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Geospatial pest-parasitoid agent based model for optimizing biological control of forest insect infestation

Taylor M. Anderson*, Suzana Dragićević

Spatial Analysis and Modeling Research Laboratory, Department of Geography, Simon Fraser University, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada

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ABSTRACT

Forest insect infestations behave as complex systems and can be represented using agent-based modeling (ABM) approaches to explore and optimize eradication strategies such as biological control. This study develops novel geospatial agent-based EAB-BioCon model for the interactions of *emerald ash borer* (EAB) with the parasitoid *Tetrastichus planipennisi* (TP) wasp in order to evaluate the spread of forest infestations. The model is implemented on geospatial data from City of Oakville, Canada and is composed of: (1) EAB-Baseline model, representing EAB geospatial dynamics; and (2) EAB-TP model that employs scenarios to measure EAB response to variations in TP-based biological control strategies. The EAB-BioCon model simulation results indicate that variations of TP densities, timing of TP release, and number of TP release points are important considerations in the EAB biological control and thus providing useful conclusions in decision making and management.

1. Introduction

The optimization of invasive insect eradication strategies is crucial in order to prevent serious ecological, economic, and social impacts to affected areas. The emerald ash borer (EAB) *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) is an invasive wood-boring beetle, native to several Asian countries (Straw et al., 2013) and is the cause of the decline of North American ash trees (Fraxinus, sp.) in eastern United States and southwestern Ontario. Studies suggest that the introduction of the EAB into the region may have been as early as 1997 (Siegert et al., 2014), probably by hitchhiking in untreated wood-packaging and subsequently spreading across the region (Buck and Marshall, 2009).

As of February 2015, EAB have infested trees in twenty-five states in the United States and two Canadian provinces (Bauer et al., 2015), becoming the most destructive and costly forest insect to invade North America (Siegert et al., 2014). Eradication has been challenging due to limited visible symptoms of ash tree infestation. Additionally, native predators and parasitoids are not populous enough to reduce EAB populations to non-damaging levels (Fahrner et al., 2014). Eradication strategies have included establishing quarantines, ash tree removal, the injection of insecticides into infested trees, and more recently long-term strategies of biological control (Bauer et al., 2015).

In 2003, a biological control program was launched to combat EAB surveyed for natural enemies to control EAB populations. Three hymenopteran parasitoids native to northern China were selected (Duan et al., 2013): an egg parasitoid, *Oobius agrili* (Hymenoptera: Encyrtidae) (Zhang et al., 2005), a larval ectoparasitoid, *Spathus agrili* (Hymenoptera: Braconidae) (Yang et al., 2005), and a larval endoparasitoid, *Tetrastichus planipennisi* (Hymenoptera: Eulophidae) (Yang et al., 2006). Although all three species have been released as biological control agents in the United States, the *Tetrastichus planipennisi* (TP) wasp species is the only suitable parasite north of 40° latitude and as such the others cannot be used as biological control agents for Canadian provinces (CFIA, 2013).

The *Tetrastichus planipennisi* is a gregarious, stingless wasp (Duan et al., 2011) that uses ash tree volatiles to identify trees infested with EAB (Fahrner et al., 2014). The TP parasitizes EAB larval galleries, controlling EAB population size and reducing the impact on North American ash trees. As the primary enemy of EAB in its native range, the TP is "species specific", meaning they only attack EAB (CFIA, 2013). In addition, this species has a short generation time, a high reproductive potential, and a high female: male based sex ratio (Duan et al., 2013), making TP a good candidate for EAB biological control. To date, TP have been released at over 300 locations in North America with an observed 1–2% of parasitism following the first year of TP release and a 12–30% of parasitism after

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* Corresponding author.
E-mail addresses: taylora@sfu.ca, taylor.marie18@hotmail.com (T.M. Anderson), suzanad@sfu.ca (S. Dragićević).

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4 years (Duan et al., 2013; Abell et al., 2014). No recent assessment has been made to determine whether these introduced biological control agents have successfully supressed EAB population growth in infested regions (Duan et al., 2013).

Regional patterns of spread that emerge from insect dynamics over space and time are very difficult to monitor in the field and in the lab (Fahrner et al., 2014). As an alternative, researchers often use modeling approaches to estimate spread and dispersal of invasive forest insect infestations (Siegert et al., 2014). Early insect infestation models use linear, top-down, equation-based representations (Campbell, 1967; Varley and Gradwell, 1968; Morris, 1963), of which the most common are diffusion models (Skellam, 1951), based on partial-differential equations (PDE). Likewise, biological control models which capture the interactions between pest and parasitoid as an eradication strategy are also mostly limited to differential equations (Milner and Patton, 1999), process models (Bianchi et al., 2002), and diffusion models (Milner and Patton, 2003). These statistical models, however, are often unable to account for the complexity and interactions inherent to insect processes (With, 2002). Specifically, insect populations are composed of adaptive, heterogeneous individuals that interact with other individuals and their hosts and are subject to spatial and temporal variations at a very local level. These small scale dynamics play a very important role in the generation of large scale patters of infestation (Leyequien et al., 2007; Vinatier et al., 2011; Epanchin-Niell and Liebhold, 2015).

Existing studies on EAB use a variety of modeling approaches to estimate spread and dispersal (Siegert et al., 2014) including the classical diffusion models (Muirhead et al., 2006; Iverson et al., 2010; Prasad et al., 2010), equation-based models using ordinary differential equations (ODE) (Barlow et al., 2014), probabilistic modeling (Marshall et al., 2011), and population dynamic modeling (BenDor et al., 2006). In order to extend these research efforts and to address the spatio-temporal complexity of EAB infestation and aspects of the individual and non-linear effects, Anderson and Dragicevic (2015) used a complex systems approach to develop an agent-based model (ABM) to represent local dynamics between discrete heterogeneous EAB individuals or "agents" in a geospatial environment from which regional patterns of stratified dispersal emerge.

Currently, using any modeling approach to represent EAB and TP pest-parasitoid dynamics has not been reported in the literature. Therefore, the main goal of this study is to propose a novel approach capable of simulating TP wasp-based biological control of EAB infestation. The main objectives of this study are to (1) develop EAB-BioCon, an ABM capable of representing local dynamics between heterogeneous EAB and TP individuals and (2) to implement scenarios concerning various release strategies including the number of TP individuals released, the timing of release, and the number of release points. The aim of the study is to better understand how variations of these factors impact the collective TP and EAB population dynamics. The study has the potential to produce a powerful tool which will compliment field based studies of EAB and TP, and contribute to the understanding of the complex spatio-temporal processes that govern host-bark beetle dynamics and aid in the optimization of EAB eradication through biological control.

2. Theoretical background

2.1. Insect infestation as a complex system

Infestation processes are composed of a large number of interacting individuals with properties and behavior that vary from individual to individual, change over space and time, and adapt to changes in their environment or to maintain their individual needs (Grimm and Railsback, 2013; Levin, 2005). This school of thought is referred to as individual-based ecology (IBE) and addresses notions of the individual often ignored by classical ecological models (Parunak et al., 1998). The incorporation of these factors results in non-linear behavior, meaning that the system properties are not simply the sum of the properties of the individuals that the system is composed of, making its overall behavior difficult to represent using traditional statistical approaches (Batty and Torrens, 2005).

ABM is a modeling methodology used to operationalize IBE and represent complex spatio-temporal phenomena. ABMs represent heterogeneous individuals or "agents" which interact among themselves and their environment, generating non-linear, complex, aggregate behavior. Moreover, the integration of geospatial data and geographic information systems (GIS) further allows for the representation of dynamic phenomena within realistic landscapes. The ABM approach is commonly applied to represent spatio-temporal phenomena in ecology including insect infestation caused by mosquito populations (de Almeida, 2010), the potato moth (Rebaudo et al., 2010), the forest tent caterpillar (Babin-Fenske and Anand, 2011), and the mountain pine beetle (Perez and Dragicevic, 2010; Perez and Dragicevic, 2011; Bone and Altaweel, 2014). It is difficult to find in the literature ABMs that are used to model pest-parasitoid interactions over space and time or to simulate these interactions in a biological control context. For example, an ABM was developed to simulate the co-evolution of the damselfly and water mites (Rolff et al., 2001) and in another example, simulate biological control of the greenhouse whitefly using the parasitoid *Encarsia Formosa* (Van Roermund et al., 1997).

2.2. Emerald ash borer

2.2.1. Life cycle

EAB typically complete their life cycle in one year or two (Cappaert et al., 2005). The life cycle consists of four stages (1) active larvae, (2) inactive larvae, (3) pupae, and (4) adulthood. EAB have an approximate sex ratio of 1:1 (Lyons and Jones, 2005). Male EAB typically live for 13 days and females EAB for 22–25 (Buck, 2015). EAB emerge in early June through to early August, with peak emergence in late June or early July with mean activity periods in mid-July (Lyons and Jones, 2005) and spend on average seven days feeding on ash leaves before mating. While feeding, female EAB emit a compound macrocyclic lactone to attract their male counterparts for mating. On average, 82% of females will become successfully fertile (Rutledge and Keena, 2012). Once fertile, female EAB search for a suitable host and will begin to oviposit 60–90 eggs on the surface of the ash tree, either individually or in groups (Jennings et al., 2014). In roughly seven days, an observed 53–65% of EAB eggs will hatch into active larvae and bore into the ash tree (Rutledge and Keena, 2012). Active larvae feed on ash tree phloem for about 140 days from mid-June to October, the main cause of ash tree death. In this stage, host tree defence, woodpecker predation, and disease may cause significant levels of mortality to the active larvae population (Duan et al., 2010). After about 140 days, active larvae move into an inactive stage where they lie dormant for the winter and are susceptible to environmental factors. In the spring, inactive larvae pupate to then emerge as adults.

2.2.2. Host selection

Patterns of EAB spread are governed by the individual decisions of which tree to infest and not surprisingly, their choice of host is not completely random (Mercader et al., 2011). Instead, EAB use olfactory and visual cues to determine which host will be most preferable. A vast number of field and lab studies have worked to determine what these preferences are and they include the following: (1) EAB females prefer to lay their eggs on stressed trees (McCullough et al., 2009), although healthy trees can be attacked