Physica A 476 (2017) 70–83

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

The stochastic resonance for the incidence function model of metapopulation[☆]

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HIGHLIGHTS

- We used econophysical approach to analyze crop yield losses caused by pests and diseases in agricultural economics.
- A metapopulation dynamical model is modified to include endogenous and exogenous periodicities.
- Agricultural loss data in China are used to fit the proposed model.
- Experimental results demonstrate that the proposed model fits the crop yield losses well.
- Expected Indemnity of Loss (EIL) and signal-to-noise ratio are discussed.

ARTICLE INFO

Article history:
Received 5 November 2016
Received in revised form 24 January 2017
Available online 28 February 2017

Keywords:
Metapopulation
Agricultural insurance
Crop diseases and pests
Signal-to-noise ratio
Econophysics

ABSTRACT

A stochastic model with endogenous and exogenous periodicities is proposed in this paper on the basis of metapopulation dynamics to model the crop yield losses due to pests and diseases. The rationale is that crop yield losses occur because the physiology of the growing crop is negatively affected by pests and diseases in a dynamic way over time as crop both grows and develops. Metapopulation dynamics can thus be used to model the resultant crop yield losses. The stochastic metapopulation process is described by using the Simplified Incidence Function model (IFM). Compared to the original IFMs, endogenous and exogenous periodicities are considered in the proposed model to handle the cyclical patterns observed in pest infestations, diseases epidemics, and exogenous affecting factors such as temperature and rainfalls. Agricultural loss data in China are used to fit the proposed model. Experimental results demonstrate that: (1) Model with endogenous and exogenous periodicities is a better fit; (2) When the internal system fluctuations and external environmental fluctuations are negatively correlated, EIL or the cost of loss is monotonically increasing; when the internal system fluctuations and external environmental fluctuations are positively correlated, an outbreak of pests and diseases might occur; (3) If the internal system fluctuations and external environmental fluctuations are positively correlated, an optimal patch size can be identified which will greatly weaken

☆ This work was supported by the grants from the National Science Fund for Distinguished Young Scholars of China (Grant No.: 11225103), the National Natural Science Foundation of China (Grant No.: 11647078, 11165016, 71263056), the China Postdoctoral Science Foundation (Grant No.: 2015M572507), Yunnan Provincial Social Science Foundation Of China (Grant No. ZDZZD201408), Postdoctoral directional training project in Yunnan province (Grant No.: C163005), the Science Foundation of Yunnan University of Finance and Economics (Grant No. YC2012D15).

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http://dx.doi.org/10.1016/j.physa.2017.02.027
0378-4371/

the effects of external environmental influence and hence inhibit pest infestations and disease epidemics.

1. Introduction

Econophysics [1,2] is a fast-growing multidisciplinary field in which ideas, models, theories and tools from statistical physics are used to model complex financial and economic systems. Recent works done by econophysicists have produced convincing evidences that standard model of finance is not fully capable of describing real markets and hence new ideas and models from Physics are called for [3]. Mandelbrot observed "fat tail" behavior of cotton prices in the United States and proposed that price changes follow a Levy stable distribution [4]. Mantegna and Stanley [2] used Levy distribution to model the distribution of stock index changes of S&P500. Gopikrishnan et al. [5] found that the distribution of returns for market indices is consistent with an asymptotic power-law behavior with exponent 3, which is well outside the stable Levy regime $0 < \alpha < 2$. Malevergne et al. [6] analyzed the tail behavior of the log-returns of the Dow Jones Industrial Average and the Nasdaq Composite index and concluded that the tails decay slower than any stretched exponential but probably faster than power laws with reasonable exponents. Various models have been introduced by econophysicists for asset returns in financial markets and original points of view on established models were proposed. Spagnolo and Valenti [7,8] studied the statistical properties of the hitting times, or escape times, in different models for stock market evolution. The research activities of econophysicists are complementary to traditional approaches of finance and mathematical finance. Meanwhile, the effects of noise on the stability of the system with the escape time and stochastic resonance are commonly used in periodically fluctuating metastable systems [9], randomly switching piece-wise metastable linear potential [10], the growth of tumor influenced by external fluctuations and periodic treatment [11], perceptual bistable system [12], a ecological system [13,14], in an energy depot model [15] and so on. Physical concepts such as scaling, universality, disordered frustrated systems, and self-organized systems are very helpful in analyzing financial markets. Jiang & Zhou [16] and Yuan & Zhuang [17] found the universality of multi scale fractal phenomenon when studying China's capital market. Huang [18] systematically elaborated the experimental econophysics concerned with statistical physics of humans in the laboratory. Frank and Matthias [19] investigated the definition and formation of financial networks and studied the influence of the time scale on their construction. Kawamoto et al. [20] discussed the relation between survival probability and k-shell decomposition.

As a newborn field of science liking economics and physics, econophysical approaches are also used to solve insurance problems, usually those including uncertainty or stochastic processes and nonlinear dynamics. Acharyya and Acharyya developed an econophysical model for a life-insurance policy, used computer simulation to calculate the net gain, and found the maximum profit [21]. Fouladvand and Darooneh modeled an insurance company's performance and predicted the annual income of the company [22]. Burnecki et al. studied the indices for losses resulting from catastrophic events in the US and found that lognormal distribution is a better fit than the Paretian one [23]. They also identified the existence of mean-reverting structure in indices returns.

Compared to other insurance products, agricultural insurance is among the most difficult to develop. Hazell discussed the appropriate role of agricultural insurance in developing countries and found that the multiple-risk crop insurance programs are expensive to governments but the outcomes have not been satisfactory [24]. Chambers discussed the insurability and moral hazard in agricultural insurance markets for the Pareto-optimal and constrained Pareto-optimal all-risk insurance contracts to [25]. Although demand for agricultural insurance has steadily increased, insurers are not really willing to cover such risks. One of the reasons is that it is very difficult to estimate the potential losses. Lai and Wu used generalized Pareto to fit the aggregated loss in rice caused by typhoons [26]. Choudhury et al. analyzed the detrending process of crop yield pattern and suggested that crop yield trend pattern is likely to be cyclical pattern rather than a linear trend [27]. Crop yield losses are normally insured by Multi-peril Crop Insurance (MPCI). Under MPCI, insured yield is calculated as a percentage of the historical average yield for the insured plot. If the realized yield is less than the insured yield, an indemnity is paid based on the difference between the realized yield and the insured yield [28]. As it is generally difficult to determine the exact cause of loss, MPCI typically protects against many different causes of yield loss [29].

Understanding and estimating the effects of agricultural diseases and pests, however, are of great importance to farmers, insurance companies, agricultural departments and organizations. As a world-wide average, the potential crop yield loss due to animal pests and pathogens have been estimated at 18% and 16%, respectively [30]. This obviously represents a massive challenge to food security and food safety, and cannot be ignored [31]. Governments or world organizations like Food and Agriculture Organization need agricultural loss information to: (1) monitor the effects of pests and diseases on crop production; (2) judge the importance of pests and diseases in relation to agriculture and environment; (3) allocate resources on the study of pests and diseases and research on crop improvement; (4) make decisions for food and economic policies; and (5) take actions to manage and control pests and diseases [32]. Xu et al. analyzed 283 invasive alien species in China during 2001 and 2003, and proposed methods for estimating direct as well as indirect economic losses to agriculture [33]. Garrett et al. observed that highly variable weather conditions would have important effects on pest and disease risk and developed a model of yield loss caused by diseases and pests [34].