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STATISTICAL ANALYSIS ON THE INFLUENCE OF THE LANDFALLING STRONG TROPICAL CYCLONES IN THE CATASTROPHIC MIGRATIONS OF NILAPARVATA LUGENS (STÅL) IN CHINA

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Abstract: In order to clarify the statistical pattern by which landfalling strong tropical cyclones (LSTCs) influenced the catastrophic migrations of rice brown planthopper (BPH), *Nilaparvata lugens* (*stål*) in China, the data of the LSTCs in China and the lighting catches of BPH that covered the main Chinese rice-growing regions from 1979 to 2008 were collected and analyzed in this work with the assistance of ArcGIS9.3, a software of geographic information system. The results were as follows: (1) In China, there were 220 strong tropical cyclones that passed the main rice-growing regions and 466 great events of BPH's immigration in the 30 years from 1979 to 2008. 73 of them resulted in the occurrence of BPH's catastrphic migration (CM) events directly and 147 of them produced indirect effect on the migrations. (2) The number of the LSTCs was variable in different years during 1979 to 2008 and their influence was not the same in the BPH's northward and southward migrations in the years. In the 30 years, the LSTCs brought more obvious influence on the migrations in 1980, 1981, 2005, 2006 and 2007. The influence was the most obvious in 2007 and all of the 7 LSTCs produced remarkable impact on the CMs of BPH's populations. The effect of the LSTCs on the northward immigration of BPH's populations was the most serious in 2006 and the influence on the southward immigration was the most remarkable in 2005. (3) In these years, the most of LSTCs occurred in July, August and September and great events of BPH's immigration occurred most frequently in the same months. The LSTCs played a more important role on the CM of BPH's populations in the three months than in other months. (4) The analysis on the spatial distribution of the LSTCs and BPH's immigration events for the different provinces showed that the BPH's migrations in the main rice-growing regions of the Southeastern China were influenced by the LSTCs and the impact was different with the change of their spatial probability distribution during their passages. The most serious influence of the LSTCs on the BPH's migrations occurred in Guangdong and Fujian provinces. (5)The statistical results indicated that a suitable insect source is an indispensable condition of the CMs of BPH when a LSTC influenced a rice-growing region.

Key words: Nilaparvata lugens (stål); catastrphic immigration; landfalling strong tropical cyclone; statistical characteristics; spatial analysis

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1 INTRODUCTION

There are three planthoppers that harm rice in China: Nilaparvata lugens, white backed planthopper and small brown planthopper, having the heaviest occurrence and harm of brown planthopper (BPH). Especially in the last ten years, in the Yangtze river basin and the southern provinces, because of changes in cultivation system, promotion of breeds with good harvest and resistance to fecundity, and increase of fertilization level, BPH once ran rampant frequently and continuously, and became the main pests of rice

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cultivation in South China[1, 2]. In China, N. lugens survive and become harmful in the tropical regions of the southern Guangdong and southern Guangxi, southern Yunnan and Hainan Island during every winter[3]. In the interim period from spring to summer, BPH's populations migrate northward continually, land and damage in succession in South China, Southwest China, the region between the Nanling Mountain and the Yangtze River, the region between the Yangtze River and Huaihe River[4]. At the end of summer and the beginning of autumn, the migrations proceed backward till the end of October or early November, during which the pests endanger the valleys along the Yangtze River, the rice-growing regions between the Nanling Mountain and the Yangtze River, South China, and Southwest China successively. With proper physiological and weather conditions, populations of N. lugens are increasing sharply in an area during a short time, and a catastrophic immigration of N.lugens is then defined to take place. Low-level jet streams, high pressure, low pressure, troughs, ridges, shears, convergence zones, the frontal surface of westerlies and the subtropical high pressure, and the tropical cyclones (TCs) of the easterly zone are the main weather systems influencing the migrations of N. lugens[5].

The warm center of a strong cyclonic vortex occurs in the tropical ocean is always accompanied by a violent storm that often causes serious disaster to the affected areas. We call it a severe tropical cyclone (STC)[6]. In this work, STC is defined as a tropical cyclone that situates west of 180°E, the wind force is more than Grade 8 on the Beaufort scale or the wind speed is larger than 17.2 m s^{-1}. It includes tropical storm, severe tropical storm, typhoon, severe typhoon and super typhoon. Located on the west coast of the Northwest Pacific, China is in an area of most active tropical cyclones in the world; there are often more than 20 even 40 STCs in a year, and in some years there are 12 STCs that landed in China. According to the statistics of the TCs, between 1970 and 2001, there were 863 TCs in the West Pacific with the average yearly number at 27. Among them, there were 256 TCs (341 times of occurrence) that landed in China during the 32 years and a yearly average of 8 STCs (11 times of occurrence) that landed in China, accounting for 30% (40%) in the total engendering TCs[7]. The atmospheric dynamic mechanisms of a landfalling STC influencing the catastrophic migrations (CMs) of BPH are as follows: It carries the insects in the air currents to transfer the populations in the horizontal streams, while the precipitation and sinking airflows are favorable for the N. lugens and BPH to land.

Based on the light-trap and air-trap data of brown planthopper from June 1 to October 31 in the area of Chikugo in Japan in 1987, 1988, 1989 and 1990, Sogawa[8] made an analysis and found that there were 21 catch peaks after the end of Meiyu rain period at the end of August and further study showed that 7 catch peaks were influenced by typhoons[5, 8]. Huo et al. studied the destruction by Chinese rice planthopper caused by climate condition, and found that there were three teams of rice planthoppers flying to China from foreign countries, one of them from the Philippines and the periphery TCs[9]. Yao et al. analyzed the effects of Typhoon Kanu (2005) on the sudden increase of Nilaparvata lugens, and mainly studied the effects of typhoons (airflow, temperature and precipitation) on the BPH takeoff, migration, and landing among other characteristics, and concluded that the influence of strong convergence airflow, heavy rains and shears are conducive to the landing of BPH, and temperatures of 17 to 20℃ help the BPH moved to fly[10]. Wang et al.[11] analyzed the effects of the flow field of typhoon Haitang on the northward migration route of rice BPH and found that the typhoon, which landed in China, resulted in different areas of landing by the BPH during different stages of the storm. During the active period of Haitang, BPH mainly landed near the shear line on the 850 hPa isobaric surface. With the decline of the typhoon, BPH mainly landed in the warm shear zone in the southeast of typhoon. After the landing, a southwest airflow was established again and caused a lot of BPH to move north[9]. The study over previous years also found that in some years although the typhoon is an important factor of BPH outbreak, it is not the only factor[11].

The research on the influence of the landfalling STCs on the CMs of *Nilaparvata lugens* (*stål*) has been rare both at home and abroad. Based on ArcGIS 9.3, a geographic information system software, and with the help of a collection of the observed data of the BPH and landfalling STCs in China from 1979 to 2008, this work conducts a statistical analysis on the spatial and temporal relationship between them and revealed the characteristics of the landfalling STCs in the CMs of *Nilaparvata lugens* (*stål*), with the aim for guidance in the forecasting and early warning of BPH's catastrophes.

2 DATA AND METHODS

2.1 *Data*

The daily BPH's light-trap data of 105 plant protection stations from 1979 to 2008 was provided by the National Agricultural Technical Extension and Service Center of Ministry of Agriculture in China.

The STC data from 1979 to 2008 was from the National Meteorological Information Center in China.

The basic map-layers were from the Chinese electronic map with the proportional scale of 1:4,000,000 and it was provided by the National

Geomatics Center of China.

2.2 *Methods of statistical calculations*

The statistical calculation method for typical migrations of BPH was as follows. The daily light-trap data of each plant protection station from 1979 to 2008 was processed and tabulated in Excel of Microsoft Office. When the light-trap number was 500 or more at two or more stations in one day or the light-trap heads of each day in a serial of days hit 500 or more at two or more stations in a rice-growing region, it could be calculated as a typical immigration event. In this way, the annual typical immigration events from 1979-2008 and the total typical immigration events for the 30 years were counted. Besides, the migrations from March to August were named as the northward migrations while those from September to October as the southward migrations. Whether the immigration at the end of August and the beginning of September was the northward migration or the southward migration could be judged by the direction of the airflow. Then the number of both migrations can be calculated statistically.

With the analysis on the relationship between the BPH's lighting catches and the landfalling STCs that passed or influenced different rice-growing regions in China, it was found that the influence varies with the strength of the storm. When the wind force is less than Grade 8 on the Beaufort scale or the wind speed is less than 17.2 m s^{-1}, the effect on the migrations of BPH's populations is small and there are small immigrating BPH's heads. Most of BPH's migrations are not typical; they do not fall into the above standard of great migration events and have no obvious meaning for the early warning of BPH's catastrophes. However, When TCs' wind force is higher than Grade 8 or its wind speed is larger than 17.2 m s^{-1}, they have great influence on the migrations of BPH's populations, the degree of the influence is high and sets off large immigrating outbreaks of BPHs. Most of BPH's migrations have remarkable values for the early warning of BPH's catastrophes. Consequently, the TC landfalls in China are divided into the two types, one being the STC with the wind force higher than Grade 8 or the wind speed larger than 17.2 m s^{-1} and the other being the weak TC with the wind force less than Grade 8 or the wind speed less than 17.2 m s^{-1}. In this work, the weak TC was not considered. Our statistical calculation method was to count the number of the landfalling STCs for each of the months in the 30 years, the numbers of the landfalling STCs during the northward migration from March to August and the southward migrations from September to November, the number of the landfalling STCs in each year, and the total amount of the landfalling STCs in the 30 years, etc. by collecting the time, place, route and the lasting time of the STC in China from 1979 to 2008.

2.3 *Methods for analyzing the relationship between the landfalling STCs and BPH's migrations*

The time series used for analysis consists of the interannual, seasonal and short-term changes. The annual variation was analyzed from two aspects: one is the correspondence between the landfalling STCs and the catastrophic migrations of BPH, and the other is the relationship between the landfalling STCs and the northward or southward migrations, in the past 30 years. For the seasonal change, the influence was light in April and November, moderate in May, June and October, and heavy in July, August and September, and the correspondence of the landfalling STCs to the catastrophic migrations of BPH's populations in every season was analyzed. For the short-term change, the focus is on the relationship and coincidence timing between each of the typical migrations of BPH and the associated landfalling STC every year.

The spatial variation is analyzed as follows. Firstly, based on the correspondence of the date to the lasting time of landfalling STCs and the migrations, the coincidence of each station was analyzed in Excel. Secondly, the migration events recorded at each of the stations of the influence by the landfalling STC in the 30 years were counted in terms of the coincidence date and the immigration peaks before and after the landfalling STC (under the premise of confirmed influence brought by the STC). If there were two or more stations for the same immigration in one province, it was taken as one incident. Then a few stations in every province influenced by the STC was selected and evaluated and these stations could represent the BPH's migrations into the province. Finally, the probability of correspondence between the landfalling STC and the immigration of BPH's populations was calculated. Put these data into ArcGIS 9.3 and draw the spatial distribution of the BPH's immigrating probability as influenced by the landfalling STCs by using the spline method in GIS.

3 RESULTS AND ANALYSIS

3.1 *Temporal variation*

3.3.1 INTERANNUAL CHANGES

BPH which has piercing-sucking mouthpart and only eats rice belongs to homoptera plant hopper families, and it is a typical snorting vascular bundle liquid insect. BPH mainly eats juice from rice bast by its needle, and causes bast to lost juice and conduction function, and then disturbs the physiological activity of root system, and eventually accelerates leaf aging. In addition, BPH is the media of some rice virus, for example grass-shape plexus dwarf virus. In recent years, BPH has been on the outbreak on the rice, and becomes the main pests that affected rice production[12]. Especially from 2005 to 2008, BPH was on Grade 5 at all times (Table 1). In 2007, the nationwide outburst on the late rice was the most serious over the past 20 years.

Table 1. Occurrence grades of destructive BPHs in China from 1979 to 2008.

year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Occurrence grade	3	4	3	3	3	3	4	3	5	3
year	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Occurrence grade	3	3	5	2	2	3	4	2	4	4
year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Occurrence grade	3	2	2	4	3	4	5	5	5	5

Note: The occurrence grade is divided into five degrees according to the population of BPH and its destruction is listed in detail in the National Agricultural Pests Telemetry Standards formulated by the Ministry of Agriculture of China in 1992.

Through a statistical analysis of the CMs of BPH and the landfalling STCs in China from 1979 to 2008 (Fig. 1), it was found that in four of the most serious years (except 1987 and 1991), the migration of BPH was significantly influenced by the landfalling STCs, and the most obvious influence occurred in 2007, followed by 2006. In the secondary serious years (Grade 4), 1980 was the most obvious, followed by 1985 and 1995. In the medium breakout years (Grade 3), 1983 was typical, followed by 1982. In the secondary light outbreak years (Grade 2), 1993 was the only year that was influenced. There were no years for Grade 1 from 1979 to 2008.

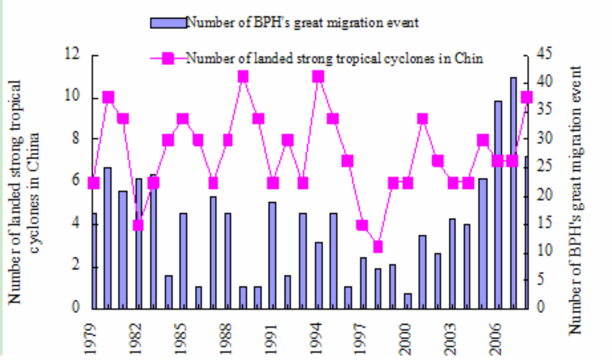

Figure 1. Number of the landfalling STCs in China and the number of BPH's great migration events from 1979 to 2008.

Fourteen of the 30 years, namely, 1980, 1981, 1984, 1985, 1986, 1988, 1989, 1990, 1992, 1994, 1995, 2001, 2005, and 2008, witnessed the STCs that made landfall frequently in China, or at a frequency of more than 8 landfalls per year, while the 10 years of 1980, 1981, 1982, 1983, 1987, 1991, 2005, 2006, 2007, and 2008 reported frequent CMs and more landfalls of BPH. In 1998 (10 STCs and 25 CMs), 1981 (9 STCs and 21 CMs), 2005 (8 STCs and 23 CMs), 2008 (10 STCs and 27 CMs), the correspondence between the landfalling STCs and the CMs of BPH was so good that the influence of the former on the latter is apparent. While in the other years, the influence is determined by the peak periods of the northward and southward migrations, as well as the active season of the landfalling STCs.

BPH can only survive the winter in the south of Guangdong and Guangxi, Fujian and the south of Yunnan, Taiwan and other regions, but the source where insects can spend winter safely was limited[9, 12]. A typical period of northward migrations is from the middle of April to late August, a typical period of southward migrations is from mid-September to the end of October, and a period of mixed migrations is from late August to mid-September, in which migration can be both northward and southward at the same time. Based on this finding, this work named the time from March to August as a period of northward migrations and the time from September to November as a period of southward migration, while the mixed migration period was determined by the direction of airflow, the source of BPH's populations and the location of their landing areas. After analyzing the landfalling STCs and the northward and southward migrations of BPH, the following profiles were made (Figs.2 and 3).

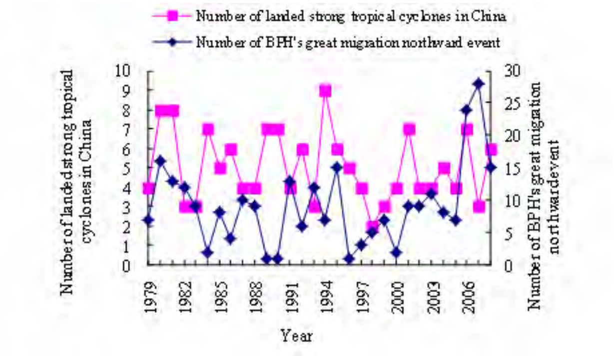

Figure 2. Number of the landfalling STCs in China and the number of BPH's main northward migration events during March, April, May, June, July, and August from 1979 to 2008.

The BPH's northward CMs vary greatly each year from March to August and it was the most serious in 2006 for the northward migrations were influenced by the landfalling STCs (Fig. 2). In 1984, 1989, 1990, and 1996, there were one or two great northward migrations each year, but the number of the landfalling STCs at the same period of 2006 was as many as 5 to 7. It appeared that there was an opposite change tendency between the landfalling STCs and main northward migrations. It showed that there are no sources of BPH for the northward migrations when the landfalling STCs influence the main rice-growing regions in China.

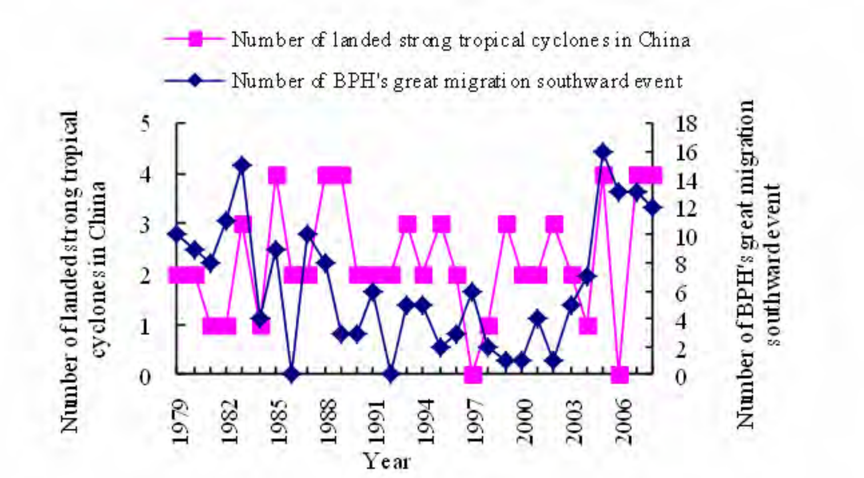

Figure 3. Number of the landfalling STCs in China and the number of BPH's great southward migration events during September, October and November from 1979 to 2008.

The time from September to November is a typical period of southward migrations of BPH. Southward migrations were much affected by the landfalling STCs in 1983, 1985, 2005, 2007, and 2008, as shown in Fig. 3. Among these years, the most typical is 2005 in which four STCs influenced the southward migrations greatly. However, there were CMs without STCs in the autumns of 1986 and 1992, while 1997 and 2006 were the opposite. Considering the general circulation and the migratory behavior of BPH, the former was due to the lack of BPH sources and the latter resulted from weather systems in the high-latitude westerlies, such as cold anticyclones, fronts or cutoff low pressures in control of the southward migrations. It also proved that a landfalling STC, in some extent, affects a migratory process of BPH and sometimes it was a major factor, but sometimes it was not the major factor, not even an influencing factor.

3.3.2 SEASONAL CHANGES

In Aprils and Novembers of the 30 years, there were few landfalling STCs (less than 1% of the total number) and the CMs were also few (Fig. 4 and Table 2). However, there were an increasing number of landfalling STCs and the CMs in May, June and October (with the average number of landfalling STCs amounting to 26.39% of the total landfalling STCs in a year and the average CMs adding up to 20% of the total CMs in a year). Because quite a number of STCs (more than 70% of the total amount of landfalling STCs) and the serious catastrophic BPH migrations (over 70% of the total migrations) occurred from July to September in a year. July to September in a year is the typical period of influence from the landfalling STCs on the CMs. However, we should remember that the landfalling STC is not the only condition controlling and affecting the migrations in spite of so many STCs and migrations. In general, in view of the proportion of the immigration caused by the landfalling STCs in the total number of migrations, the landfalling STC is not the major influencing factor but the secondary one in the atmospheric controlling and affecting factors of BPH's migrations.

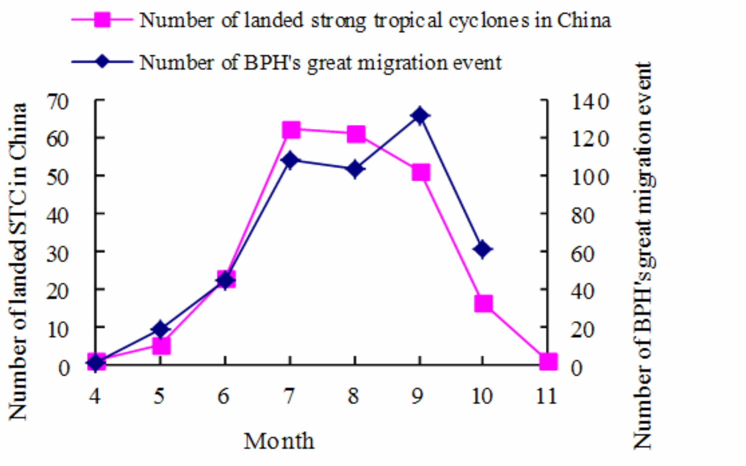

Figure 4. Number of the landfalling STCs in China and the number of BPH's great migration events from April to November from 1979 to 2008.

Table 2. Statistic probability of the BPH's main migration events influenced by the landfalling STCs in the Chinese continent regions for the different periods of a year from 1979 to 2008.

period	April and November	May, June and October	July, August and September
percentage in the total landfalling STCs	0.91%	20.00%	79.09%
percentage in the total immigration events	0.21%	26.39%	73.39%

3.3.3 SHORT-TERM CHANGES

In general, in the period of BPH migration, if there are proper sources of BPH, the landfalling STC may cause an obvious migration. As shown in the statistics, there were 220 STCs making landfall in China and 466 great migration events occurred from 1979 to 2008. According to the observed data of BPH and the atmospheric circulation backgrounds, 73 migrations were affected by the landfalling STCs. As shown in Fig. 5, all the landfalling STCs in 2007 caused the CMs of BPH. Over 70% of the landfalling STCs caused the CMs of BPH in 1982, 1993, 2005, 2006, while the landfalling STCs rarely caused the migrations of BPH in 1984, 1990, 1997, 1998, 1999, and 2003.

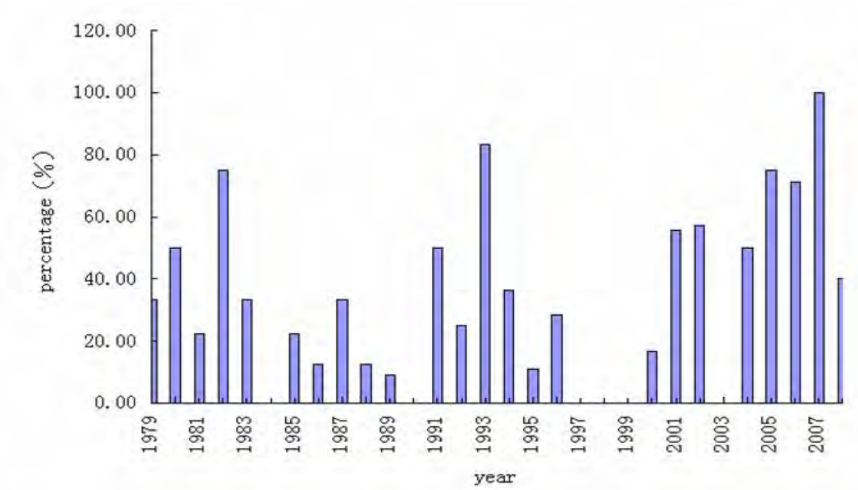

Figure 5. Annual percentage of the landfalling STCs resulting in the BPH's main migration events as against the total number of STCs ever making landfall in the same year from 1979 to 2008.

Annual percentages taking up in the total number by the BPH's great migration events as influenced by the landfalling STCs varied from 1979 to 2008 (Fig. 6), with the most in 1996, as high as 50%. The years that were above the 20% level were 1980, 1986, 1989, 1992, 1993, 1994, 2000, 2001, 2002, 2004, 2005, while the rest was less than 20%.

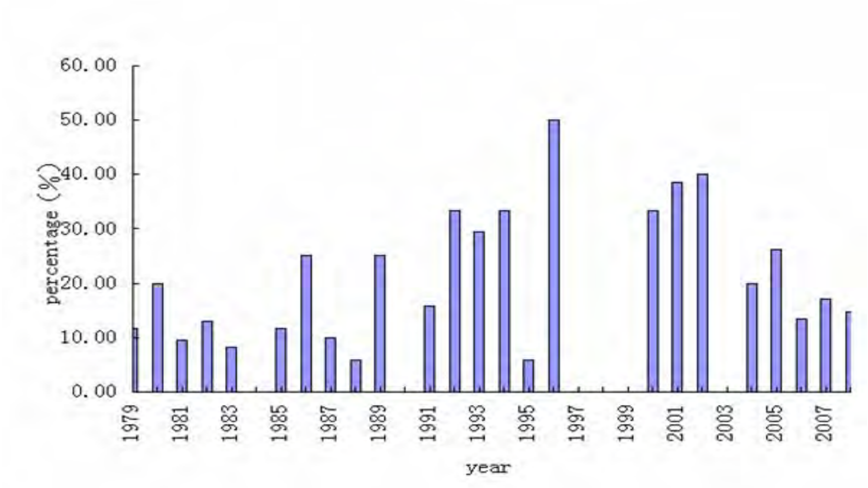

Figure 6. Annual percentage of the BPH's great migration events influenced from the landfalling STCs as against the total number of the BPH's great migration events that occurred in the same year from 1979 to 2008.

It was also found that cases with both landfalling STCs and great migrations take up 33.18% (73/220) in the total number of landfalling and 15.67% (73/466) in the total number of great migrations. Research showed that the landfalling STCs caused the CMs of BPH to some extent, but not every landfalling STC can do so and it depends on whether there is a BPH source.

3.2 *Spatial variation*

The probability of STCs landfalling in Guangdong, Fujian and Zhejiang provinces was the highest in the time of BPH's great migrations from March to November and the landfalling sites of STCs are situated in the coastal areas between 110°E and 122°E from July to September[13, 14]. In this work, based on the calculations of the statistic probability of the influence of every plant protection station, a spatial analysis was made under the assistance of ArcGIS9.3, a geographic information system software (Fig. 7).

The stations were influenced by the landfalling STCs with the CMs of BPH mainly distributed in Fujian, Guangdong, Zhejiang, Guangxi, Shanghai, Jiangsu, Jiangxi, Anhui, Guizhou, Hunan, Hubei, Chongqing, etc. Although there were a few migrations in Sichuan and Yunnan provinces, the influence of landfalling STCs was little if the orographic factor was taken into account. Hence the stations of the two provinces were not calculated in the influence of the landfalling STCs on BPH's migrations. The influencing areas of the landfalling STCs on the CMs of BPH are the largest in Fujian and Guangdong (50% to 60%), as shown in Fig. 7. Guangxi, the southern part of Jiangxi and the southeast part of Hunan took the second place (42% to 51%). The northwest part of Hunan, the southeast part of Hubei, the north part of Jiangxi, and the south part of Anhui had the influencing probability (33% to 42%) and most of Zhejiang, Shanghai, Jiangsu, the north part of Anhui, the northeast part of Hubei, most of Chongqing and Guizhoue were in the bottom with the probability between 15% and 33%. Theoretically, when there is a STC landfalling in southeast coastal areas in China, the frontier flow field would be conducive to the CMs of BPH in the south of China, and the pests will travel anticlockwise with the airflow of STC systems. After a period of time and a distance of lasting fly, the BPH's populations make landfall in the areas of the sinking airflow of STCs' peripheral region or heavy rainfall. If a STC is powerful when landfalling on the Chinese mainland, the sinking airflow at the periphery area of a STC will be strong and the probability of BPH's landing will be high. Meanwhile, as the landfalling STC strikes Guangdong and Fujian frequently, the CMs of BPH in the two provinces are high in the occurrence frequency. With the invasion and extension of the landfalling STC into the mainland, its power is declining. As a result, the power of the peripheral downdraft weakens. The influenced area shrinks and the influencing frequency reduces, resulting in the distribution as shown in Fig. 7.

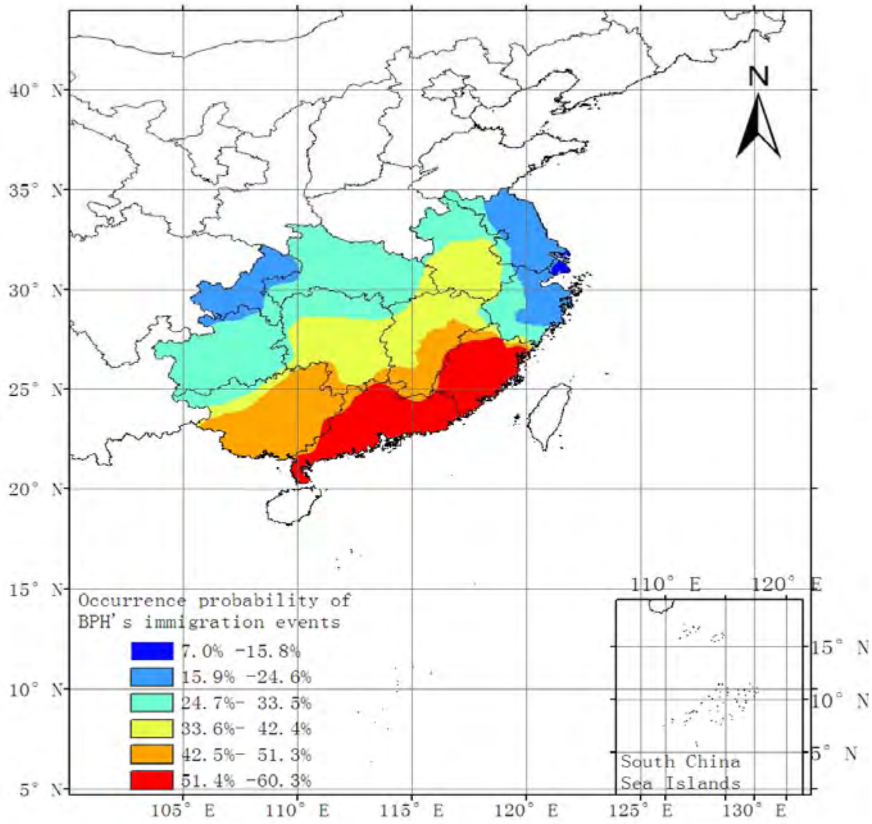

Figure 7. Spatial distribution of the probability of BPH immigrations resulting from the landfalling STCs in China that covered the rice-growing areas of southeastern China from 1979 to 2008.

4 CONCLUSION AND DISCUSSION

Based on the analysis on the temporal and spatial relationships between the great migration events of BPH and the landfalling STCs from 1979 to 2008, the following conclusions are obtained.

(1) In the 30 years from 1979 to 2008, the years of BPH's migrations greatly influenced by the landfalling STCs were 1980, 1981, 2005, 2006 and 2008.

(2) In 2007, a series of main migration events driven by the landfalling STCs were witnessed. The impact of the landfalling STCs on BPH's northward (southward) migrations was most obvious in 2006 (2005).

(3) The frequency of STCs landfalling was the highest from July to September when the BPH's great migration events occur most frequently.

(4) In China, 220 landfalling STCs passed the main rice-growing regions and 466 great events of BPH's migration occurred in the 30 years. 73 of the 220 landfalling STCs resulted in the occurrence of BPH's migration events directly and 147 of them produced indirect effect on the migrations.

(5) Based on the spatial analysis of GIS, it was found that the migrations of BPH affected by the landfalling STCs in the southeast part of China varied, and the influence was the most serious in Guangdong and Fujian. The influence decreased from the southeast coastal areas to the northwest inland of China.

The study on the influence of STCs in the CMs of the BPH is just at the beginning at home and abroad, and the previous researches focus on the analysis of the case studies of STCs or the dynamical influence of a STC on the landing of BPH[9-11]. This work, from the statistics angle and with the help of GIS, concentrates on the influence of landfalling STCs on the CMs of BPH from 1979 to 2008 according to the patterns of the temporal and spatial variations. This study tries to find the statistical relationship between the landfalling STC and the CMs from the viewpoint of temporal and spatial variations. Meanwhile, some valuable conclusions are very important to the explanation of the catastrophic physical mechanism of BPH, as they provide scientific basis for the forecasting and early warning of CMs of BPH in China. However, it is difficult to make extensive studies because of insufficient data provided by the National Plant Protection System in China, such as limited number of monitoring stations in some years. So far, there have been a great number of studies on TCs and BPH at home and abroad, but those on the relationship between the two are few. It will be helpful to the forecast and early warning of the CMs of BPH through accurate forecasting of the landfalling STC. Moreover, the full understanding on the influencing mechanism of STCs on the CMs of BPH will be beneficial for the early pre-warning and the effective controlling of BPH's destruction.

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