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APHIDSim: A population dynamics model for wheat aphids based on swallowtail catastrophe theory

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ABSTRACT

Controlling aphids is vital since they are serious pests of wheat as well as many agricultural crops in the world. To avoid adverse effects of total reliance on chemical insecticides so as to ensure the ecological well balance of the agricultural ecosystems, there is a need to have eco-friendly control measures like biological control. For this, a good understanding of their population dynamics is critically important. Though there are several criticisms, a number of experiments have been conducted to develop forecasting models or expert systems for identifying the population, rates of growth or the damage. Those models are based on a number of mathematical models, including catastrophe theory, especially the cusp model. However, many of them are limited to the theoretical models but not to the practical systems or software. This study is aimed to analyze population dynamics of wheat aphids and to build a computer program (APHIDSim) integrating the swallowtail catastrophe theory. We built a swallowtail model from the aphid population as a function of three controlling factors: weather, crop and natural enemy in order to analyze the swallowtail behavior of population dynamics of wheat aphids. The APHIDSim is implemented integrating the swallowtail model and analyzed aphid population data for swallowtail behavior. The results show that the increase of wheat aphid population (population dynamics) is essentially a catastrophic behavior and sudden jumps may occur from one state to another even though the control factors change smoothly.

1. Introduction

Controlling of aphids is vital since they are serious pests and vectors of causative agents of wheat and many agricultural crops in the world. Many authors reported that several aphid species have attained the status of potential insect pests of wheat (Ankersmit and Carter, 1981; Chander et al., 2006; Freier et al., 2007; Morgan, 2000; Parry et al., 2006; Rabbinge et al., 1979; Wains, 2010). Some of them are adapted specifically to some regions of wheat plant and to the set of environmental and physiographic conditions in which wheat is grown. To avoid adverse effects of total reliance on chemical insecticides so as to ensure the ecological well balance of agricultural ecosystems, there is a need to have eco friendly control measures like biological control. For this, a good understanding of their population dynamics is critically important. Though there are several criticisms, a large number of experiments have been conducted to develop forecasting models or expert systems for identifying the population, rates of growth or the damage. They have dealt with various biological aspects of aphids and based on several mathematical theories, including catastrophe model, especially the elementary cusp theory. Computer technology offers an efficient and effective way to resolve the complex problems in agricultural systems, especially in the population dynamics. Scientists have started modeling of aphid population dynamics from 1960s (Hughes, 1965 cited in Kindlmann and Dixon, 2010; Ma et al., 1965 cited in Dianmo and Zhongwei, 2000). Most of them, deterministic or stochastic models, discuss the abundance of the major pests like *S. avevae*, *Rhopalosiphum padi* and *Diuraphis noxia* (see e.g., Carter, 1985; Gosselke et al., 2001a,b; Morgan, 2000; Rabbinge et al., 1979; Skirvin et al., 1997). Some authors (Matis, 2009; Matis et al., 2005, 2008; Prajneshu, 1998) have used cumulative population density with correlating the resource scarcity of offspring due to honeydew secreted by the adults. A computer based advisory system which is run on a server is presented by Mann et al. (1986). It is directly farmer-oriented and advises the farmer to economical use of pesticide. Klueken et al. (2009) has presented a comparative explanation of some existing software systems with validated results. Others, those who dealt with single-species populations have most of the time based on well known logistic equation (Verhulst, 1838 cited in Brauer and Castillo-Chavez, 2010) with more or less modifications:

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$dN/dt = rN(1 - N/K)$, where N denotes the population, r denotes the intrinsic growth rate and K denotes the carrying capacity. This process is self limiting and density-dependent: the population is balanced on the carrying capacity K. There are advantages and disadvantages using of a particular theory for a particular model. Some models are critically reviewed by Kindlmann and Dixon (2010) in detail.

The population dynamic models for aphids which use the catastrophe model, earliest mathematical theory, are less documented or development has been slower. The first application of the butterfly catastrophe model in ecology has been reported in 1989 (Loehle, 1989). Catastrophe theory is a modeling strategy which can be used to analyze complex nonlinear systems (Arnold, 1984; Glimore, 1981). It describes that continuous and smooth change of a control variable may cause a sudden jump (catastrophe) of a behavioral variable in a dynamical system. Aphid population dynamics in agricultural systems is normally characterized this behavior, and some attempts have been taken to describe that behavior (see e.g., Ma and Bechinski, 2009; Wei et al., 2009; Zhao et al., 1993; Zhao, 1989, 1991; Zhao et al., 2005; Zhao and Wang, 1993) and all these scientists have used fold or cusp theory with two control variables like weather and natural enemy. The cusp catastrophe model built by Ma and Bechinski (2009) explores the relationship between intrinsic rate of increase of aphids *D. noxia* and environmental factors. They have used the temperature and plant growth stage as controlling variables, and concluded that the population growth is intrinsically catastrophic with smooth change of temperature and plant growth stage. APHIDSim is also based on this concept but we use three control variables and swallowtail model instead of cusp model.

However, the lack of research evidence about swallowtail model or more complex models among seven elementary models (Deakin, 1990) reveals the difficulty of using catastrophe theory in ecological modeling. Some experiments have been conducted based on swallowtail model in some other areas like catalytic CO oxidation reactions (Cui et al., 2011), flashover in building fires (Weng and Fan, 2003), traffic flow forecasting (Tang and Huang, 2005), evaluations of smooth blast effects (Fang, 2010), transient stability analysis of a multi-machine power systems (Tripathy, 1998) and evaluations of earthquake processes (Youquan and Jing, 1994). This project is aimed to develop a detailed aphid population dynamics analysis and forecasting system on three control factors: weather, crop and natural enemy, based on the swallowtail catastrophe model and recent advances in computer programming technologies. We propose the swallowtail catastrophe model because this is the model which describes three control parameters with one behavior variable among the seven elementary catastrophe models. The aim of using three control parameters is to obtain more accurate results for population dynamics of wheat aphids.

2. Materials and methods

2.1. Processes, variables and constants

The APHIDSim is implemented with object oriented programming language, Microsoft Visual Basic® on .NET platform. A database is run under the system constructed with SQL server compact, an embedded database engine which can be easily integrated for distribution. The APHIDSim simulates the swallowtail behavior of population dynamics of aphids and it requires population data for aphid and predator occurrences and weather data relevant to the location and time duration of data collection (temperature, rainfall, relative humidity and sunshine hours). The predator satiation point (d) and number of minimum aphids which predation ensures (N_m) are needed as constants. Aphid carrying capacity

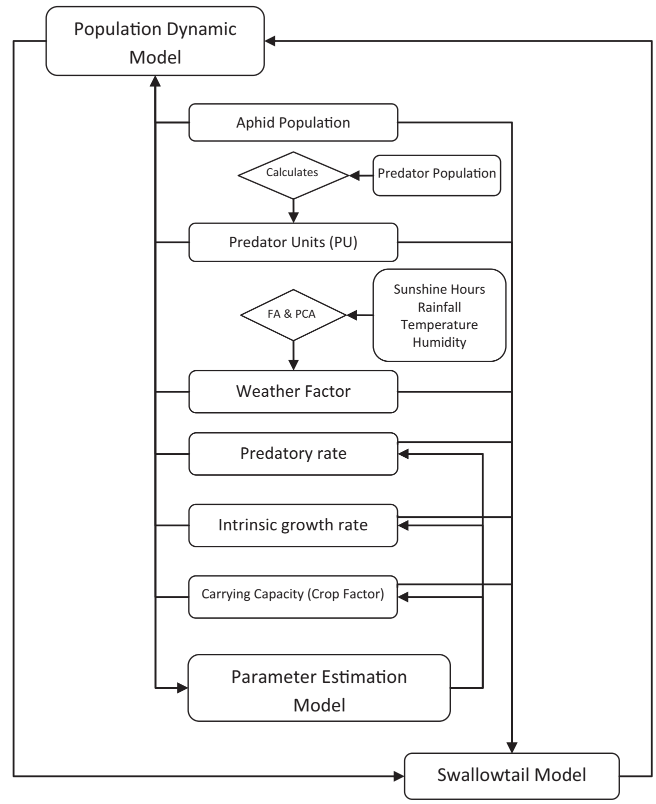

Fig. 1. Basic organizational diagram of the APHIDSim model.

(K), intrinsic growth rate of aphids (r) and predatory rate (k) are estimated by the APHIDSim using initially fed data. The weather factor (e) is also estimated by the APHIDSim using initially fed weather data. A complete list of variables and symbols used in the APHIDSim is furnished in Appendix. The system includes three sub models: population dynamic model, parameter estimation model and swallowtail model. Each sub model includes algorithms for calculations. The population dynamic model uses the modified logistic equation (Zhao, 2005) and prepares variables which are to be fitted in the swallowtail model. It also includes algorithms for generating weather factor and predator units. Parameter estimation model estimates unknown parameters which are to be applied in the swallowtail model. Swallowtail model executes the algorithms and analyze the swallowtail behavior of aphid population data. As the process of in between sub models, the modified population equation is fitted into the equilibrium surface to analyze the population behavior in the swallowtail module. The basic organizational diagram of the APHIDSim is shown in Fig. 1.

2.2. Population dynamic model

Identifying the population regulating factors would be a major objective of developing simulation models in population dynamics. There may be a number of factors influenced the population dynamics, like rate of increase, population itself (e.g., competition), weather condition, quality of the host plant and predation, etc. The carrying capacity is the major regulating factor which probably depends on the available food resources and the competition. In APHIDSim, we use modified logistic equation (Eq. (1)) which is described in Zhao (2005) and Wei (2009) with incorporating three control parameters: weather factor (temperature, rainfall,