PHYS 4091 - Undergraduate Research Project

Modeling of the Spread of Spotted Lanternfly (*Lycorma delicatula*) in Vineyards

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1 Abstract

Spotted lanternfly (SLF), an invasive pest, poses a significant threat to agriculture, particularly vineyards. This study presents a simple model that depicts the spread of SLF within vineyards and adjacent forests. Various scenarios were investigated including different invasion onsets and different distribution areas. The results indicate that the initial conditions in the forest significantly influence the profile, direction, and intensity of the invasion of SLF infestation in the vineyards. Closer proximity of SLF sources to vineyards leads to faster and more intense invasions, which decrease in speed over time. However, the maximum penetration depth into the vineyard remains relatively consistent across scenarios, suggesting potential implications for insecticide treatment areas. Insights from this research can inform more targeted and efficient management strategies for SLF infestations, benefiting both vineyard owners and environmental conservation efforts.

2 Introduction

Lycorma delicatula (Spotted Lanternfly - SLF), native to Eastern Asia, is an invasive species in the northeast of the United States that causes both ecological and economic problems. The estimated current economic impact is around $50 million per year. It is also invasive in South Korea, where it has been documented to be a pest for fruit trees and grape vines.

SLF is univoltine, and the egg masses hatch between May - June while staying dormant during the winter. They reach their adult instar at the end of July in which the wing development gets completed. In the adult stage, SLF is in its most mobile form and looks for host plants. Tree of Heaven (*Ailanthus altissima*), another invasive species in the U.S., is one of its preferred hosts and is known to increase their survival chance and reproductive investment [1]. SLF was first detected in PA in 2014 and currently has spread to multiple neighbor states. *Ailanthus altissima* is also present in PA forests. Current control strategies include removal of tree of heaven, exclusion netting, placing sticky traps on trees, destruction of egg masses, and treatment with insecticides. SLF infestations in vineyards mostly observed around the edge and the recommended insecticide treatment area is the first 50 feet from the edge [5].

3 Background

3.1 The Model of the Spotted Lanternfly Spread

This part of the model is created by Jacob Samuel Woods.

3.1.1 Flight

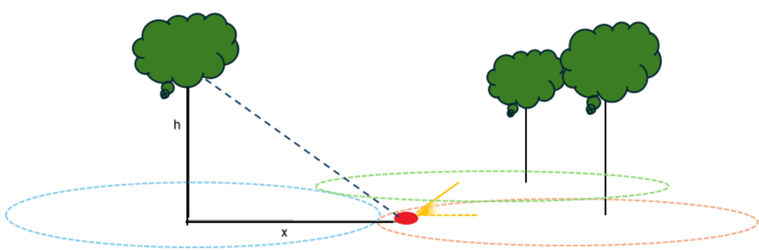


Figure 1: The demonstration of SLF's gliding motion

In our model, SLF's mobility is proportional to the height of the host tree, which is similar to a projectile motion; however, it's linear to capture the SLF's gliding behavior and is directed randomly from the tree using a jump kernel. SLF jumps off the tree 4 times a day.

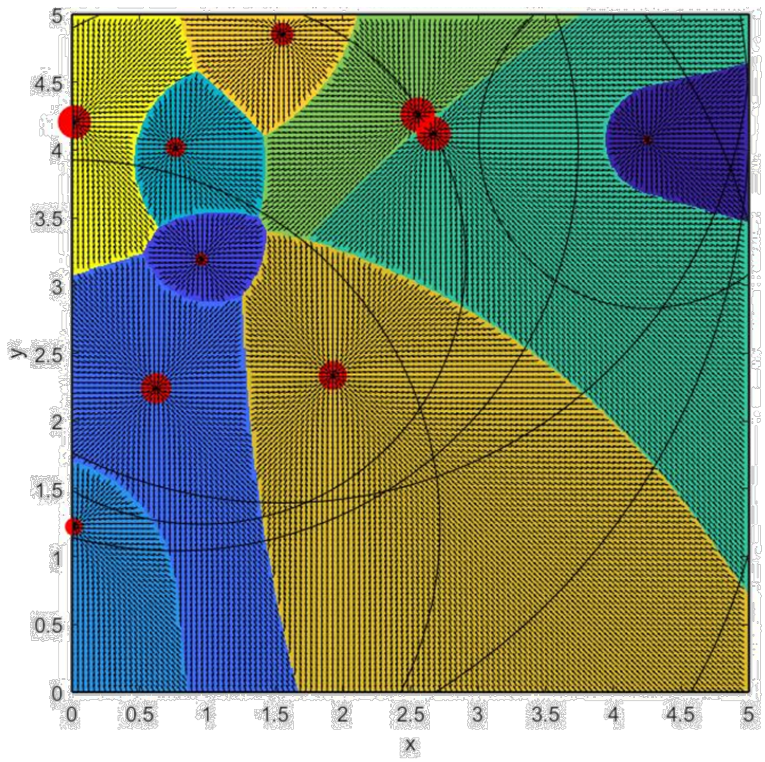


Figure 2: The zones of attraction of each tree

The attractiveness of each host at a point on the map is defined as the host's relative height times its attractiveness coefficient. After landing, the lanternfly moves towards the most attractive tree, as seen from its location. It changes its course along the way if the most attractive tree changes. The sets of points where each tree is most attractive induce a weighted Voronoi tessellation of the domain. An SLF in a Voronoi cell, or "zone of attraction," will head directly toward the corresponding host. Once it reaches the tree, it climbs up.

3.1.2 Random Walk & Transition Matrix

For simplification, we assume that the time SLF spent off the hosts is small relative to the time on the hosts. This results in a random walk on hosts, which is simulated by a Markovian Transition Matrix, which could be calculated using jump kernel and attraction zones, that determines the change of the population size hosted by trees or the vines

$$P_{n+1} = (1 - \tau)P_n + (\tau)MP_n \tag{1}$$

Here, $\mathrm{P_n}$ is the population vector for trees at time n, $\mathrm{P_{n+1}}$ is the next time step's, and τ is the moving portion. Different initial conditions result in different SLF infestation maps on the vineyard.

4 Materials and Methods

This model was programmed on Matlab. The areal views are acquired and inspected via Google Earth. Some of the quantitative analysis were carried out on R.

4.1 Modifications on the Original Model

The average SLF jump is between 21.3 m - 4.9 m, according to Wolfin et al. 2019. The reason for the given range was the presence of individuals with very different flight capabilities, which were explicitly categorized as two distinct groups. To include all varieties, the ratio of jump distance with respect to height of the host was set to 1, while tree height was ranging from 9-20 m and the grapevines are 1.5 m tall.

It has also been observed that SLF prefers plants with high turgor pressure and with high sap-sugar concentration, like grapevines, which allows them to feed on sap with greater efficiency [4]. This preference was incorporated into the model as 3x grapevines' default attractiveness related to their height and distance. This adjustment made grapevines to be more attractive relative to their height of 1.5 m but still far less attractive than the shortest tree (9 m).

The plotting of the model was also adapted to the increased quantity of hosts. Previously, the visual output of the simulation was as in Figure 3.

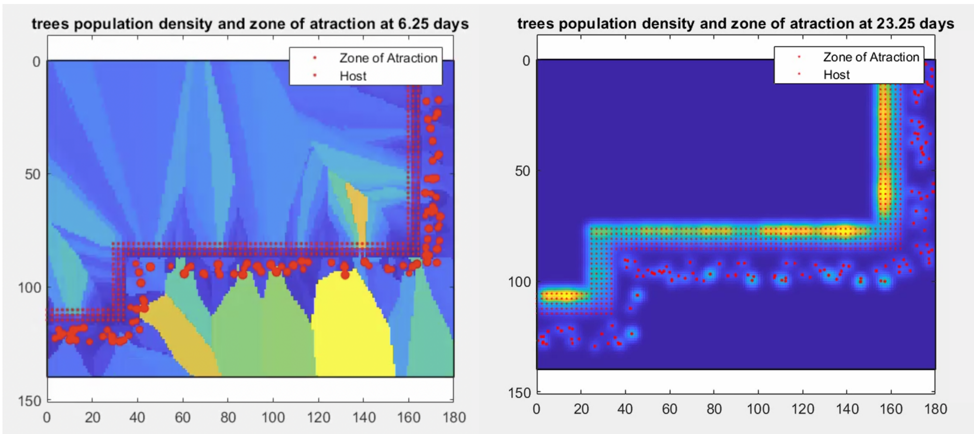


Figure 3: The old plotting and the new version

The domain was partitioned into attraction zones based on trees and each attraction zone was colored based on the SLF population in the corresponding tree. To make simulation maps more user friendly, they were converted into heat maps where population density at each point $z(x, y)$ on the heat map was calculated with a Gaussian function as follows:

$$z(x,y) = \sum_{i \in Trees} P(i) \frac{1}{2\pi\sigma^2} \exp\left[-\frac{(x-x_i)^2 + (y-y_i)^2)}{2\sigma^2}\right] \tag{2}$$

The Gaussian heat map was later improved by adding contour lines to represent invasion fronts.

4.2 Modeling of a Specific Landscape

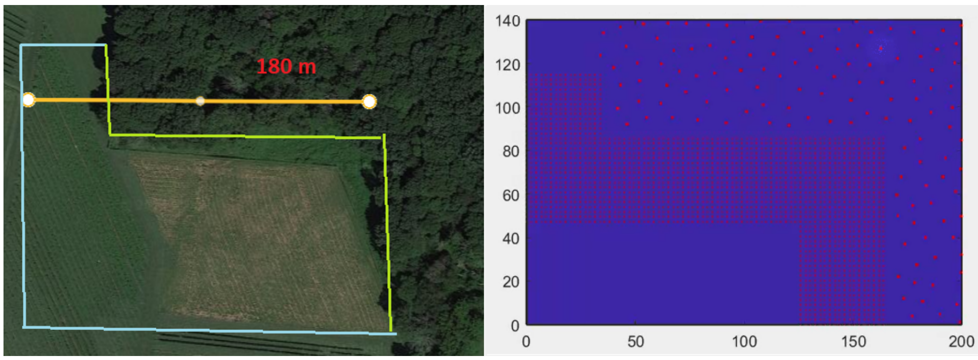


Figure 4: The areal view of 1723 Vineyards, LLC and the landscape model

In this model, we have selected a specific vineyard (1723 Vineyards, LLC) where interesting lanternfly invasion patterns were observed by the vineyard's owner. The vineyard was very close to a dense forest which had a Tree of Heaven population. The lanternflies were observed, moving into the vineyard from the forest and remaining in the vineyard rather than going back to the forest with *Ailanthus altissima*.

The landscape was replicated from its aerial view with its exact dimensions around a particular corner with a unique shape. The vines are 1.5 m tall and placed uniformly 2.25 m apart from each other. The dense forest consists of randomly placed trees with varying heights (from 9-20 m) with a minimum distance of 8 m, which is a consideration of the crown width of an average tree. *Ailanthus altissima* a larger crown width of 10 - 15 m [7]. The forest spacing was planned as a combination of (average) trees and rather bigger trees like Tree of Heaven. In all simulations, SLF invasions start from certain trees that are labeled as "source trees" which have a fixed population of SLF to portray great abundance or the heavy lanternfly flux from the deep forest.

4.3 The Simple Model

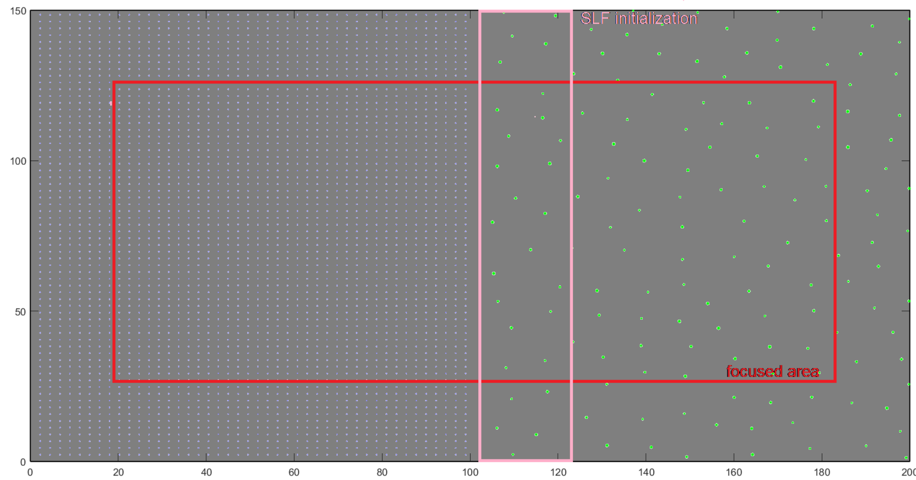


Figure 5: The plotting and the SLF initialization areas of the simple model

The simple model was created to make more quantitative inferences for the spread by reducing the complexity of the landscape. Spacing and height of the plants were kept the same with 1723 vineyards model. There is a 6 meter gap between the vineyard and the edge of the forest which was also initially used to model the 1732 Vineyards. The SLF infestation was started on a larger map [0,200] $\times$ [0,150] as in Figure 5, then focused on a smaller area [20, 180] $\times$ [20, 130] to exclude the effects of the no-flux borders. The focus area was selected based on the spread profile in the larger map.

In this setup, the goal is to investigate how the distribution of the SLF in the forest affects the invasion into the vineyard. The average number of adult lanternflies on an infested vine was measured as around 10 [5], so the initialized number of SLF was selected as "10$\times$ number of hosts (31840 agents)" and kept the same in all runs.

The initialization area in the forest was increased with 20 m increments on the x axis to create a comparison for different distribution levels in the forest.

5 Results

5.1 Spread in the 1723 Vineyards, LLC

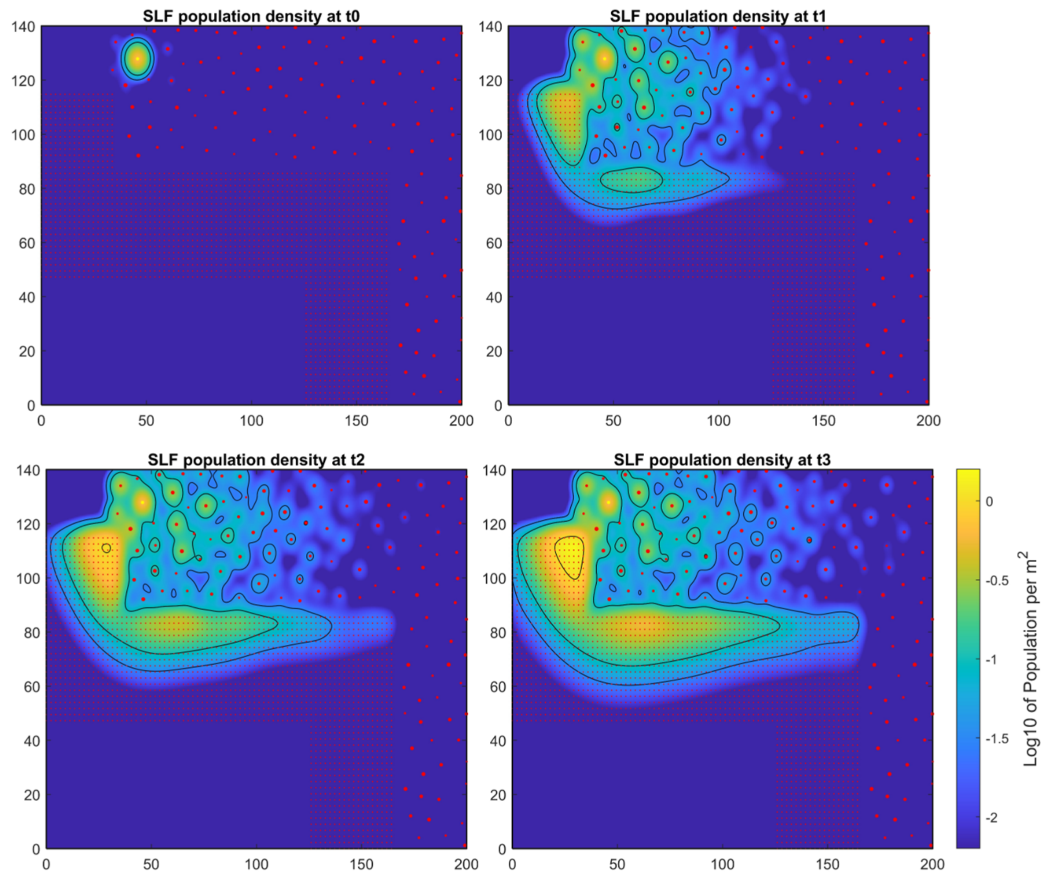


Figure 6: Simulation of SLF Spread from Single Tree from North

A single source tree at the northern side of the vineyard. This arrangement could depict a new introduction of the species to the habitat, like a hatch of an egg mass or the survival of a population on a tree after an insecticide treatment.

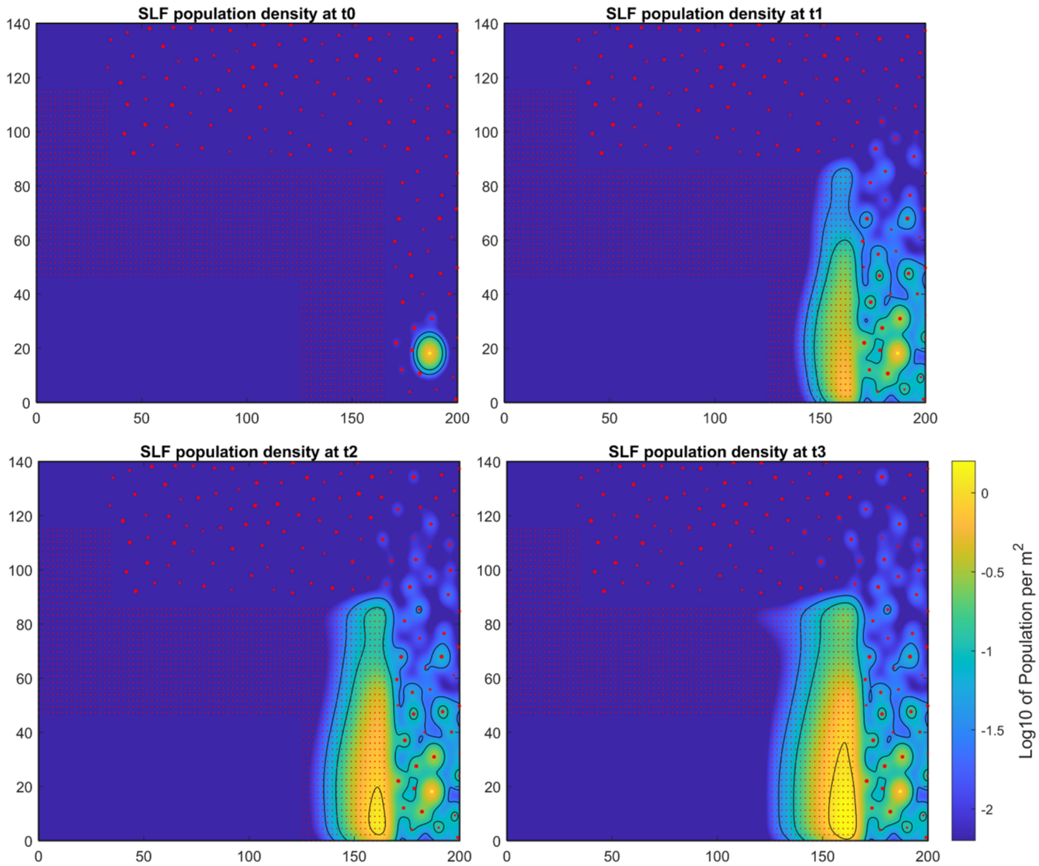


Figure 7: Simulation of SLF Spread from Single Tree from East

Same conditions happening at the eastern side of the vineyard. This variation shows how the initial population's location can affect the appearance of the invasion in the vineyard.

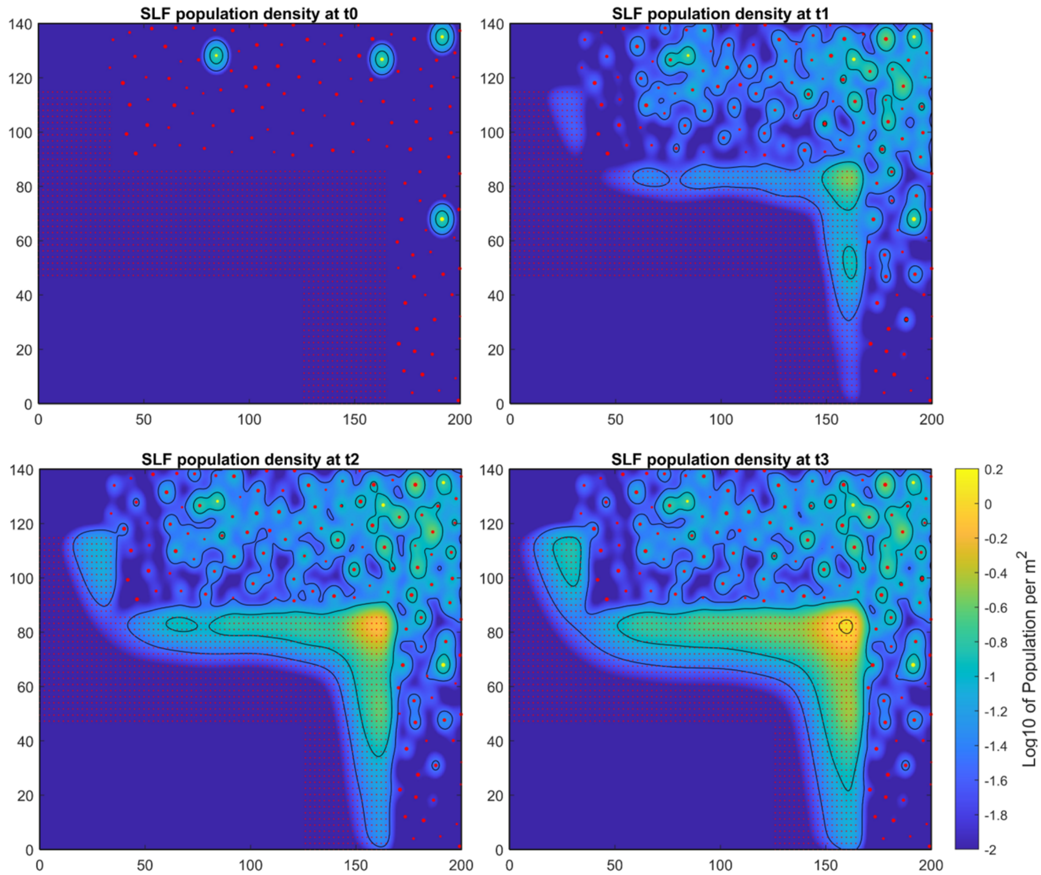


Figure 8: Simulation of SLF Spread from Random Trees in the Forest

This model represents greater abundance in specific trees in the forest. Some trees can be more preferable to SFL especially for egg laying. For example, Tree of Heaven was observed to increase the number eggs laid by females approximately 7 times [1].

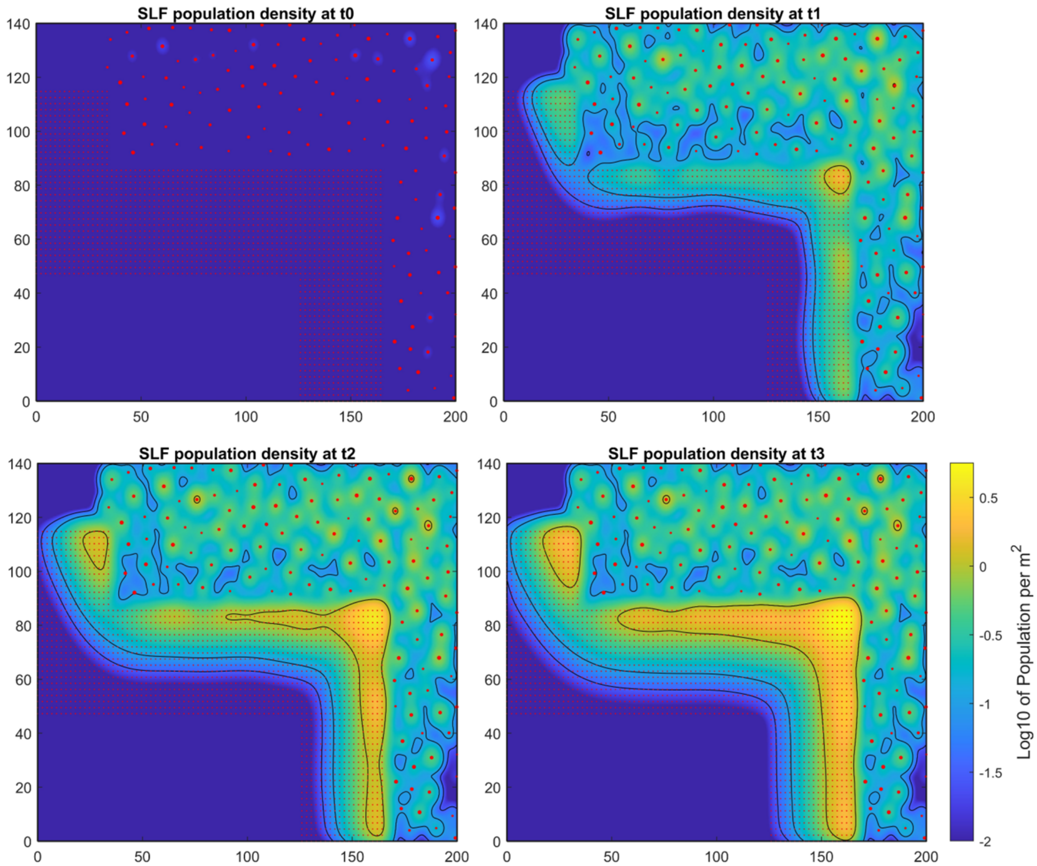


Figure 9: Simulation of SLF Spread from the Deep Forest

In this setup, the source trees are hidden at the outer line of the plot, which simulates the SLF flux coming from the part of the dense forest that is not included in the modeled landscape.

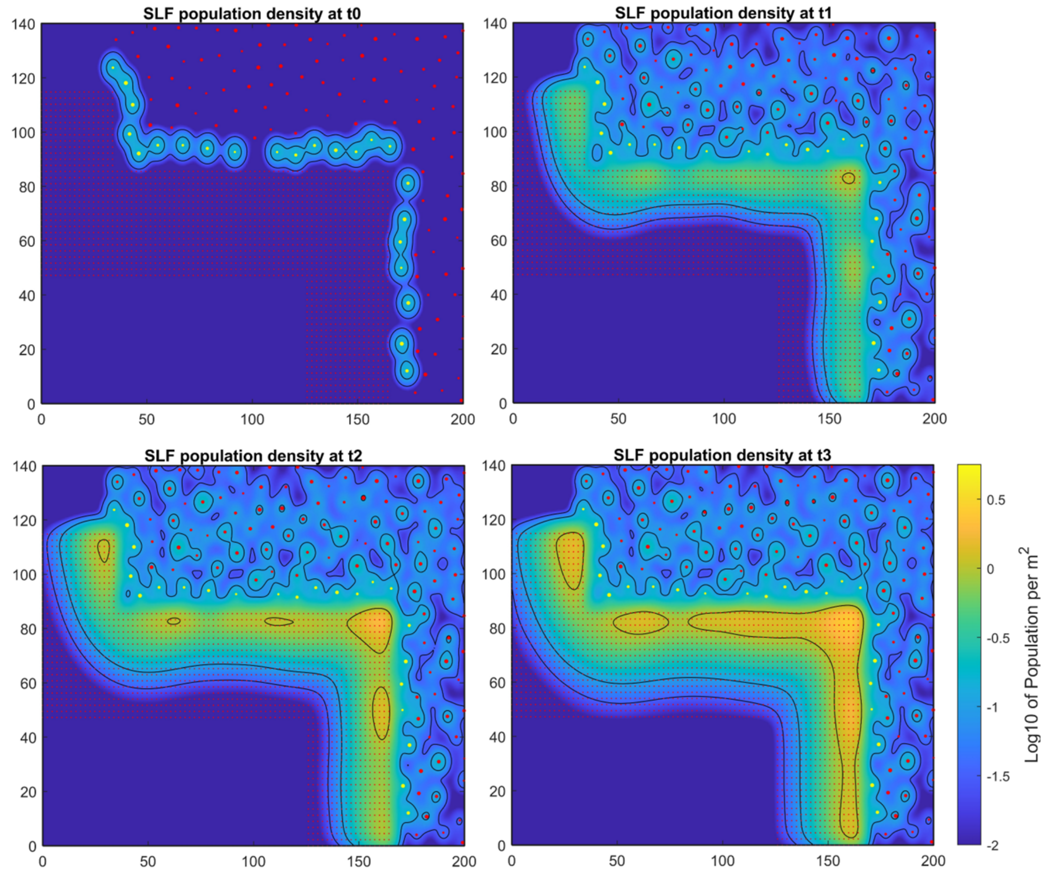
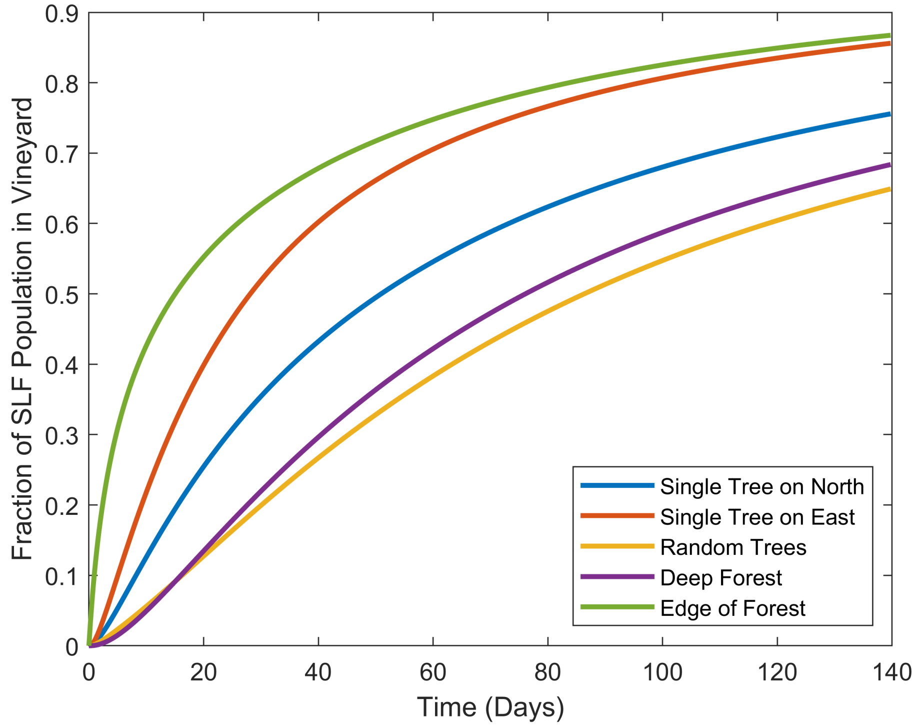


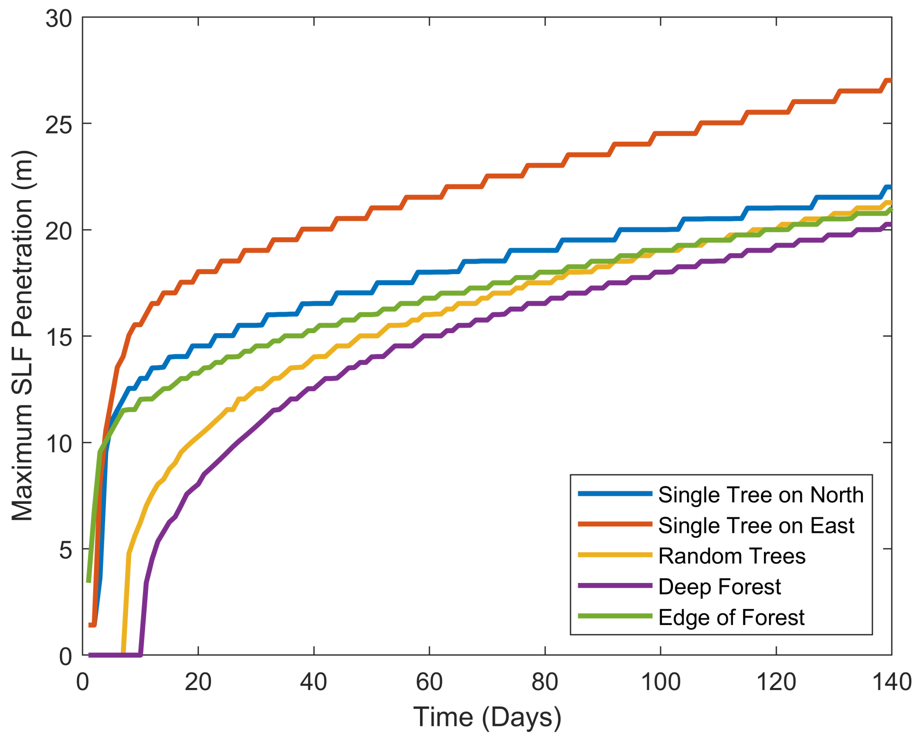
Figure 10: Simulation of SLF Spread from the Edge of the Forest

Same amount of total fixed population with the deep forest setup above was placed at the edge of the forest. It's shown that some insects develop " sun-seeking " behavior depending on their body size or their thoracic temperatures [8]. There is a chance that SLF prefers edge trees which could provide more sunlight exposure.



Graph 1: Fraction of SFL Populations Invading the Vineyard over Time

In Graph 1, the fraction of the total SLF population in the vineyard was plotted over time. It can be seen that the fraction of the total SLF population in the vineyard increases over time. Nevertheless, the increase rate is decreasing.



Graph 2: The Max. Penetration Depth into the Vineyard for the Same Population Density of SLF

For Graph 2, the normalized population density at each point on the map were calculated and the points where the normalized population density was above a certain threshold inside the vineyard were filtered. The maximum distance among the points to vineyard border were plotted over time.

5.2 Spread in the Simple Model

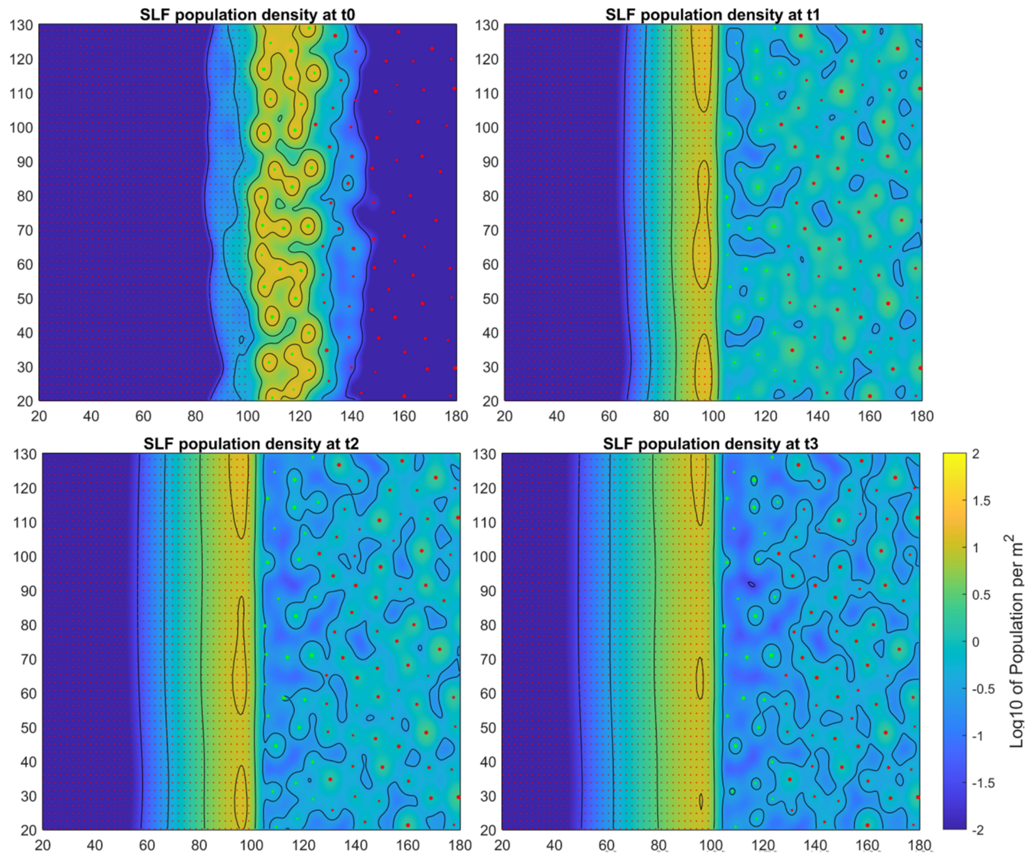


Figure 11: Simulation of SLF Spread from Trees between 106m-126m

The spread of SLF from the very edge of the forest can be seen in Figure 11. Different then the 1723 Vineyards model, here, the Gaussian diameters were adjusted to match the spacing of the vines in the vineyard and amplified for the forest. Initialization trees are shown as green.

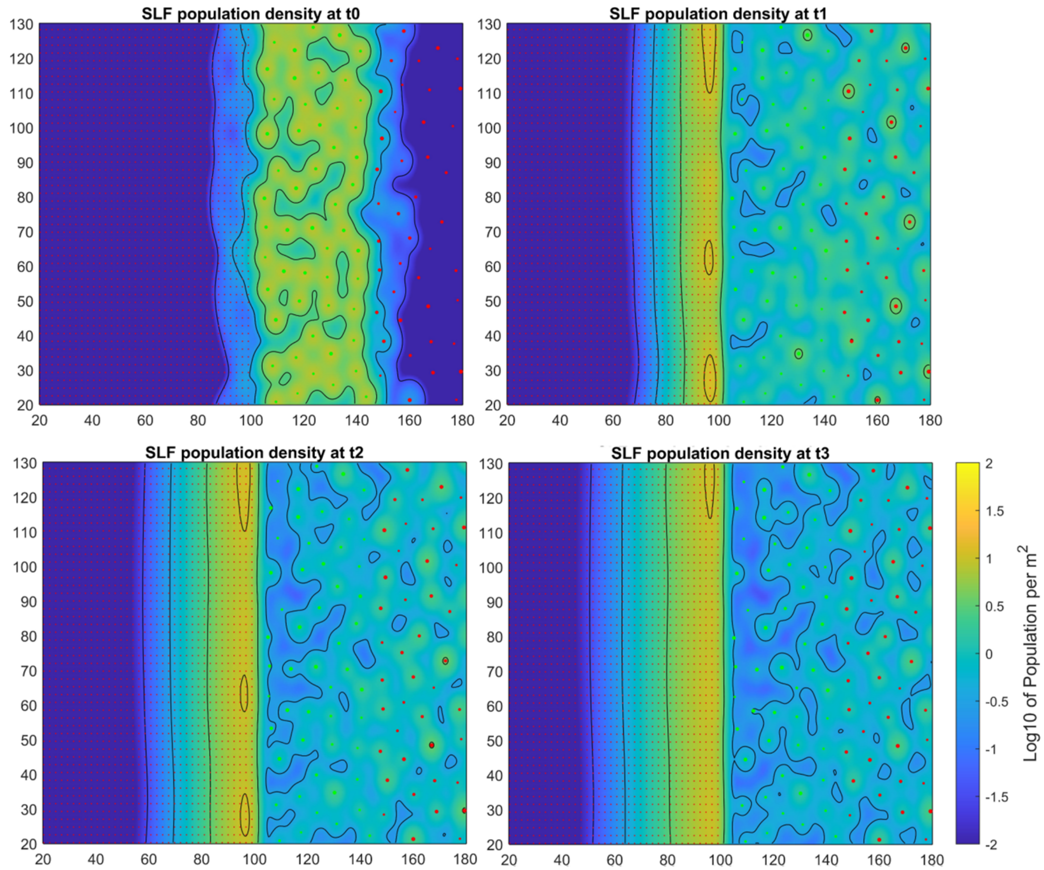


Figure 12: Simulation of SLF Spread from Trees between 106m-146m

In Figure 2, the initialization area was doubled for the same number of agents. Once again, this type of placement could represent possible suns-seeking behaviour of spotted lanternfly. By changing the initialization area, we could represent the variations of sunlight penetration into the forest.

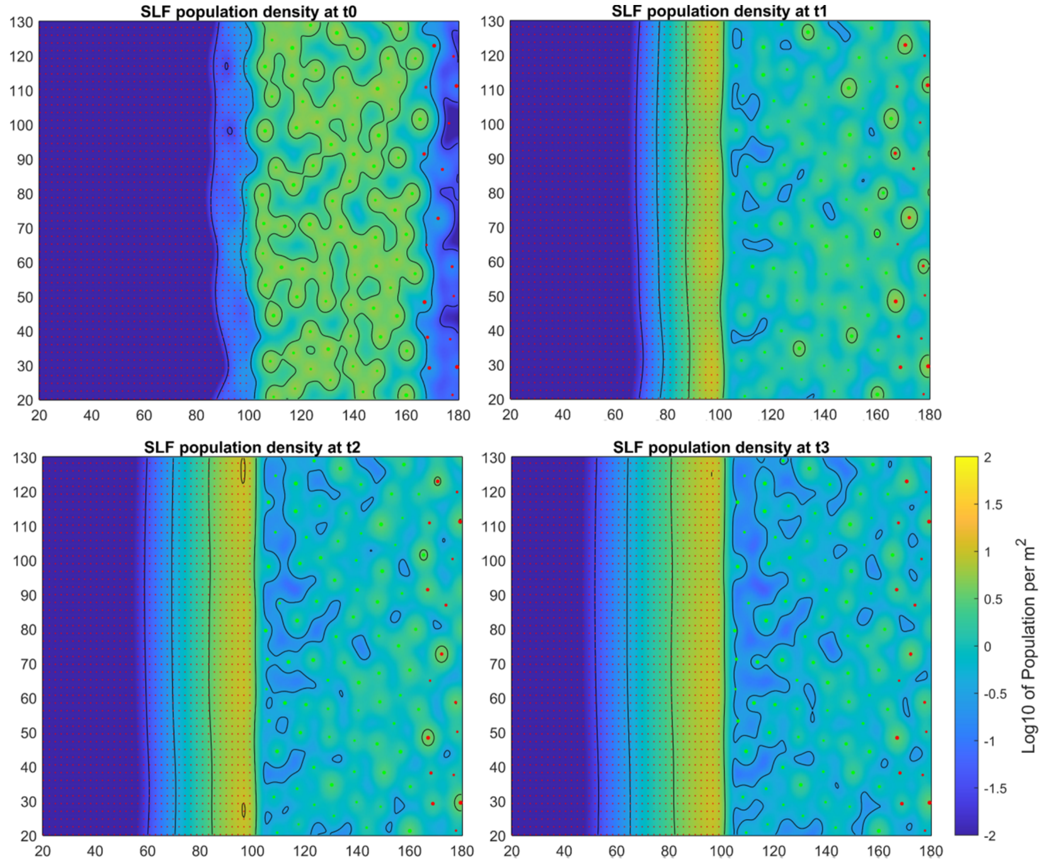


Figure 13: Simulation of SLF Spread from Trees between 106m-166m

Here, the spread starts between 106 - 166 m interval on the x-axis which is around 2 times more trees than simulation 1 in Figure 11.

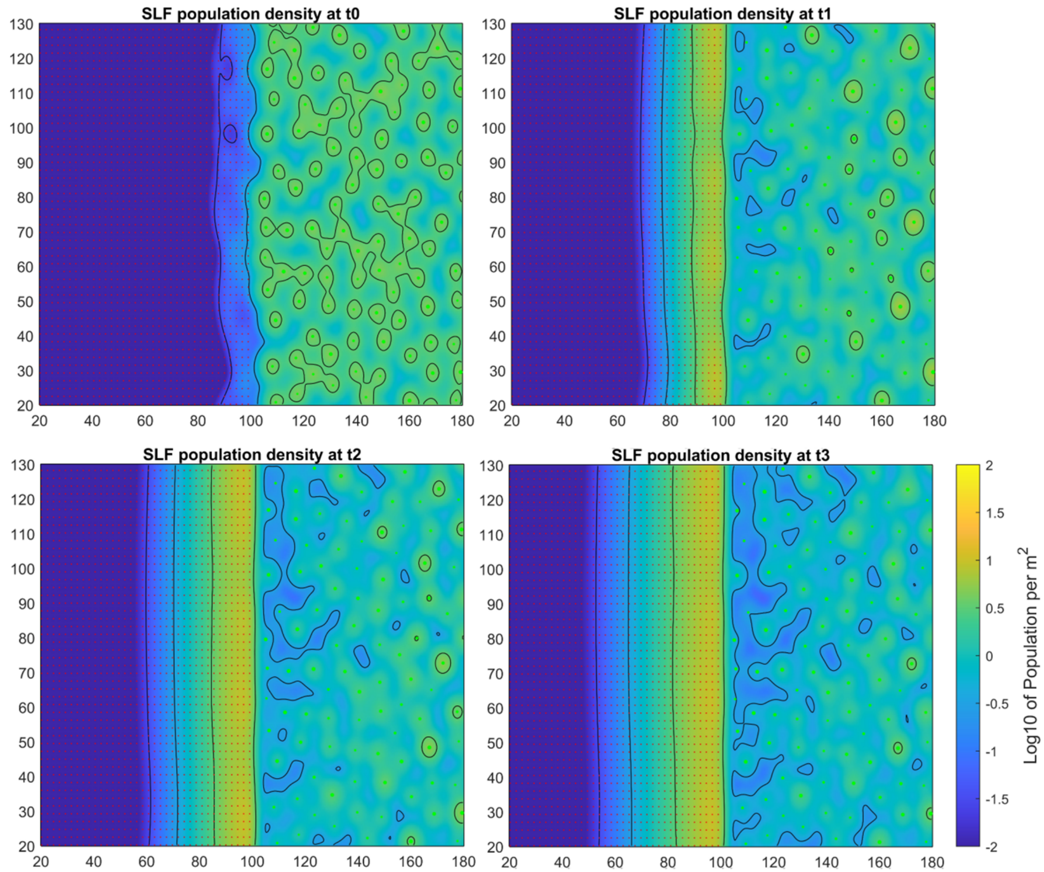
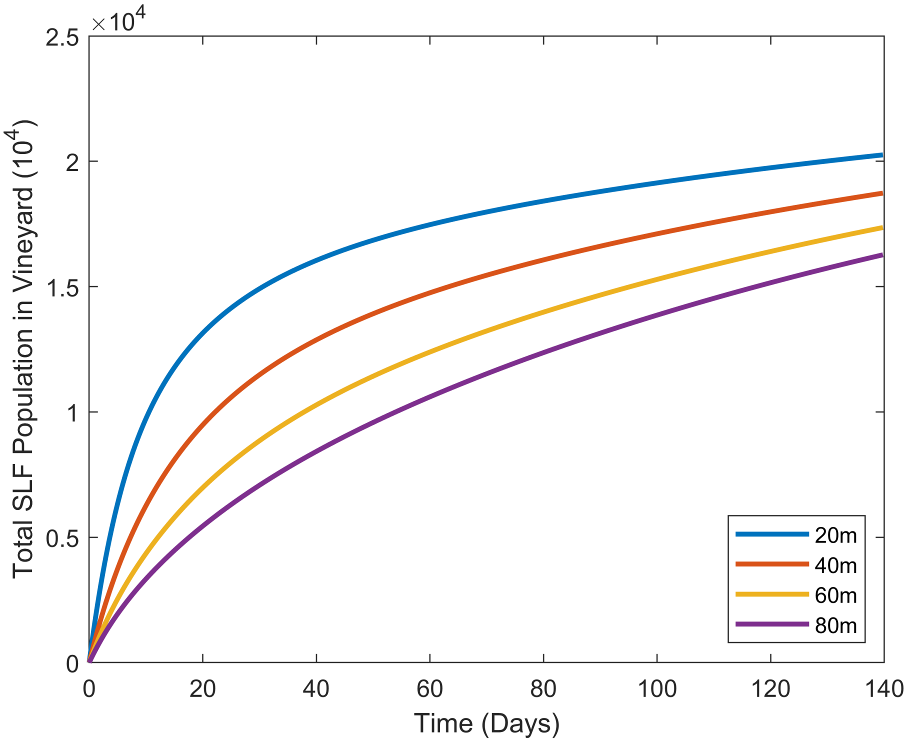


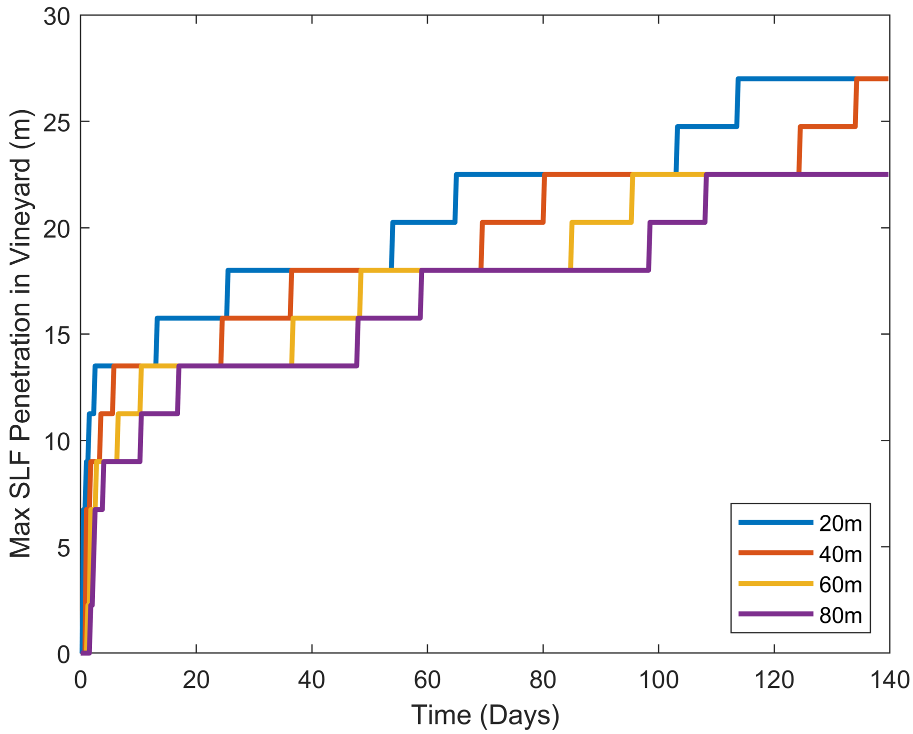
Figure 14: Simulation of SLF Spread from Trees between 106m-186m

In this simulation, even though all trees may seem to be initialization trees, since the actual calculated map is [200, 200] there are trees that SLF can spread outside of the plot.



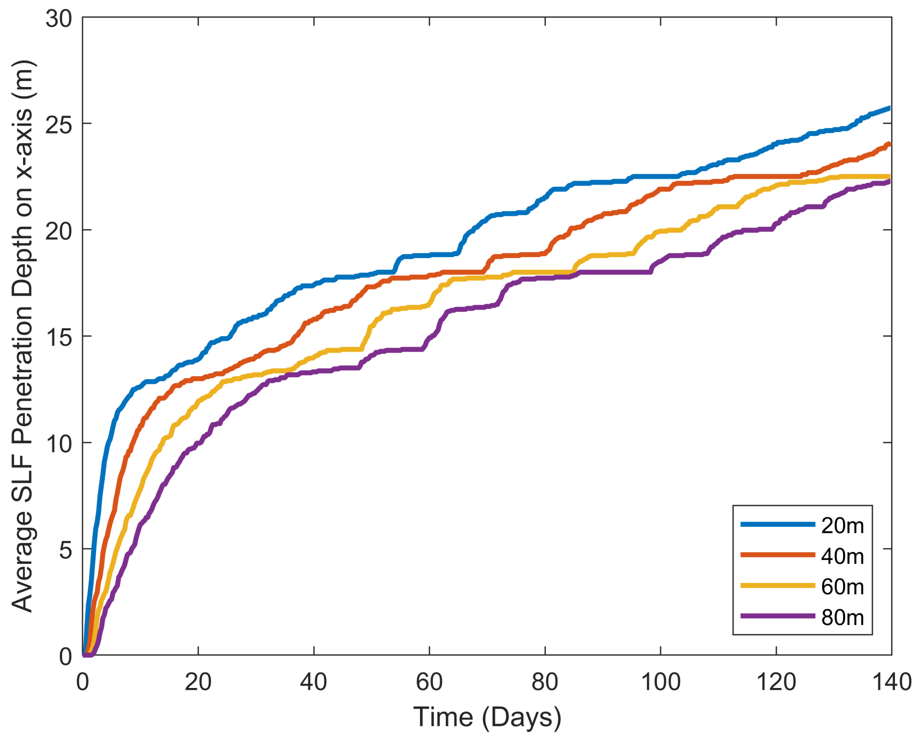
Graph 3: The number of SLF in the vineyard through time with different forest distribution areas.

In Graph 3, the total number of SLF in the vineyard was plotted over time. 20, 40, 60, and 80 m refer to the width of the initialization area on the x-axis, all starting from the 106 m mark. The population increased much faster at the beginning when the SLF population initialized closer to the vineyard. We could observe this in time period 0-20 days. In the later period, the population increase in the vineyard speed became similar.



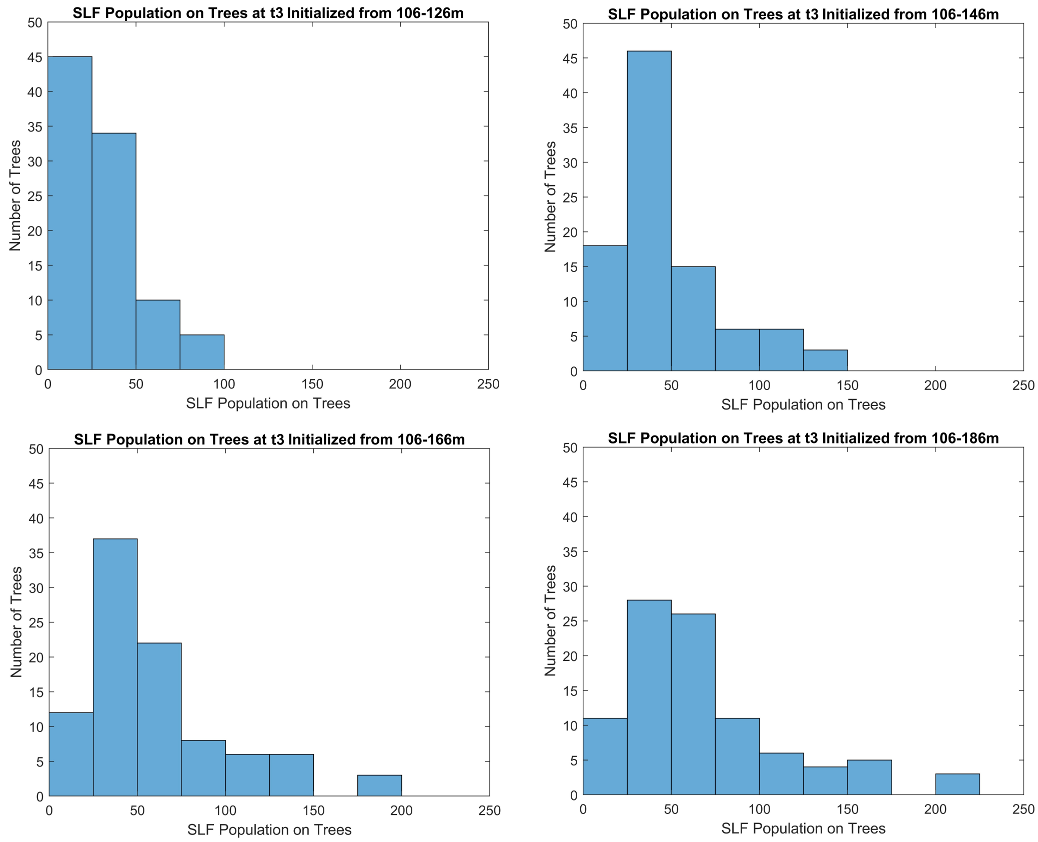
Graph 4: Max penetration depth on the x-axis for vines infested with more than 10 lanternflies

To plot maximum SLF penetration in vineyard, the vines with SLF population above the threshold (10 agents) were filtered, the maximum distance to the vineyard border was measured and plotted through time.



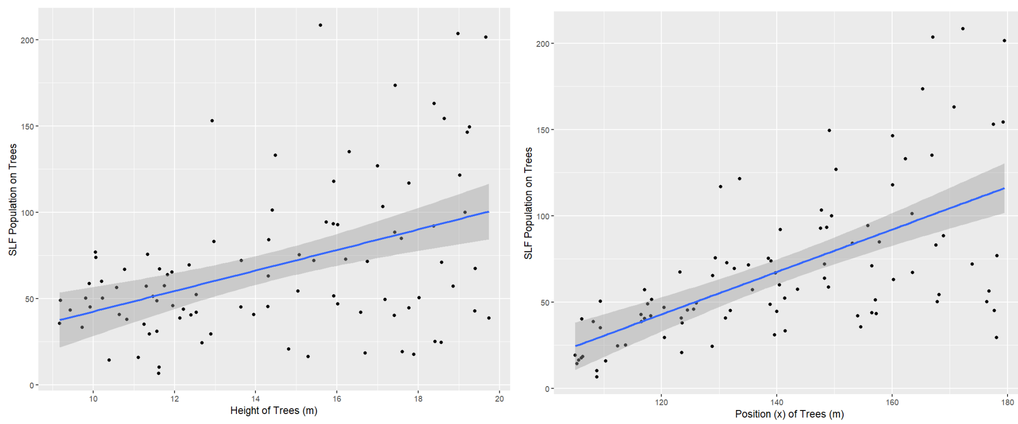
Graph 5: Average penetration depth on x-axis for vines infested with more than 10 lanternflies

The average penetration was calculated by selecting the vines with more than 10 lanternflies. The number of selected vines multiplied with the distance among neighbor vines (2.25m) on the x-axis and divided to the number of vines in one column on y-axis. In graph 4 and 5, we observe that penetration difference between different initialization areas emerges in the beginning. After some point, this difference in penetration remains almost constant.



Graph 6: The number of trees with their populations of SLF for all scenarios at t3

This histogram shows the distribution of the SLF among the forest trees for different initialization areas. The total number of forest trees in the plotting area was 94, which means the number of trees also approximately represents the percentage of total trees. Here, we show that there is a significant variation in the populations of the forest trees, which could not be clearly perceived from the heat maps.



Graph 7: The height of the trees or the x-positions vs. the population sizes on the trees at t3 for initialization from 106 - 186 m

In Graph 7, the clear relationship between the population size and, the height of the tree & the distance from the vineyard were shown. As the meters on the x-axis increase, the distance from the vineyard increases. This is explanatory for the variations in population size in the forest.

	Dependent variable:
	SLF Population on Trees
x-position of Trees	1.302***
	(0.131)
Height of Trees	6.623***
	(0.910)
Constant	$-$210.374***
	(23.583)
Observations	94
R^2	0.610
Adjusted R^2	0.601
Residual Std. Error	28.137 (df = 91)
F Statistic	71.176*** (df = 2; 91)
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 1: Regression results of Population $\sim$ Height + x for Trees

The significance of the distance from the vineyard and the height of the tree is more quantitatively analyzed with regression. Both of the elements we investigated were significantly correlated ($p < 0.01$) to the population size which suggests that according to our model, the SLF population on trees increases with the height of trees and their distance to the vineyard. These two variables alone could explain 60% of the population variation among trees in our model.

6 Discussion

The vineyard's invasion profile, the direction, and the speed of the invasion, depends on the initial conditions in the forest and the proximity to the vineyard. When the source of the SLF is closer to the vineyard, the invasion is faster and more intense. Our model for 1723 Vineyards is explanatory for the vineyard's owner's observation of SLF remaining in the vineyard. When we compared the deep forest flux (Simulation 3) to the edge of the forest (Simulation 4), it is noticeable that if the invasion starts close to the vineyard, a lower fraction of the population will invade the forest trees even though they're more attractive.

In the simple model, we investigated the effect of distribution in the forest on the invasion of the vineyard. The number of agents in the vineyard increased faster with a more dense population in the forest closer to the vineyard. The maximum and the average penetration also increased with the closer initialization of the SLF population. However, the major difference in penetration emerges in the earliest times. The effect of the initialized area of SLF disappeared over time, and the differences stayed the same in later times. Our suggested treatment area is around 25 m into the vineyard from its edge based on vines infected with more than 10 lanternflies. Penn State's suggestion is around 15 m, which represents the 54% of the population in the vineyard [5]. Furthermore, we verified and demonstrated that the SLF population on the forest trees is increasing with the distance from the vineyard and the height of the trees.

An increased predictability of SLF's behavior and invasion patterns would be a very important advancement for controlling strategies not just as pests but also as invasive species. Understanding of the behavioral patterns of SLF can increase efficiency and reduce the costs of these management approaches for vineyards or other infested areas. Our model can be applied to various landscapes and can also guide further research and field studies of SLF. One of the areas of improvement is time dependency. The current model may not represent the realistic time frame since we only estimate number of jumps per hour,day or week for SLF without precise data. However, information is available on their hatching time and mobile period, vines growth cycle, and harvest time.

The model currently focuses on strategies for treatment areas however, it can be also useful for investigating other management methods like exclusion netting.

In exclusion netting, a net with narrow openings is used to create a physical barrier at the edge to prevent SLF entering the vineyard. This method is quite effective because of SLF's poor capability of flight [5]. The model can be modified to investigate optimal height for netting for given parameters of the environment.

Further knowledge on SLF's functioning can increase our model's precision.

References

[1] Urban, J. M., & Leach, H. (2023). Biology and management of the spotted lanternfly, lycorma delicatula (Hemiptera: Fulgoridae), in the United States. Annual Review of Entomology, 68(1), 151–167 `annualreviews.org/content/journals/10.1146/annurev-ento-120220-111140`

[2] Kim, J.G., Lee, EH., Seo, YM.*et al.* Cyclic Behavior of *Lycorma delicatula* (Insecta: Hemiptera: Fulgoridae) on Host Plants. J Insect Behav 24, 423–435 (2011) `link.springer.com/article/10.1007/s10905-011-9266-8#citeas`

[3] Wolfin, M.S., Binyameen, M., Wang, Y. et al. Flight Dispersal Capabilities of Female Spotted Lanternflies (Lycorma delicatula) Related to Size and Mating Status. J Insect

Behav 32, 188–200 (2019). doi.org/10.1007/s10905-019-09724-x

[4] Uyi, O., Keller, J.A., Swackhamer, E. et al. Performance and host association of spotted lanternfly (Lycorma delicatula) among common woody ornamentals. Sci Rep 11, 15774 (2021). doi.org/10.1038/s41598-021-95376-x

[5] Biddinger, D., Acevedo, F., & Centinari, M. (2023, July 7). Spotted Lanternfly Management in Vineyards. Penn State Extension. extension.psu.edu/spotted-lanternfly-management-in-vineyards

[6] Duke, A. (n.d.). Scientists examine potential economic impact of Spotted Lanternfly in PA.. Penn State University psu.edu/news/research/story/scientists-examine-potential-economic-impact-spotted-lanternfly-pa/

[7] Gilman, E. F., & Watson, D. G. (1993). Ailanthus altissima. Tree-of-Heaven. Department of Agriculture Forest Service, Fact Sheet ST-67. https://hort.ifas.ufl.edu/database/trees/trees_scientific.shtml

[8] Moore, P. Insect pollinators see the light. Nature 387, 759–760 (1997). nature.com/articles/42815#citeas