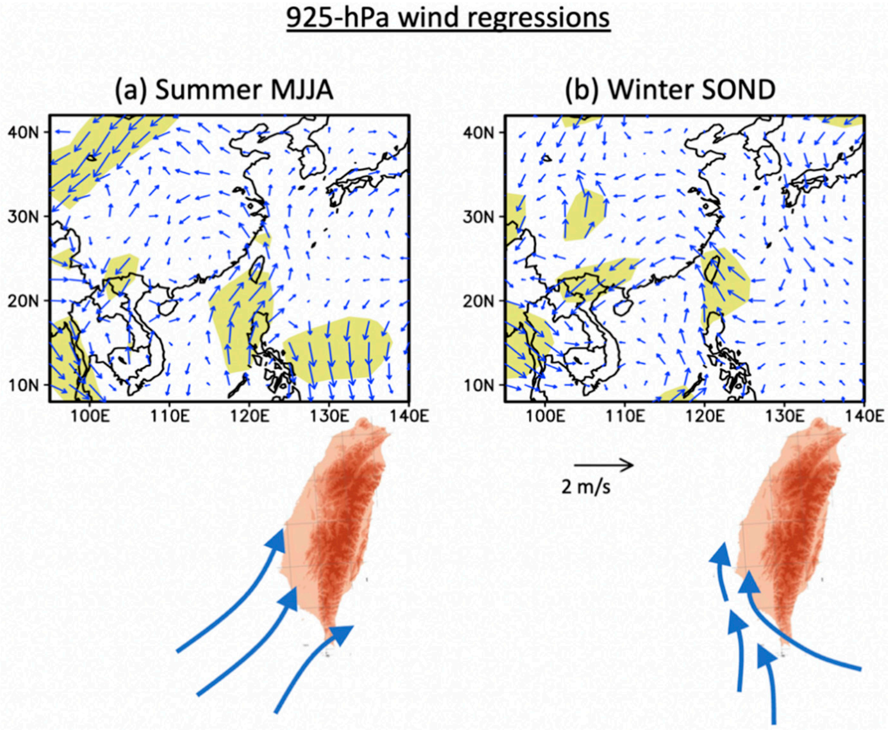

Figure 5. Same-year 925-hPa wind anomalies (vectors) regressed with the Pest Index for the (**a**) summer and (**b**) winter seasons, while the shading indicates significant regression coefficients of the wind speed. Schematic illustrations of the wind pattern near Southern Taiwan are shown in the bottom maps.

In the winter, the regression pattern reveals a southeasterly wind anomaly in Southern Taiwan (Figure 5b). This pattern is characteristic of a cold air outbreak with the anticyclonic (clockwise) rotation of cooler near-surface winds. A paired cyclonic (counterclockwise) rotation of the air mass over the South China Sea associated with this cooler air mass forms southerly winds from the Philippines as well. These two anomalous circulations produce a confluence of low-level winds near Southern Taiwan (bottom of Figure 5b), suggesting a possible transport of insect pests from the Philippines. The statistical association between the Pest Index and the wind pattern, as shown in Figure 5, implies the possibility of immigrants that is modulated by the large-scale, low-frequency climate variations controlled by the hemispheric SST variations. Recent research [21] has observed a marked multi-decadal variation in Taiwan's climate anomalies and its close association with the global SST patterns. The authors of [22] also found tree ring evidence of the PDO's long-term effect on Taiwan spruce height growth.

4. Discussion

4.1. Climate Dynamics

By examining 40 years of the trap net data for brown, white-back, and small brown planthoppers collected in Southwestern Taiwan, we found the year-to-year variation in the annual accumulation of rice planthoppers (after the logarithmic transform) exhibits a marked multi-decadal variability. Moreover, this multi-decadal variability of rice planthoppers can be "mimicked" by the multivariate time series of SST anomalies derived from different parts of the world. The SST anomalies suggest the constructive phases of low-frequency NAO and the PDO, two well-known large-scale climate variability modes. Indeed, the temporal correlations of the SST Index with the NAO and PDO are 0.56 and 0.48, respectively ($p < 0.01$). The highly significant correlation between the Pest Index and the SST Index (Figure 3a) may not be a coincidence because the regional climate anomalies show corresponding changes, including the enhanced southerly winds that imply an increase in the emigrated insect pests. The climate linkage inferred here is twofold: Ref. [23] reported that Taiwan experienced a "summer regime shift" during the 1950s (see their Figure 7). The SST variation associated with the "summer regime shift" reveals a PDO signal that explains domain "C", and an Indian Ocean response that echoes domain "D" in Figure 3b's SST pattern [23] concluded that the "corresponding change in mean sea level pressure was characterized by the rising pressure in continental East Asia and the Philippine Sea, and the falling pressure over the extratropical western North Pacific (which reflects) a weakening thermal low in continental East Asia". This pattern coincides with Figures 4 and 5, even though the time period analyzed in [23] was outside our study period (before 1980). Thus, the consistent patterns of the SST and atmospheric circulation lend support to the large-scale climate driver of Taiwan's Pest Index.

Regarding the NAO connection on the inter-decadal variation in Taiwan, ref. [24] proposed that the "teleconnection pattern associated with the NAO suggests that the Siberian high, the ridge upstream of Lake Baikal and the East Asian trough . . . favorable for cold surge occurrences, were enhanced in the negative NAO phase". Ref. [24] further noted the teleconnection process in which "the suppressed upper-level convergence in the Mediterranean-Sahara region (forces) a wave train emanating toward East Asia along the subtropical jet stream, which acts as a Rossby waveguide". The teleconnection pattern associated with the NAO (negative phase) across the Atlantic and the Eurasian continents strengthens the Siberian high that controls Taiwan's winter monsoon, for these circulation characteristics favor the occurrence of cold surges. Concurrently, the southern node of the NAO (corresponding to domain "B" in Figure 3b) can trigger an atmospheric wave train along the subtropical jet stream and lead to a northerly anomaly over subtropical East Asia; this pattern echoes what we showed in Figure 5b with a phase reversal (positive NAO).

4.2. Implication on Insect Pests

The rice brown planthopper is the most destructive rice insect pest species in Taiwan, capable of severe infestation. Since 1978, many researchers have also found that these two planthoppers can migrate to Taiwan under appropriate weather conditions [2,25]. Future research is needed to provide details about the percent of change in the rice planthopper population that is local versus that from immigration, a challenging task.

Regardless of the local processes of either climatic or entomological origin, Figure 3a implies a potential change in the future climate conditions that may increase rice planthoppers in Taiwan. This implication is illustrated in Figure 6, which follows the red line and the Pest Index in Figure 3a. Still, it shows a long SST record using the entire length of the Kaplan SST data starting from 1856, which was detrended and normalized from the multivariate regression of the SST domains in Figure 3b (year 0). The SST Index reveals periods of a positive phase and periods of a negative phase alternating at a random pace, with a tendency for each phase to last over several years. The SST index represents the compound influences of the NAO and PDO (Supplementary Figure S1), meaning that they oscillate without the impact of anthropogenic global warming. Previous research [14,26] mentioned that brown and white-back rice planthoppers caused "sporadic damages" before 1960 and then became a dominant cause of the severe infestation, accompanied by an emigrated population from "south of 19° N" [27–30]. From the SST Index in Figure 6, one can see such a tendency as described in the literature with multiple years of positive phases between 1947 and 1982, even without the data of the Pest Index. Even though the most recent "climate shifts" associated with the decadal climate oscillation may be affected by anthropogenic warming to certain degrees [31], it is prudent to assume that the next phase of favorable climatic conditions for rice planthoppers may return.

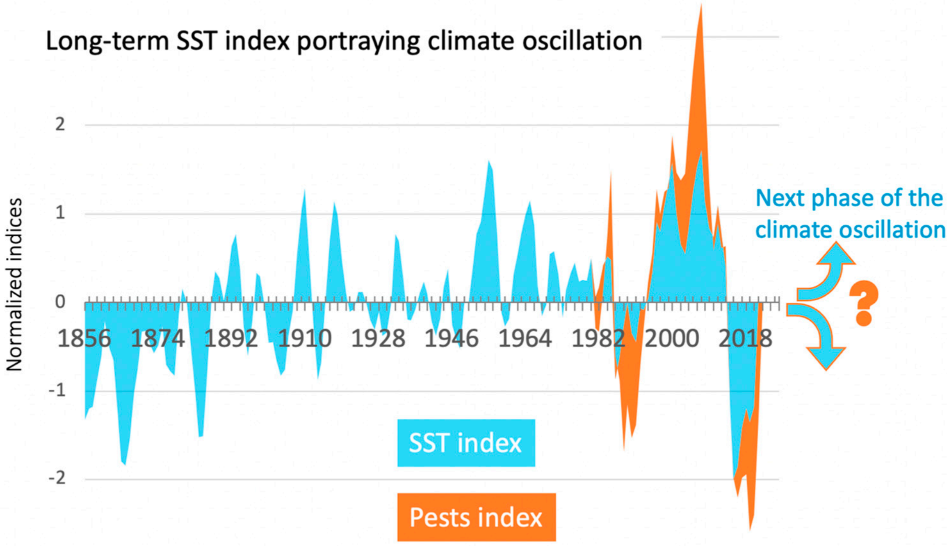

Figure 6. Long-term SST Index derived from the Kaplan SST data indicating the oceanic climate oscillation in blue overlaid with the Pest Index (annual mean all species rice planthoppers) in orange. The arrows on the right illustrate possible phase reversal of the natural climate variability in the future and how the Pest Index may change correspondingly.

Facing the projected increase in rice planthoppers, an effective pest control strategy to increase mortality and reduce reproduction [32] becomes paramount. Since rice planthoppers are typical "R-type insect" pests with high fecundity and short generation times, synthetic chemicals and a resistant variety work well to suppress them. Meanwhile, it is also important to develop new pesticides with a novel action mode for controlling R-type pest populations. Some research showed that the application of neonicotinoid insecticides could control the pests and induce the plant defense materials, such as salicylic acid, which enhances plant tolerance ability to biotic and abiotic stress [33–35]. Furthermore, ongoing efforts in breeding resilient varieties to minimize the impact of climate change conditions have shown success [34]. It will be crucial to increase the host plant resistance for pest control under climate change by modifying the resistant genes [36]. Moreover, farmers can also adopt integrated pest management, such as crop rotation and diversification, lowering the planting density, fertilizer applications, and habitat management on the edges of paddy fields to promote natural enemy numbers. Such management can build a higher level of resilience into agricultural production by reducing pest outbreaks [3,10,37].

5. Conclusions

Given the oscillatory nature of the SST Index and the natural variability it implies, one can anticipate a phase reversal from its recent negative phase to positive soon. From the climate perspective, the reversal of the SST Index towards the next positive phase is not a question of if but when, which is a question for climate prediction. When the

SST Index changes its phase, the Pest Index can arguably also increase by following the pronounced association that has existed during the past 40 years. The next question is whether the current pest control and rice cropping practices are ready to adapt to this likelihood of increased pests. Since the rice planthoppers analyzed here are typical r-type and semiaquatic insect pests, reducing the microclimatic moisture through the adjustment of cultural practices, such as lowering the planting density, lowering fertilizer applications, and adopting the alternation of shallow flooding and dryness water management, could be used to slow down the rice planthoppers' population growth. Other integrated control methods include combining the planthopper-resistant varieties, biological control, and the insecticide as needed for curbing the pest population to under acceptable levels. Past research has developed prediction models based on the development, incidence, and population dynamics of insect pests during climate change and identified ecological hotspots and pest risk areas for the future [10,38,39]. Therefore, the successive monitoring of the species and population changes should continue to be the priority for pest management.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/cli10050071/s1: Figure S1: Patterns of the SST anomalies for (a) the NAO and (b) the PDO obtained online from the National Oceanic and Atmospheric Administration (source: NOAA). As mentioned in the text, black circles indicate the SST domains of interest for deriving the SST Index.

Author Contributions: Conceptualization, S.-Y.W. and S.-Y.H.; methodology, S.-H.H. and S.-Y.W.; validation, P.-Y.L., W.-R.H. and K.B.; formal analysis, S.-H.H. and S.-Y.W.; writing—original draft preparation, S.-Y.W.; writing—review and editing, S.-H.H., W.-R.H., K.B. and S.-Y.W.; visualization, S.-Y.W.; funding acquisition, S.-Y.H. and S.-H.H. All authors have read and agreed to the published version of the manuscript.

Funding: WRH was supported by the Ministry of Science and Technology (MOST), Taiwan, under grant MOST 110–2111–M–003–003.

Data Availability Statement: Not applicable.

Acknowledgments: Scientific computational software GrADS was used.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Liu, C.C.; Cheng, C.H.; Chen, C.C.; Wang, S.S.; Chu, Y.I. Immigrations of planthoppers from oversea to Taiwan in 1987. *Chin. J. Entomol.* **1989**, *9*, 1–11.
2. Cheng, C.H. Studies on population dynamics and forecasting of population abundance of brown planthopper, Nilaparvata lugens in Chia-nan area. *Chin. J. Entomol.* **1990**, *10*, 1–25.
3. Huang, S.H.; Cheng, C.H.; Chen, C.N.; Wu, W.J.; Otuka, A. Estimating the immigration source of rice planthoppers, Nilaparvata lugens (Stål) and Sogatella furcifera (Horváth) (Homoptera: Delphacidae), in Taiwan. *Appl. Entomol. Zool.* **2010**, *45*, 521–531. [CrossRef]
4. Huang, S.H.; Cheng, C.H.; Chen, C.N.; Wu, W.J. The trend of occurrence and present status of brown planthopper and white-backed planthopper in Taiwan. In Proceedings of the International Workshop on Forecasting and Management of Rice Planthoppers in East Asia: Their Ecology and Genetics, Kumamoto, Japan, 4–5 December 2007; pp. 27–35.
5. Otuka, A.; Huang, S.H.; Sanada-Morimura, S.; Matsumura, M. Migration analysis of Nilaparvata lugens (Hemiptera: Delphacidae) from the Philippines to Taiwan under typhoon-induced windy conditions. *Appl. Entomol. Zool.* **2012**, *47*, 263–271. [CrossRef]
6. Yamamura, K.; Yokozawa, M.; Nishimori, M.; Ueda, Y.; Yokosuka, T. How to analyze long-term insect population dynamics under climate change: 50-year data of three insect pests in paddy fields. *Popul. Ecol.* **2006**, *48*, 31–48. [CrossRef]
7. Cheng, C.H.; Lu, J.L. Detection of the transoceanic immigration of rice planthoppers, Nilaparvata lugens Stål and Sogatella furcifera Horváth to the southwestern Taiwan and their relative weather-conditions. *Chin. J. Entomol.* **1990**, *10*, 301–324.
8. Sutherst, R.W.; Constable, F.; Finlay, K.J.; Harrington, R.; Luck, J.; Zalucki, M.P. Adapting to crop pest and pathogen risks under a changing climate. *Wiley Interdiscip. Rev. Clim. Chang.* **2011**, *2*, 220–237. [CrossRef]
9. Nguyen, C.; Bahar, M.H.; Baker, G.; Andrew, N.R. Thermal tolerance limits of diamondback moth in ramping and plunging assays. *PLoS ONE* **2014**, *9*, e87535.
10. Sharma, H.C.; Prabhakar, C. Impact of climate change on pest management and food security. In *Integrated Pest Management: Current Concepts and Ecological Perspective*; Abrol, D.P., Ed.; Academic Press: San Diego, CA, USA, 2014; pp. 23–36.

11. Kaplan, A.; Cane, M.; Kushnir, Y.; Clement, A.; Blumenthal, M.; Rajagopalan, B. Analyses of global sea surface temperature 1856–1991. *J. Geophys. Res.* **1998**, *103*, 18567–18589. [CrossRef]
12. Hersbach, H.; Bell, B. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **2020**, *146*, 1999–2049. [CrossRef]
13. Jones, P.D.; Moberg, A. Hemispheric and Largescale Surface Air Temperature Variations: An extensive Revision and an Update to 2001. *J. Clim.* **2003**, *16*, 206–223. [CrossRef]
14. Cheng, C.H. The occurrence and control of the rice brown planthopper (Nilaparvata lugens Stål) in Taiwan. In *Brown Planthopper*; Indonesian Institute of Science: Bali, Indonesia, 1978; pp. 103–133.
15. Newman, M.; Alexander, M.A.; Ault, T.R.; Cobb, K.M.; Deser, C.; Di Lorenzo, E.; Mantua, N.J.; Miller, A.J.; Minobe, S.; Nakamura, H.; et al. The Pacific decadal oscillation, revisited. *J. Clim.* **2016**, *29*, 4399–4427. [CrossRef]
16. Knight, J.R.; Folland, C.K.; Scaife, A.A. Climate impacts of the Atlantic multidecadal oscillation. *Geophys. Res. Lett.* **2006**, *33*, 747. [CrossRef]
17. Weisheimer, A.; Schaller, N.; O'Reilly, C.; MacLeod, D.A.; Palmer, T. Atmospheric seasonal forecasts of the twentieth century: Multi-decadal variability in predictive skill of the winter North Atlantic Oscillation (NAO) and their potential value for extreme event attribution. *Q. J. R. Meteorol. Soc.* **2017**, *143*, 917–926. [CrossRef] [PubMed]
18. McCabe, G.J.; Palecki, M.A.; Betancourt, J.L. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 4136–4141. [CrossRef]
19. Wu, C.H.; Tsai, P.C.; Huang, W.R.; Wang, S.Y. Winter–summer contrast of the 1990s decadal change in relation to Afro–Asian monsoons. *Clim. Dyn.* **2022**. [CrossRef]
20. Kanoppaiah, V.; Sujayanad, G.K. Impact of climate change on population dynamics of insect pests. *World J. Agric. Sci.* **2012**, *8*, 240–246.
21. Huang, W.-R.; Wang, S.-Y.; Guan, B. Decadal fluctuations in the western Pacific recorded by long precipitation records in Taiwan. *Clim. Dyn.* **2017**, *50*, 1597–1608. [CrossRef]
22. Guan, B.T.; Wright, W.; Chung, C.-H.; Chang, S.-T. ENSO and PDO strongly influence Taiwan spruce height growth. *For. Ecol. Manag.* **2012**, *267*, 50–57. [CrossRef]
23. Lo, T.T.; Hsu, H.H. The early 1950s regime shift in temperature in Taiwan and East Asia. *Clim. Dyn.* **2008**, *31*, 449–461. [CrossRef]
24. Hong, C.-C.; Hsu, H.-H.; Chia, H.-H.; Wu, C.-Y. Decadal relationship between the North Atlantic Oscillation and cold surge frequency in Taiwan. *Geophys. Res. Lett.* **2008**, *35*, L24707. [CrossRef]
25. Liu, C.H. Analysis on the major factors causing the eruptive occurrence of the brown planthopper in Taiwan. *Chin. J. Entomol.* **1988**, *8*, 119–130.
26. Cheng, C.H. Studies on integrated control of brown planthopper, Nilaparvata lugens (Stål) in Taiwan. In *Ecology and Control of the Brown Planthopper*; Plant Protection Center: Taichung, Taiwan, 1984; pp. 149–167.
27. Otuka, A.; Dudhia, J.; Watanabe, T.; Furuno, A. A new trajectory analysis method for migratory planthoppers, Sogatella furcifera (Horváth) (Homoptera: Delphacidae) and Nilaparvata lugens (Stål), using an advanced weather forecast model. *Agric. For. Entomol.* **2005**, *7*, 1–9. [CrossRef]
28. Otuka, A.; Matsumura, M.; Watanabe, T.; Dihn, T.V. A migration analysis for rice planthoppers, Sogatella furcifera (Horváth) and Nilaparvata lugens (Stål) (Homoptera: Delphacidae), emigrating from northern Vietnam from April to May. *Appl. Entomol. Zool.* **2008**, *43*, 527–534. [CrossRef]
29. Sogawa, K.; Watanabe, T.; Tsurumachi, M. Emigration areas and meteorological factors inducing overseas migration of the brown planthopper. *Proc. Assoc. Pl. Prot. Kyushu* **1988**, *34*, 79–82. [CrossRef]
30. Sogawa, K. The monsoon-dependent migration of rice planthoppers in east Asia. In *Migration and Management of Insect Pests of Rice in Monsoon Asia*; China National Rice Research Institute: Hangzhou, China, 1997; pp. 217–230.
31. Zanchettin, D.; Gaetan, C.; Arisido, W.M.; Modali, K.; Toniazzo, T.; Keenlyside, N.; Rubino, A. Structural decomposition of decadal climate prediction errors: A Bayesian approach. *Sci. Rep.* **2017**, *7*, 12862. [CrossRef]
32. Stenseth, N.C. How to control pest species: Application of models from the theory of island biogeography in formulating pest control strategies. *J. Appl. Ecol.* **1981**, *18*, 773–794. [CrossRef]
33. Horii, A.; McCue, P.; Shetty, K. Enhancement of seed vigour following insecticide and phenolic elicitor treatment. *Biores. Tech.* **2007**, *98*, 623–632. [CrossRef]
34. Fand, B.B.; Kanble, A.L.; Kumar, M. Will climate change pose serious threat to crop pest management: A critical review. *Int. J. Sci. Res. Publ.* **2012**, *2*, 1–14.
35. Ford, K.A.; Casida, J.E.; Chandranb, D. Neonicotinoid insecticides induce salicylate associated plant defense responses. *Proc. Natl. Acad. Sci. USA* **2010**, *10*, 17527–17532. [CrossRef]
36. Kuang, Y.H.; Fang, Y.F.; Lin, S.C.; Tsai, S.F.; Yang, Z.W.; Li, C.P.; Huang, S.H.; Hechanova, S.L.; Jena, K.K.; Chuang, W.P. The impact of climate change on the resistance of rice near-isogenic lines with resistance genes against brown planthopper. *Rice* **2021**, *14*, 64. [CrossRef] [PubMed]
37. Andrew, N.R.; Hill, S.J. Effect of climate change on insect pest management. In *Environmental Pest Management: Challenges for Agronomists, Ecologists, Economists and Policymakers*; Coll, M., Wajnberg, E., Eds.; John Wiley & Sons: Hoboken, NJ, USA, 2017; pp. 197–223.

38. Sharma, H.C.; Srivastava, C.P.; Durairaj, C.; Gowda, C.L.L. Pest management in grain legumes and climate change. In *Climate Change and Management of Cool Season Grain Legume Crops*; Yadav, S.S., McNeil, D.L., Redden, R., Patil, S.A., Eds.; Springer Science and Business Media: Dordrecht, The Netherlands, 2010; pp. 115–140.
39. Yadav, D.S.; Subhash, C.; Selvraj, K. Agroecological zoning of brown plant hopper, (*Nilaparvata lugens* (Stal.)) incidence on rice (*Oryza sativa* (L.)). *J. Sci. Ind. Res.* **2010**, *69*, 818–822.