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Short Communication

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Modeling *Agrilus planipennis* F. (Coleoptera: Buprestidae) Spread in New Jersey

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Abstract

Pests and disease have become an increasingly common issue as globalized trade brings non-native species into unfamiliar systems. Emerald ash borer (*Agrilus planipennis*), is an Asiatic species of boring beetle currently devastating the native population of ash (*Fraxinus*) trees in the northern forests of the United States, with 85 million trees having already succumbed across much of the Midwest. We have developed a reaction-diffusion partial differential equation model to predict the spread of emerald ash borer over a heterogeneous 2-D landscape, with the initial ash tree distribution given by data from the Forest Inventory and Analysis. As expected, the model predictions show that emerald ash borer consumes ash which causes the local ash population to decline, while emerald ash borer spreads outward to other areas. Once the local ash population begins to decline emerald ash borer also declines due to the loss of available habitat. Our model's strength lies with its focus on the county scale and its linkage between emerald ash borer population growth and ash density. This enables one to make accurate predictions regarding emerald ash borer spread which allows one to consider various methods of control as well as to accurately study the economic effects of emerald ash borer spread.

Key words: reaction diffusion, invasive species, forest health, timber losses

The emerald ash borer (*Agrilus planipennis* F.), is an invasive species that has proven difficult to control. While this small beetle is largely harmless in its natural Asian habitat, in the United States, it has caused significant harm to ash, *Fraxinus spp*. L. (Lamiales: Oleaceae) Emerald ash borer has the potential to kill upwards of 99% of standing native ash, valued at $282.5 billion in the United States (Poland et al. 2015). The natural spread rate of emerald ash borer is slow, but is accelerated via anthropogenic spread, including inadvertent transport on wood products and vehicles (Evans 2016). Though control is difficult, methods such as forest thinning, pesticide use, and firewood transport regulations have been considered in theoretical frameworks and implemented to some effect (Mercader et al. 2011, Pugh et al. 2011, McCullough et al. 2015, Siegert et al. 2015).

New Jersey has become home to significant populations of emerald ash borer, and currently faces growing management costs. New Jersey possesses 1,447,695 acres of timberland, within which there are over 17,000,000 ash trees vulnerable to emerald ash borer (Miles 2017). Estimates, such as the one performed by Kovacs et al. (2011), place the potential costs to the state to be between $606 million and $670 million for urban forests for removal and replacement over 10 yr. However, these estimates do not factor in externalities such as damage to ecosystem services, or species habitats (McKenney et al. 2012).

Thus, it has become necessary to account for monetary, timber, and ecosystem service losses over time. To this end, we propose a new model rooted in field-based information. The case study is based in Essex County in northern New Jersey, United States (Fig. 1). This county is a well-suited testing ground for our model, as infestation originates at a point source at the approximate center of the county (Fallon 2017).

Several approaches have been proposed to model the spread of emerald ash borer. Generally, these models are landscape scale, or are designed for a forest plot. The first efforts to model emerald ash borer spread were published in 2006, and focused primarily on large scale, dynamic spread and gravity model methods; while innovative, the models were limited due to a lack of data on emerald ash borer (Bendor and Metcalf 2006, Bendor et al. 2006, Muirhead et al. 2006). Kovacs et al. (2011) predicted the state-by-state spread of emerald ash borer and completed an assessment of economic damage from street-tree loss and replacement. While useful for understanding trends, this estimate was coarse, as it only accounted for loss of street-trees and used a statewide approach, where each area was defined by state boundaries. While a hallmark economic paper on emerald ash borer,

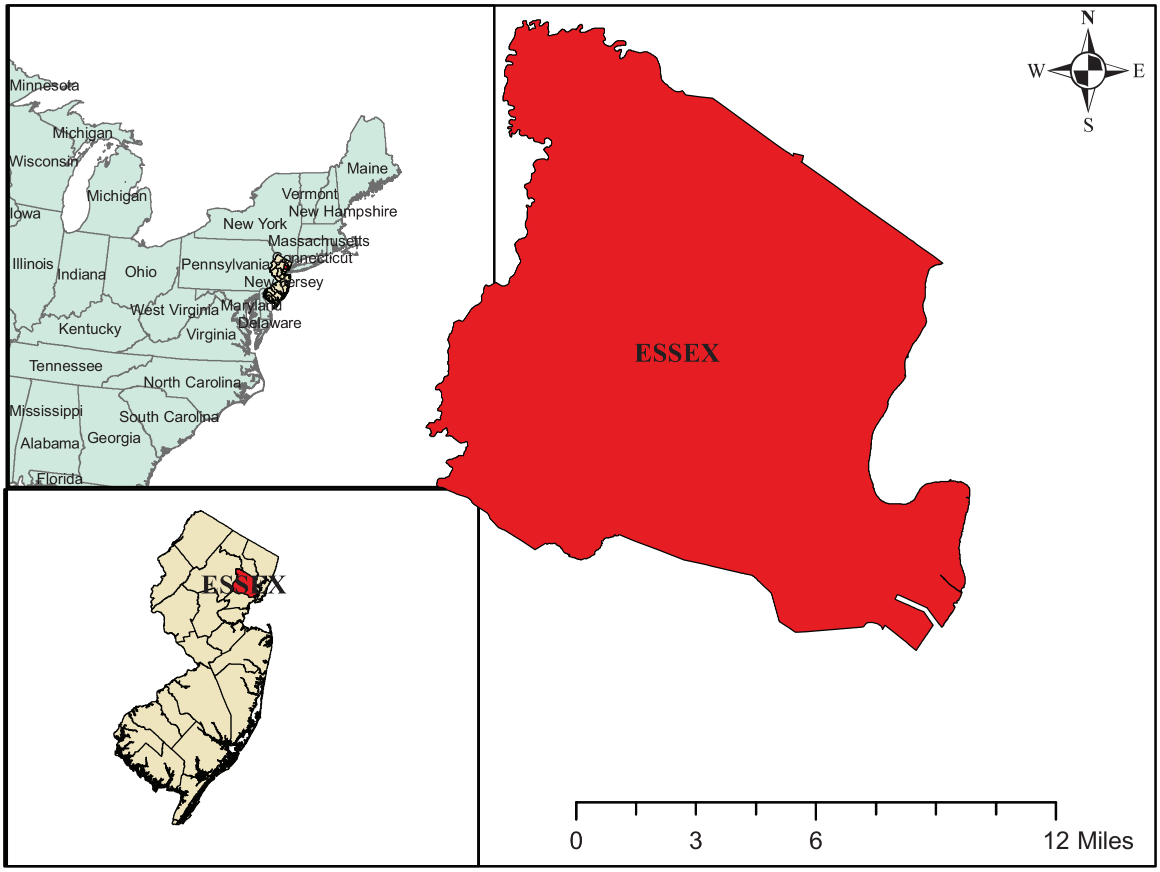

Fig. 1. Essex County in the Northeastern United States.

it does not consider standing timber, or ecosystem services. Mercader et al. (2016) applied a plot-based spread estimation approach, but required an intensive ash inventory and high-resolution data, limiting its applications. Prasad et al. (2010) developed a risk estimation procedure using a gravity model with diffusion to assess the risk over Ohio in a cellular system. While unique, it was concerned solely with identifying areas where new infestations would be detected, and therefore the death rate of ash and emerald ash borer populations were not simulated, limiting application. One reason they developed their method is due to the complexity of partial differential equation (PDE) models which are difficult to develop in heterogeneous systems and tend to treat the landscape as univariate.

We have overcome these challenges by developing a PDE model combined with landscape GIS data to predict the spread of emerald ash borer and the resulting growth/decline of ash throughout the region of interest. The predictions enable one to implement control methods and to perform accurate economic analysis.

Methods and Theoretical Framework

We have developed a reaction-diffusion PDE model in a heterogeneous system. The model employs a logistic growth term to capture the interplay between ash growth/decline and emerald ash borer growth. In the model, active emerald ash borer diffusion occurs over a 4-mo period, known as the 'on-season', while the remaining 8 mo, known as the 'off-season' are characterized by emerald ash borer dormancy. During the off-season, emerald ash borer consumption is discounted to mimic emerald ash borer overwintering (Poland et al. 2015); this allows for ash growth and recovery. For tractability, the study area is divided into cells measuring 100 m^2.

On-season growth and spread of emerald ash borer is modeled as

$$\frac{\partial E}{\partial t} = D\left(\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2}\right) + \bar{G}EA - \bar{C}E^2 - \omega E,$$

where E is the population density of emerald ash borer, A is the density of ash, D governs the diffusion of emerald ash borer, $\bar{G}$ is a growth constant for emerald ash borer, $\bar{C}$ is an emerald ash borer crowding constant, and ω determines natural mortality of emerald ash borer. Additionally, x and y are respectively the latitudinal and longitudinal spatial variables, while t is the time variable in years. Note that the diffusion of emerald ash borer does not depend on the presence of ash, while the growth of the emerald ash borer population is logistic and depends on the presence of both ash and emerald ash borer. The temporal evolution of ash is dependent on the abundance of emerald ash borer and is given by

$$\frac{\partial A}{\partial t} = \hat{G}A - \hat{C}F_C A^2 - CEA.$$

Ash trees do not spread outside their cells and are assumed to grow and regenerate according to the growth rate $\hat{G}$, while the population was capped by the crowding rate $\hat{C}$. Crowding is modified by F_c which describes the local canopy cover, as an approximation for forest cover (United States Geological Survey 2013). Ash is reduced due to consumption by emerald ash borer with rate C.

During the off-season, the governing equations are given by

$$\frac{\partial E}{\partial t} = 0,$$

and

$$\frac{\partial A}{\partial t} = \hat{G}A - \hat{C}F_C A^2.$$

The off-season equations are simpler as emerald ash borer are dormant under the bark of host trees, reducing their consumption rate to zero. Additionally, we assume that during the off-season emerald ash borer do not die or reproduce (Poland et al. 2015).

Table 1 contains the list of parameters and sources for data used in this model. A range of diffusion values were used in all simulations and multiple runs varied the growth, crowding and consumption rates of emerald ash borer within 1 SD from the mean. All other parameters are single-valued. In the future, further sensitivity analysis will be necessary. Parameterization of the model was based upon experimental results from regions of the United States already affected by emerald ash borer. Ash density data for Essex County, New Jersey are based upon 2009 data from the Forest Inventory and Analysis (FIA) (Wilson et al. 2013), while canopy cover was sourced from the national map by the United States Geological Survey (United States Geological Survey 2013).

Emerald ash borer growth was approximated as 12 (±0.57) emerald ash borer born per year per individual based on multiple sources (McCullough and Siegert 2007; Mercader et al. 2011, 2016). The average distance diffused was determined to be approximately 27 meters per year using Mercader et al.'s (2009) negative exponential function. The actual distance of spread varied between zero meters and over 800 meters. To account for the rare long-distance spread, multiple simulations were performed with a range of diffusion coefficients (D) which varied based on a linear spread distance between 5 m and 805 m (separated by 10-m increments). A weighted average was calculated based on the probability of each D value (Mercader et al. 2009), which was approximated using the area under the probability density function (PDF). The average emerald ash borer carrying capacity on ash was found to be 88.9 (±4.6) beetles per square meter of ash surface area based on the experimental results of McCullough and Siegert (2007). From this, we calculated an experimental consumption rate for emerald ash borer scaled to square meters basal area. Ash growth was approximated using growth and yield models from the U.S. Forest Service for northeastern even-aged stands. Growth over the lifetime of ash was simplified into a single growth factor based upon the growth of ash from establishment to failure (Schlesinger 1990). The carrying capacity of ash was sourced from the northeastern variant of the forest vegetation simulator, FVS (Dixon 2018). As an initial condition in the model, we set the emerald ash borer population at the point of infestation as 20 individuals due to limited introduction and egg mortality based on Poland et al. (2015).

Results

Figure 2 shows the advance of the emerald ash borer infestation from t = 0 to t = 20, and demonstrates the spread of emerald ash borer across the county along with an increase in emerald ash borer population, with many areas having populations in excess of 50,000 individual emerald ash borer per hectare. Figure 3 shows the response of ash to the infestation. Ash declines near the epicenter where the emerald ash borer population is greatest, and begins to collapse after just 5 yr under this pressure, which is in line with other experiments (Poland et al. 2015). Independent testing at the site cannot be done due to a lack of infestation data. However, our early-stage predictions of emerald ash borer activity do agree with data on emerald ash borer capture in traps placed throughout the region (NJDA 2018).

As a potential spread control method, we halved the ash density at t = 0 to simulate thinning, which is an established practice (McCullough et al. 2015). We compared the populations of ash and emerald ash borer under this 'managed' scenario to the base scenario in which no treatment options are pursued as a control (Figs. 4 and 5). The thinning of ash resulted in a reduction of the emerald ash borer population by approximately two-thirds after 20 yr, and an increase in the growth rate of ash by 25% by the end of the 20th year. This result indicates that crowding of emerald ash borer could potentially be an important factor in relation to population growth, and indicates that many of the forests in the study area are already at, or near, capacity. Thinning the entire population results in a far lower final ash population and is thus effective for lowering emerald ash borer populations. However, it has a far more deleterious effect on ash compared to the no control case.

The model was used to determine the economic and environmental cost of emerald ash borer infestation. Using FIA data, timber losses in the base case were estimated to be $817.22 per square meter of basal area by current New York timber prices discounted at 3% per year (New York Department of Environmental Conservation 2017). Figure 6, computed using the model's predictions, shows the total estimated monetary loss from potential sawtimber sales due to infestation by emerald ash borer to be between $420,000–$450,000. Using this same data, we calculated the potential standing dead timber added through the actions of emerald ash borer, which appears to be a potentially critical cost in terms of management. With over 6,000 metric tons of carbon litter produced from this site, emerald ash borer stands to be a significant source of decreased forest sequestration due to ash mortality (Fig. 7).

Furthermore, our model and its associated predictions enable capabilities that are beyond those observed in the current body of literature, such as the linkage of ash density to emerald ash borer growth and the method of stratified dispersal for emerald ash borer. The model allows for testing different configurations of ash trees to simulate selective culling to slow the spread of emerald ash borer; these simulations have shown that thinning ash tree density can have a significant effect on the spread of emerald ash borer (Figs. 4 and 5). The model results show that this is an effective, if somewhat

Table 1. Model parameters

Parameter	Symbol	Units	Definition	Source
Diffusion	D	$\frac{m}{t}$	Assumed Circular. Varied from 5 to 805	Mercader et al. 2009
Emerald ash borer growth	$\bar{G}$	$\frac{ha}{m^2 * t}$	0.087108 ± 0.004128	Mercader et al. 2016
Emerald ash borer crowding	$\bar{C}$	$\frac{ha}{in * t}$	0.0000017267	Duan et al. 2013
Emerald ash borer death rate	ω	$\frac{1}{t}$	$\frac{1}{24.7}$	Poland et al. 2015
Ash growth	$\hat{G}$	$\frac{1}{t}$	0.00483	Schlesinger 1990
Ash crowding	$\hat{C}$	$\frac{ha}{m^2 * t}$	0.0001403	Dixon 2018
Ash consumption by emerald ash borer	C	$\frac{ha}{in * t}$	0.0000002724 ± 0.0000000253	McCullough and Siegert 2007

The uncommon unit 'in' is defined as individual emerald ash borer, all other units are in standard SI units.

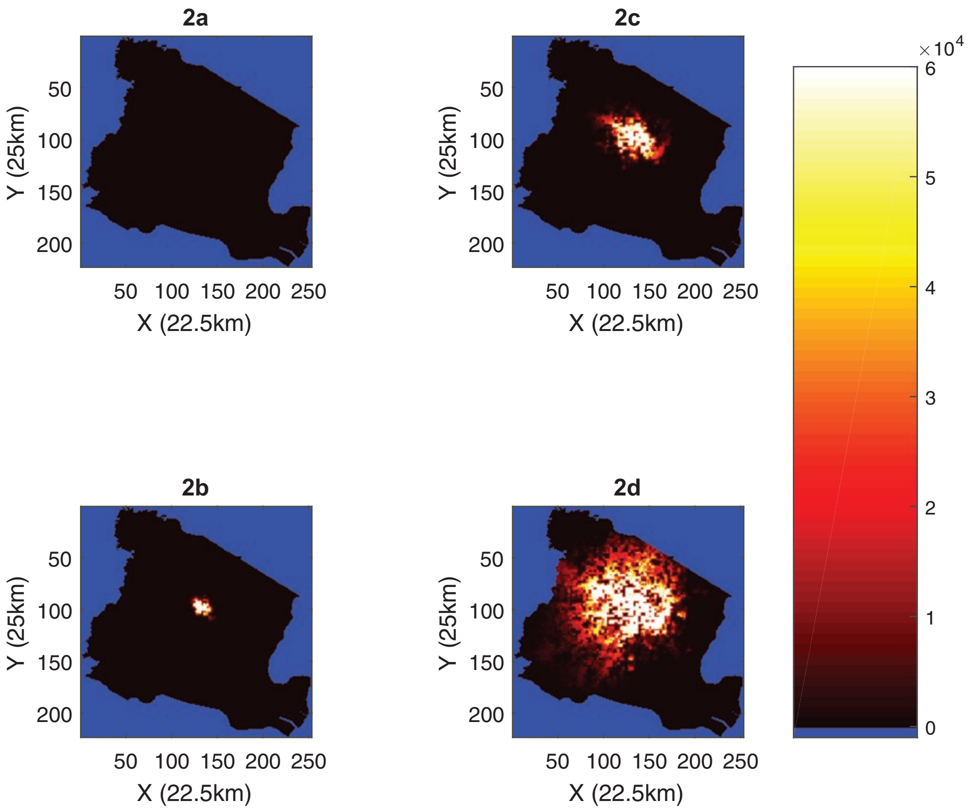

Fig. 2. Emerald ash borer population density at (2a) $t = 0$, (2b) $t = 5$, (2c) $t = 10$, and (2d) $t = 20$ yr.

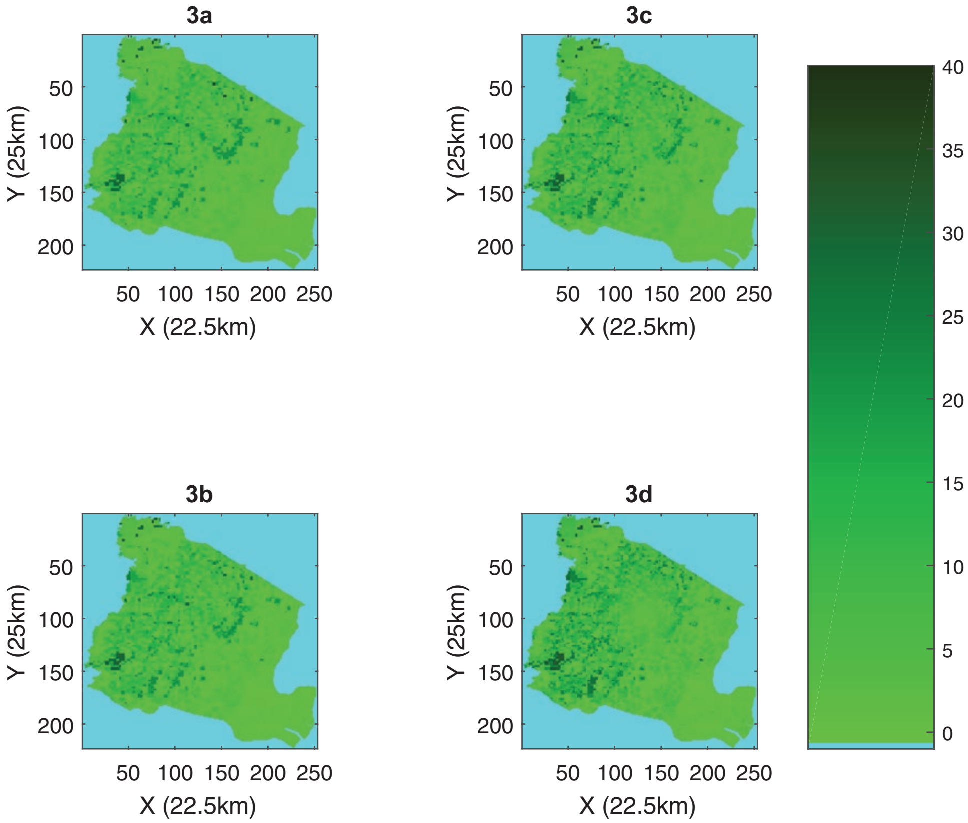

Fig. 3. Ash population over the course of 20 years. At (2a) $t = 0$, (2b) $t = 5$, (2c) $t = 10$, and at (2d) $t = 20$ yr. Due to the influence of emerald ash borer one sees a decline in ash. By year 20 there is a sizable gap that is kilometers across.

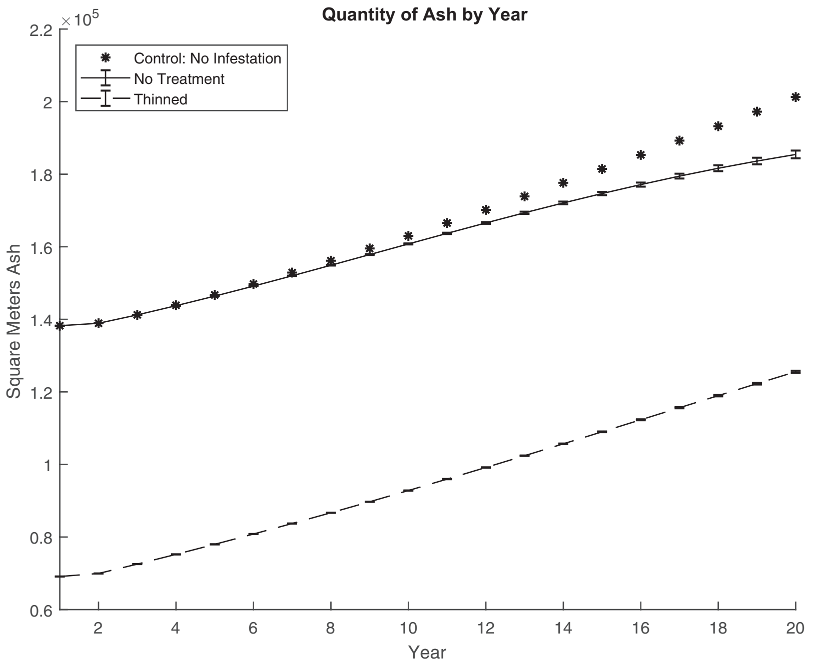

Fig. 4. Ash population under different scenarios. One sees that the greatest rate of growth occurs when there is no emerald ash borer. Although emerald ash borer causes a significant decrease in the ash population, thinning the ash forest results in a much greater decline.

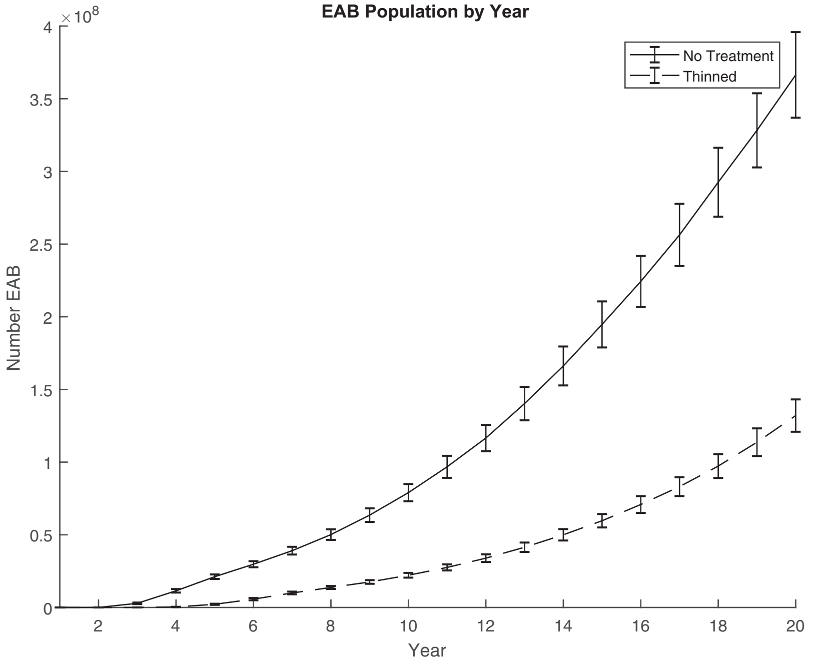

Fig. 5. Emerald ash borer population with and without thinning of the ash forest.

paradoxical method for reducing populations of emerald ash borer to ultimately preserve more ash.

Discussion

This modeling process serves to fill a gap by accurately modeling spread and mortality on a county scale. Since many models so far have operated on much smaller or larger scales, this model is significant since it provides a tool that can be used for management on a county, or state level. Additionally, the model can provide more accurate information on the county level, including seasonal fluctuations of emerald ash borer populations, and can be useful for local decision makers in counties that are either suffering from, or at risk of invasion from emerald ash borer (Kovacs et al. 2011, Prasad et al. 2010, Siegert et al. 2015, Mercader et al. 2016). Similarly, accurate maps of the area in question can help managers locate and eliminate trees to slow the spread of emerald ash borer. Finally, our model's predictive capabilities can be used to compute some of the

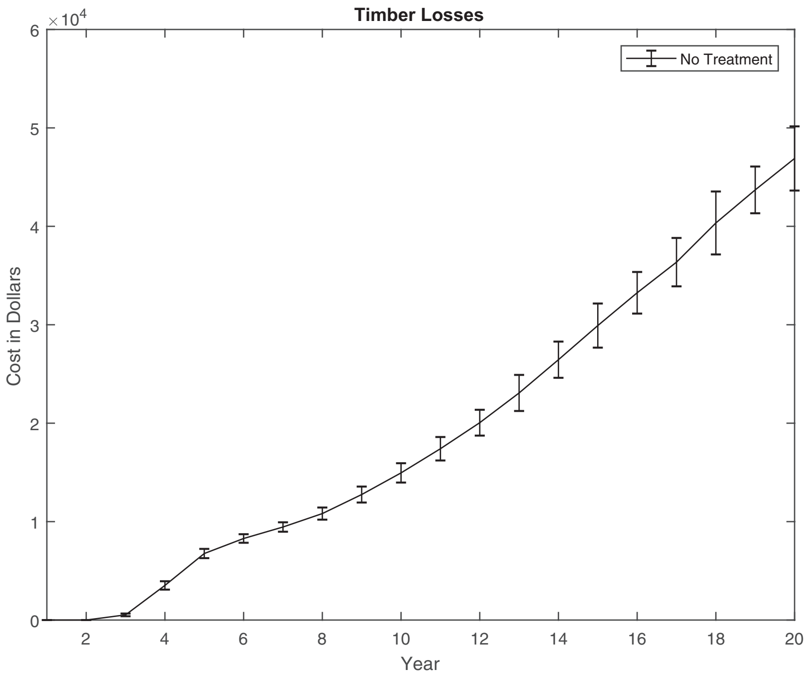

Fig. 6. timber costs. Timber costs per year with a 3% discount per year. The sum is over four hundred thousand dollars based on potential growth from a scenario run with no emerald ash borer.

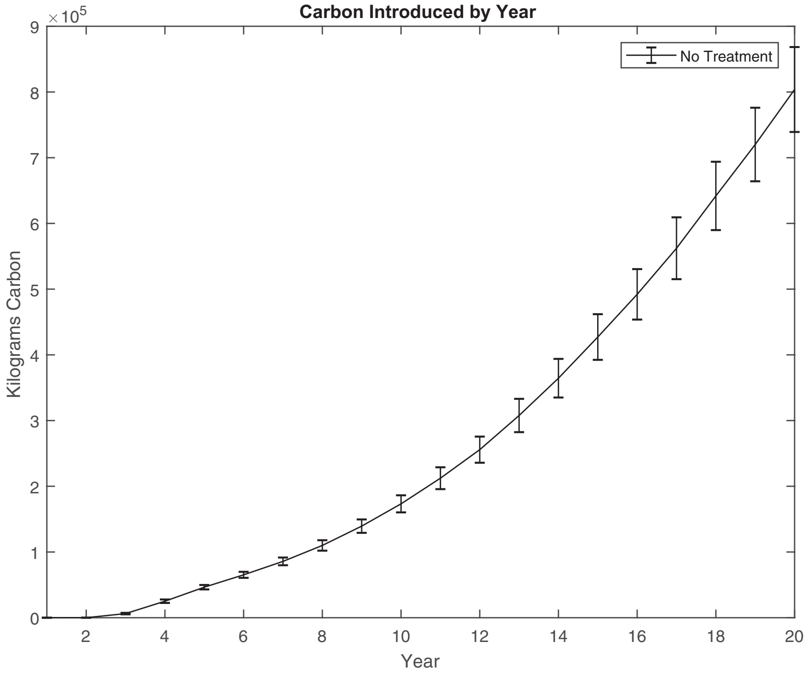

Fig. 7. Carbon content of killed and damaged trees. The addition of standing dead timber over 20 yr is over 6,000 metric tons.

economic and environmental costs of emerald ash borer infestation. The current model will be used by county and state level supervisors in New Jersey to identify the spread and impact of isolated populations over time.

While our initial results are promising, there are improvements that can be made. Satellite populations are currently difficult to map due to the random nature of their human-induced spread; future work on the model can incorporate roads so that one can predict how transport affects the long-range spread of emerald ash borer (Ali 2015; Barlow 2014). While the model is currently optimized for county-level mapping, it can be adjusted to perform either city or statewide analysis. Additional biophysical parameters can be added, such as predation related mortality. In the future, we plan to develop a multi-stage emerald ash borer model where different life classes are included to more accurately relate crowding and mortality to different life classes. Finally, future studies will focus on more sophisticated economic structures to better predict the monetary losses from emerald ash borer in rural and urban environments. Moreover, the model is general and can easily be adapted for studying invasive spread of other pests.

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