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Toward anticipating pest responses to fruit farms: Revealing factors influencing the population dynamics of the Oriental Fruit Fly via automatic field monitoring

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ABSTRACT

The Oriental Fruit Fly (OFF), *Bactrocera dorsalis* (Hendel), is one of most devastating insect pests that have periodically caused serious damage to fruit farms in Taiwan and many countries in the world. In the past, many studies reported that the population dynamics of OFF was partially correlated to the weather and the historical population development of OFF in the field. By making the best use of modern info-communication technologies (ICTs), long-term pest population data and microclimate variables measured with uniquely fine spatiotemporal resolution are now available to reveal the population dynamics of OFF. An analysis of data over three years using the Vector Auto-Regressive and Moving-Average model with eXogenous variables (VARMAX) was proposed to unravel the regulatory mechanism between the population dynamics of OFF and microclimate factors. In addition, the proposed model provides a 7-day forecast for population dynamics of OFF. The accuracy of 7-day risk level forecasting yielded by the proposed model ranges from 0.87 to 0.97, and the average root-mean squared errors of forecasting the population dynamics fall in the interval between 0.31 and 4.95 per day per farm. The proposed forecasting model can allow authorities to gain a better understanding of the dynamics of OFF and anticipate pest-related problems, so they can make preemptive and effective pest management decisions before the real problems occur.

1. Introduction

Bactrocera dorsalis (Hendel), commonly referred to Oriental Fruit Fly (OFF), is one of the most influential phytophagous insects to the agricultural economy of Taiwan and 22 other countries around the world (Vargas et al., 2007). The high mobility and short reproductive cycle of OFF, around 16 days per generation (Vargas et al., 1984), make it capable of causing great damage to more than 150 kinds of tropical and subtropical fruit and vegetables (Armstrong et al., 2004; Chen et al., 2006a; Malacrida et al., 2007), and thus reduce the income of small-scale rural farmers (Mwatawala et al., 2009a,b). In recent decades, severe outbreaks of OFF have caused damage of up to 10–30% of fruit production annually. For example, OFF infestations caused an economic loss of 1.4–1.9 billion U.S. dollars solely in the island of Taiwan (Hung et al., 2008). Understanding the factors that affect the population dynamics of OFF would enable interventions without delay, as well as to increase the efficiency of pest control measures.

Many previous studies gave contradictory conclusions on abiotic or biotic factors influence the fluctuation of OFF populations in the field (Ye and Liu, 2005; Jiang et al., 2008; Okuyama et al., 2011). For example, monthly mean temperature, the number of raining days, and the number of host plants were identified to be influential factors that regulates the population of OFF in Yunnan Province, China (Chen et al., 2006b). Temperature and rainfall were also closely related to the population increment and distribution of OFF (Duyck et al., 2006). In addition, relative humidity and aforementioned meteorological factors were reported to show a

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significant correlation with the population fluctuation of OFF (Sarada et al., 2001). However, only a few studies have targeted to predict the population dynamics of OFF using these variables. For instance, a linear regression model has been utilized to model the weekly population density of Melon Fly, *Bactrocera cucurbitae* (Coq.), with the daily average, maximum, and minimum temperatures (Inayatullah et al., 1991). A farmer-friendly fly trap was designed by Verghese and Sudhadevi (1998) for monitoring the population density of Melon Fly, and meteorological data was used to model the dynamics of the fly via multi-regression models (Verghese et al., 2006a,b). The same research group also employed back propagation neural network models to model the population dynamics of OFF (Jayanthi et al., 2011). Furthermore, a software-based tool was introduced to simulate the spatiotemporal development of a pest outbreak event under different environmental conditions (García-Adeva et al., 2012).

Some evidence, however, shows that weather information acquired from the meteorological stations established by local governments may deviate considerably from the microclimate experienced in the agricultural fields. Another limitation of using the weather information is that these meteorological stations only provide monthly averages of daily meteorological values across a large area, so the information can only generate monthly predictions. Considering the short reproductive cycle of OFF (16 days), monthly prediction is insufficient in preventing OFF outbreaks that usually happen within several days. Furthermore, in most existing studies, only abiotic factors (weather information) were considered during the modeling process. The auto-regulation of OFF's populations that can directly influence the population growth rate of OFF addressed in our previous study (Okuyama et al., 2011) were not taken into account. And lastly but most importantly, the distributions of OFF are subject to change in response to global climate change. It is urgent to rebuild new forecasting models by reexamining the ecological behaviors of OFF, so fruit and vegetable production can be improved. The analytical methods used by the aforementioned studies and their conclusions are summarized in Table 1.

Nowadays, OFF has been found in more than 23 countries or regions. Fruit growers in these countries all agree the importance of monitoring the population fluctuations of OFF (or other closely related species) throughout the year. Most of farmers and official authorities still use yellow sticky papers or bottle traps with methyl eugenol inside to capture OFF. However, due to the lack of manpower, it takes several days to count the number of flies captured in all fly traps, and a few more days for government agencies to collect the data of the flies from the farmers. In addition, once a large number of fruit flies are detected, it means that the pest outbreak event is undergoing. At that time, because it is already too late to apply the integrated pest management (IPM) strategies to suppress OFF population, the most dominant method of eliminating the flies used in many countries is to apply pesticides. In countries located in a tropical region, OFF can be detected throughout the year, but continuously spraying pesticides is definitely not considered as a good solution, since the negative impact of pesticide use on the environment would be too great to bear.

This paper describes the development of a remote agro-ecological monitoring system, its data collecting and preprocessing method, and the modeling for the population dynamics of OFF. This study is conducted based on a multi-year research and development efforts. First, a system built upon automatic fly counting traps with a standalone monitoring station was developed (Jiang et al., 2008). By adopting wireless sensor network (WSN) technologies, the standalone monitoring system was then transformed to monitor microclimate, meteorological and pest data in the field (Jiang et al., 2009, 2013). With these networks and great amount of real-world sensor data, we have investigated the auto-regulation of the dynamics of pest population (Okuyama et al., 2011), and to send warning messages to farmers and government officials automatically once a pest outbreak event has been detected (Liao et al., 2012). This system is an excellent tool to automatically observe the fluctuations of OFF populations and measure the microclimate factors simultaneously in the various fields. Also, the system helps shorten the sampling interval from days to minute-scale, which is a sufficient resolution for the analysis focusing on the changes taking place within one day (24 h). The real-time data is transmitted to a server located in the control center using the WSN technology and Global System for Mobile Communications (GSM) system. In our field trials, most of feedbacks obtained from farmers are mostly positive since the overall fabrication and installation cost per system is around 3000 USD, which is only a fraction of regular fruit farm's annual revenue (Jiang et al., 2013).

The aforementioned pre-studies are the foundations of this work – to anticipate pest responses to fruit farms, and to uncover endogenous and exogenous factors that influence the population dynamics of pests, that are the main contribution of this study. Before we can achieve these goals, missing values in the data sets have to be taken care of. Since the WSN technology implemented in this study operates in a connectionless communication mode, data missing may occur. In this work, a data preprocessing method is used to impute missing data by reasoning from incomplete data sets. The processed data are then used to investigate the relationship between OFF populations and exogenous factors (microclimate measurements) using a detailed time scale that has never been conducted before. The forecast model may also vary over time due to the variations of microclimate factors (e.g. temperature and humidity). Remote monitoring is a common but challenging issue for improving the management of agricultural systems (Shea et al., 1998; Lindenmayer and Likens, 2009). The system presented in this study can be a promising solution for adaptive farm management (McLain and Lee, 1996; Berkes et al., 2000; Shea et al., 2002; Allan and Stankey, 2009; Jacobson et al., 2009), and the latter could be further improved if monitoring difficulties that have been encountered are solved (Ringold et al., 1996; Smit, 2003).

2. Materials and methods

2.1. System architecture

In the past five years, a series of research projects were initiated to construct a real-time remote agroecological monitoring system based on the WSN and GSM technologies (Jiang et al., 2008, 2013; Okuyama et al., 2011; Liao et al., 2012). Using photovoltaic cells, this system is self-sustainable and supports for long-term monitoring tasks in wild fields. A total of 12 monitoring systems have been deployed at fruit farms under the jurisdiction of four individual experiment stations (Taiwan Agricultural Research Institute, Chiayi Agricultural Experiment Station, Tainan District Agricultural Research and Extension station, and Kaohsiung District Agricultural Research and Extension Station) located in the northeastern, western, and southern regions of Taiwan since February 2009, as summarized in Table 2. Each system was comprised of a gateway and a number of sensor nodes. The sensor nodes were placed in the farms in different ways according to the terrain features of the fields, and they covered an area of 1.605 ha in total. Each paired neighboring sensor nodes were 9–15 m apart. Short distance between nodes enabled the system to form a mesh network, so that redundant links between nodes also account for the instability of wireless links. Each sensor node was equipped with temperature, humidity, and illumination sensors, and an automatic pest counting trap. The data was automatically collected every 30 min (discussed in the next subsection). Poisoned