Susceptibility of Montgomery Park Trees to Emerging Invasive Pests

Justin Derato, Kelsey Gump, Nan Himmelsbach, Sarah Lank,
Marina Peterson, Bradley Simpson, Maggie Wartman, Tianchi Zhang

Under the supervision of Professor Carroll

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Gerrit Knaap, NCSG Executive Director
Uri Avin, PALS Director

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Executive Summary

This report provides recommendations to the Montgomery County Department of Parks on the management of four invasive pests: Asian longhorned beetle (*Anoplophora glabripennis)*, spotted lanternfly (*Lycorma delicatula),* oak wilt, and thousand cankers disease in managed park regions. To prepare for these potential infestations, an analysis of the risk to current park tree populations was performed using unique spatial and tree data characteristics. Additionally, a comprehensive interactive toolkit that provides park staff with information on best management practices was developed.

Researching the Pests

To evaluate risk of each pest, literature was reviewed to identify host species, relevant life history traits, and possible management strategies applicable to Montgomery Parks. The host species for each pest was then overlaid with a list of managed trees species to identify host species important for the final recommendations. Pest characteristics were considered when developing pest specific management strategies. General information on increasing park resiliency was also explored to propose the most effective management strategies.

Designing the Equation

To produce meaningful pest risk values for each park, a novel risk equation was designed using an array of current pest risk assessments. It utilizes a parameter of diversity, representing ecosystem resiliency, as well as a weighted measure of the host species' biomass available to each pest. The final risk values are then incorporated into ArcGIS to generate risk maps for the county.

Using ArcGIS

The intended function of the ArcGIS web application is to provide the Montgomery County Department of Parks management staff and administration with a detailed tree inventory analysis. The module is equipped with a mapped tree inventory complete with park statistics such as diversity, total tree count, species distribution and a risk value for each pest of concern. This tree inventory can be viewed on a spatial scale, allowing for visual representation of park and tree data across the county within various environmental management regions. The data is also intended to model risk susceptibility for four invasive pests within the region. This data can assist Park staff with mitigation planning and in developing an effective response to a spread of these specific pests. While it is intended for professional use, other functions can be added for public access to report potential sightings and include general information about invasive pests in urban parks.

Ecosystem Service Analysis

To inform future management actions, potential ecosystem services lost for each high risk host species were calculated. Results assigned a monetary value for each tree species based on mean tree characteristics provided by the Parks department. A general benefit evaluation of all the trees inventoried in Montgomery County parks was also generated using the iTree database.

Description of Problem

Invasive pests can threaten the health of urban forests and can cause significant environmental damage to parks. This project addresses four invasive pests that have the potential to enter Montgomery County in the near future. The pests of major concern to the Montgomery County Department of Parks include the Asian longhorned beetle, spotted lanternfly, oak wilt, and thousand cankers disease. Modeling the spread of invasive pests through spatial analysis and GIS methods can provide valuable insight for Park management staff. The development of a tree risk susceptibility model based on various attributes such as park biodiversity and host sensitivity allow for quantitative risk analysis leading to effective and timely mitigation strategies.

Key Goals and Objectives

Goal 1: Produce a comprehensive toolkit for each pest, including strategies for preventing and mitigating infestation, history of spread, and relevant supporting information.

Rationale: By synthesizing scientific literature and the management strategies of other locales, the toolkits will provide Montgomery Parks with contemporary recommendations for managing each pest of concern. These will be delivered concisely to make the management planning process more efficient for Montgomery Parks.

Objectives:

- Characterize the pest species, the history of their spread, and the damage and symptoms they cause in host trees.
- Identify environmental, spatial, and tree property characteristics that will influence the spread and susceptibility of trees found within the parks.
- Compile promising management strategies from scientific studies and established national and state management plans.

Goal 2: Create a risk equation to quantitatively assess park diversity and pest susceptibility based on a defined set of parameters from tree inventory data.

Rationale: Susceptibility of the parks to Asian longhorned beetle, spotted lanternfly, oak wilt, and thousand cankers disease can be predicted based on the initial park diversity and abundance of host trees. Research from Goal 1 can be used to identify host species and their level of susceptibility to each pest. Using this information and the tree inventory data from Montgomery Parks, the susceptibility of tree species and forests within the parks can be generally estimated.

Objectives:

- Determine host tree species for each pest under study.
- Assign each host species a risk factor value for each pest (scale 1-3).

Goal 3: Develop interactive maps that identify areas at risk for Asian longhorned beetle, spotted lanternfly, oak wilt, and thousand cankers disease infestation within Montgomery Parks.

Rationale: Visuals will be presented in the form of an online interactive map providing insight to risk susceptibility of four invasive pests based on park diversity and weighted host species cover.

Objectives:

- Spatially analyze unique park diversity and tree susceptibility values across Montgomery Park management regions.
- Apply GIS methods to park and tree risk through weighted factor quantification known as Risk Terrain Modeling (RTM).
- Deliver an ArcGIS Online tree inventory application with park and tree risk for each pest of interest within Montgomery County Parks.

Goal 4: Analyze the ecosystem services provided by at-risk trees.

Rationale: To help determine which parks or tree species should be prioritized, a cost analysis was conducted for host species.

Objectives:

- Quantify the tree value based on the structural and function approach.
- Determine the potential loss caused by the invasive species without appropriate management.

Background Research

Emerald Ash Borer: A Case Study for Invasive Species Management

Invasive pest species have become a considerable concern for forests in the United States. With the rise of international trading and traveling, humans are accidentally introducing non-native pests from all over the world. Indigenous insects and fungi typically pose little or no threat to forest ecosystem function. However, the introduction of host-specific invasive pests can dramatically alter the composition of native forests. Such alterations are exacerbated when the pest's host species comprises a significant portion of a forest's biomass. For instance, ash trees make up a significant portion of forests in the central and eastern U.S. and the introduction of the emerald ash borer (*Agrilus planipennis*) caused major changes in forest community assemblages (BenDor et al., 2006). Since its initial introduction in 2002, the emerald ash borer (EAB) has spread to 31 states and caused five species of ash to be "Critically Endangered" (USDA, 2018; Carrington, 2017). The EAB spread quickly across the U.S. and park managers are desperate to find ways to manage current infestations and prevent future spread to preserve native ash trees. The EAB and its management attempts can serve as a case study to prevent or manage other potential invasive pests.

Managing current populations of an invasive pest relies heavily on detecting infestations early and implementing aggressive control methods. Early detection of invasive pests like the EAB allows forest managers to stop an infestation before it grows uncontrollably large. Once detected, infestations can be controlled through pesticide application and eradication procedures. These control methods are effective for managing EAB but are extremely costly—federal and state resource managers spent $25 billion to treat, remove, and replace nearly 40 million ash trees in urban areas (USDA, 2018).

Preventing invasive pest spread can be achieved through federal quarantines, public outreach, and risk models. Federal quarantines can be used to regulate the transport of host tree material, preventing accidental introductions through infected wood. Another way to prevent accidental introductions is to increase public awareness of invasive species and common signs of infestations. While quarantines and outreach can help prevent introductions, risk models show promise in helping predict the spread of invasive pests and prompt forest managers to implement more aggressive management strategies. Forest managers can use tree survey data and tree susceptibility to model the risk a pest poses to their parks based on the tree species they target.

Pest Background and Hosts

When trying to identify successful management options for invasive pests, it is important to be aware of their life histories and biology. This information provides insight into formulating ways to manage a species. Here, we have species-specific general information about each pest studied for this project.

Asian Longhorned Beetle (ALB)

Life History: The Asian longhorned beetle (ALB) is a wood-boring beetle in the *Cerambycidae* family native to China and the Korean peninsula. In its adult stage this insect is from 1 to 1.5 inches long and possess long antennae. ALB has four general life stages: egg, larvae, pupa, and adult (USDA APHIS "ALB - About"). Its first outbreaks were identified in China in the 1980s, linked to a project that introduced many applicable ALB host trees to the area. In 1992, ALB was beginning to spread via trade routes through wood packaging. This beetle is now seen in North America as well as Europe (Haack et al., 2010).

Host Trees of Significance: Throughout ALB's entire life cycle, it feeds on a wide range of hardwood trees. These include: *Acer* (Maple), *Aesculus* (Buckeye), *Betula* (Birch), *Koelreuteria paniculata* (Golden Rain Tree), *Platanus* (Plane Tree), *Albizia julibrissin* (Persian Silk Tree, *Salix* (Willow Tree), and *Ulmus* (Elm Tree) (Sawyer, 2010; USDA APHIS "ALB - About"; Massachusetts Department of Agricultural Resources; Parker, 2012; Invasive Species Centre, 2015).

Damage: Signs of ALB emerge between 3 to 4 years after infestation of the tree. The tree dies over the next 10 to 15 years. Once a tree is infected, it cannot recover or regenerate. Signs include exit holes, egg sites, frass (sawdust), tunneling, weeping sap (flow from wounds or egg sites), unseasonable yellow leaves (stress), and branches dropping or dying (USDA APHIS "ALB - About").

Dispersal Methods: When female beetles are ready to produce, they lay eggs beneath the bark of host trees. Larvae then bore into the hardwood tree and feed on the tissues that provide the tree with nutrients. After many weeks, larvae tunnel into and continue to feed on tree tissues to develop over winter. As larvae feed, they form tunnels or galleries in tree trunks and bases. They tunnel into the growing layers (phloem and cambium), and eventually into the woody tree tissue (xylem). Trees infested with larvae can be identified by frass, a sawdust-like material, found at the trunk or branch bases. Frass is a product of the insect's burrowing. Over a year, the larvae develop into adults. After the adults emerge, they chew their way out of the tree, leaving exit holes about ⅜-inches wide. They then feed on the tree's leaves and bark for 10 to 14 days before mating and laying eggs. Adult females chew about 90 oval depressions (oviposition sites) and lays one egg beneath the bark at each. Adults can emerge at different times because the insect can overwinter in many life stages. This results in feeding, mating, and laying eggs throughout summer and fall.

Adult beetle activity takes place primarily in the summer and early fall, but adults have been seen from April until December. Adults usually remain on the tree from which they emerged; resulting in infestation for many generations. However, they can fly 400 yards or more to find a tree or mate (USDA APHIS "ALB - About").

Known Occurrences within the United States: ALB has been introduced in New York, Massachusetts, Ohio, Chicago, Illinois, New Jersey, California, Florida, Hawaii, Indiana, Michigan, North Carolina, Texas, Washington, and Wisconsin (University of Vermont "ALB Frequently Asked Questions"). Infestations in these areas are limited in size with eradication possible. Current quarantines include New York, Massachusetts, and Ohio (USDA APHIS "ALB - Quarantines"). A few regulated areas in New York (in 2011 and 2013), Chicago (2008), New Jersey (2013), and Canada (2013) have eradicated the pest via quarantines.

Spotted Lanternfly (SLF)

Life History: The Spotted Lanternfly, *Lycorma delicatula*, is an invasive planthopper native to China that has recently been reported in the United States (Order *Hemiptera*, Family *Fulgoridae*). An adult spotted lanternfly (SLF) will grow to around 1-inch long and have visibly striking spots along its forewings.

Host Trees of Significance: The diet of SLF consists of primarily *Ailanthus altissima* (tree of heaven), and *Vitis vinifera* (grapevine), however its known diet extends to a range of fruit producing trees and shrubs such as apple, apricot, maple, and plum trees, as well as hops and almonds. SLF is known for its affinity for hosts with a high sugar (sucrose and fructose) content (Dara et al., 2015; PDA, 2018).

Damage: Damage to host species is caused mainly by feeding from both nymph and adult. Feeding on the leaves reduces photosynthesis, weakening the plant. Additionally, consumption causes the plant to ooze and weep sap, inhibiting water and nutrient transport. Prolonged inhabitation of SLF on a plant leads to mortality of that plant (APHIS, 2014).

Dispersal Methods: Eggs are laid on smooth surfaces, of both natural and artificial origin. Eggs hatch in late spring through early summer and nymphs immediately start feeding by sucking sap, on any available species (Dara et al., 2015). Nymphs are agile and can climb up trees as soon as they emerge from egg. SLF uses its straw-like mouthpart to pierce the phloem tissues of plant's stem and leaves. Sap is removed through a sucking mechanism. When feeding, SLF secretes honeydew that further inflicts sap-saturated wounds. Exposed sap and honeydew contribute to the growth of sooty mold underground, which then attracts other insects such as bees, hornets, wasps, and ants that feed on the plant (APHIS, 2014).

Known Occurrences within the United States: Spotted lanternfly was first reported in the United States in Pennsylvania in 2014. By 2017, the range expanded across Pennsylvania and into Delaware and New York. Most recently, in January of 2018, SLF was reported and confirmed in Virginia. SLF is expected to arrive in Maryland by April 2018.

Oak Wilt (OW)

Life History: The pathogen responsible for oak wilt (OW) is a fungus called *Ceratocystis fagacearum.* In red oaks, the fungus produces pressure cushions that push the bark away from the wood, forming cracks. Fungal mats then form in these cavities. Chemical compounds released by the fungal mat may be detected several meters away from an infected tree and are responsible for the sweet fragrance that attracts beetle vectors (Juzwik et al., 2011). The origin of oak wilt is unknown; however it is generally believed to be non-native to the United States. Evidence indicates that it most likely originated in Mexico, Central America, or northern South America and that it arose from a single introduction (Juzwik et al., 2008).

Host Trees of Significance: The oak wilt fungus infects oak species (*Quercus* spp.). Red oaks display the highest susceptibility to the disease. White oaks are the most resistant. Live oak susceptibility falls in between that of red and white (Koch et al., 2010).

Damage: The fungus invades the vascular system of the host species and clogs the xylem. This hinders the transport of water and nutrients throughout the tree, which leads to leaf browning, wilting, branch dieback, canopy loss, leaf drop, and mortality. Red oaks generally develop symptoms within a few weeks and die within a few months after infection. White oaks have prolonged symptom onset and usually take years to die, if at all. Live oaks, an evergreen species of oak, have symptom onset within a few months and typically die around a year after infection. Fungal mat production occurs in red oaks (Juzwik et al., 2011).

Dispersal Methods: Oak wilt is spread through both above and below ground mechanisms. Beetles and humans are responsible for long-distance overland spread. Various species of nitidulid beetles (Nitidulidae: *Carpophilus* spp. and *Colopterus* spp.*)*, also known as sap beetles, act as primary vectors and transport spores from fungal mats to open tree wounds. Oak bark beetles (Curculionidae:

Pseudopityophthorus spp.) act as a minor vector and are generally considered insignificant to oak wilt spread. Humans can transport infected wood; however this cannot effectively spread the disease unless there are beetles available at the new location to transport the spores to uninfected trees (Hayslett et al., 2008; Juzwik et al., 2011). The main form of spread is locally through underground root grafts. Red oaks actively form root grafts, which are not seen in white oaks, therefore limiting white oak potential to spread the disease. When the roots connect they allow for the exchange of xylem contents between trees, which creates a means for fungal transport. Roots of infected red oaks can spread the disease for several years after tree death. Infection usually occurs in groups of nearby trees, called infection centers, due to root grafts. Infection centers expand through underground spread and increase in number as a result of overland spread (O'Brien et al., 2011).

Known Occurrences within the United States: Oak wilt was first reported in Wisconsin in 1942. It is now recognized in 24 states, including three counties in western Maryland (Figure 1) (Juzwik et al., 2011).

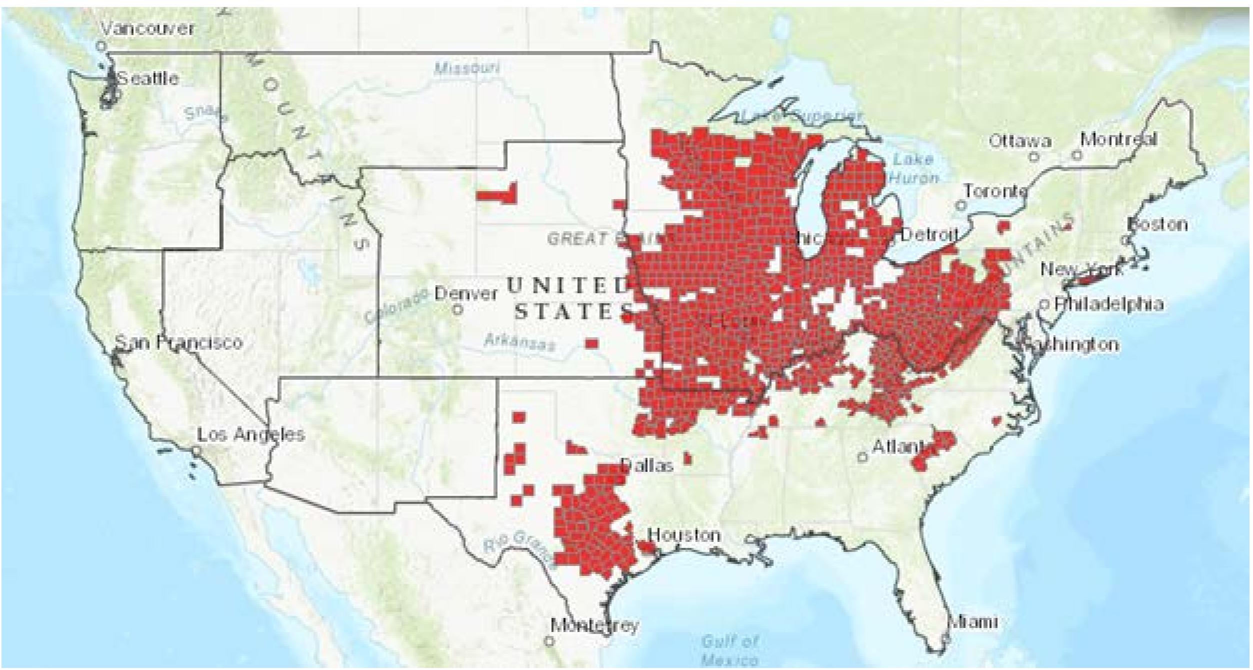


Figure 1: Oak wilt distribution as of 2016.

Figure source: https://foresthealth.fs.usda.gov/portal/flex/fpc?&level=2&center=-9846306.230683826,3706269.144424693&pC=24021&pN=Oak_Wilt

Thousand Cankers Disease (TCD)

Life History: The pathogen responsible for thousand cankers disease (TCD) is a fungus called *Geosmithia morbida*. Spores cling to the walnut twig beetle (WTB - *Pityophthorus juglandis*) and germinate in galleries carved beneath the bark of hosts (Daniels, et al., 2016). Native to Mexico and the southwest U.S., WTB is a small (1.5 to 1.9 mm) bark beetle that colonizes trees in the spring for reproduction, takes flight mid-April to late October, and winters in galleries dug into host trees. Larval development takes 6 to 8 weeks, producing about two generations per year. TCD likely originated via close coevolution between *G. morbida* and WTB along with at least one *Juglans* species (Faccoli, Simonato, & Rassati, 2016).

Host Trees of Significance: TCD causes the highest mortality in eastern black walnut (*Juglans nigra*) trees. All walnuts (*Juglans* spp.) occurring in the U.S. display susceptibility to TCD infection. Additionally, TCD may infect several wingnut (*Pterocarya)* species; none occur naturally in U.S. forests (Daniels et al., 2016).

Damage: The damage comes primarily from the girdling *G. morbida* cankers that restrict water and nutrient transport (Daniels et al., 2016). WTB entrance holes may be the size of a pinhead; galleries are 2.5 to 5 cm long. *G. morbida* grows slowly, manifesting as numerous coalescing cankers in the phloem near entrance holes and galleries of WTB, visible only after bark removal. Infected trees exhibit symptoms akin to drought stress: wilting and yellowing leaves, branch dieback, and canopy loss (Faccoli, Simonato, & Rassati, 2016). In the southwest, severe TCD infection can kill healthy trees within 2 to 3 years after initial symptoms appear. Since the disease has recently entered the east, the timeframe of mortality requires further study of the impact of different environmental conditions in the region. Low precipitation may worsen TCD symptoms, while high precipitation may induce recovery (Griffin, 2015).

Dispersal Methods: *G. morbida* spores cling to the wing cases of WTB. When the beetle burrows beneath the bark of a host tree, the spores germinate and spread throughout the phloem (Faccoli, Simonato, & Rassati, 2016). Distributive studies suggest a direct correlation between the spread and range of both species. High genetic diversity of *G. morbida* suggests multiple points of origin, likely via transport of wood products (Daniels et al., 2016).

Known Occurrences within the United States: TCD has been confirmed in 15 states (Figure 2), having started in the west around 2001 and spread throughout the region. Via transport of wood products, infestation of the east began around 2010. It was reported in Cecil County, Maryland on October 14, 2014. Land managers in Cecil County have not yet found evidence of severe infections or spread of WTB; pheromone traps are monitored regularly (Maryland Department of Agriculture, 2015).

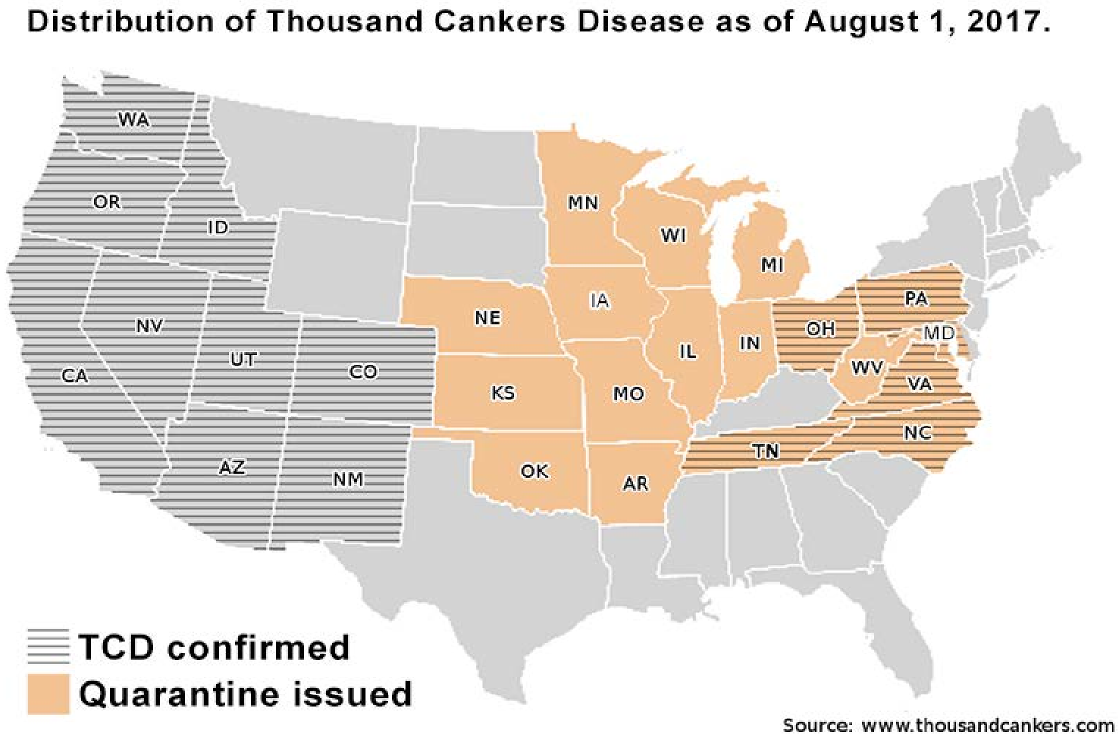


Figure 2. As of August 2017, known distribution of TCD in the United States. Unconfirmed but quarantined states have high walnut tree populations.

Risk Equation Methods

Host Tree Susceptibility

Each tree species present in areas managed by Montgomery Parks were assigned a value of risk for each pest. Classification of host species risk was based on a literature review that provided reported susceptibility ratings unique to each pest. Risk was assessed on a scale of 1 to 3 with 1 assigned to tree species not susceptible to the pest, 2 assigned to species having a moderate susceptibility to the pest and 3 to tree species that were highly susceptible to the pest of concern (Table 1). Literature was reviewed for each individual pest and host species were assigned a rating based on reported susceptibility ratings unique to each pest. Species present on Montgomery Park's inventory but not reported in literature were assigned a risk value of 1. In this report, risk values don't indicate the level of damage a host tree species is likely to experience if infected by a pest, only the level of susceptibility to infestation.

Table 1. Tree species susceptibility to Asian longhorned beetle (ALB) , spotted lanternfly (SLF), oak wilt (OW), and thousand cankers disease (TCD).

	Risk Value*			
Host Tree Species	**ALB**	**SLF**	**OW**	**TCD**
Acer buergerianum	3	1	1	1
Acer campestre	3	1	1	1
Acer ginnala	3	1	1	1
Acer griseum	3	1	1	1
Acer negundo	3	1	1	1
Acer nigrum	3	1	1	1
Acer palmatum	3	3	1	1
Acer platanoides	3	1	1	1
Acer pseudoplatanus	3	1	1	1
Acer rubrum	3	2	1	1
Acer saccharinum	3	2	1	1
Acer spp.	3	1	1	1

Acer x freemanii	3	1	1	1
Aesculus flava	3	1	1	1
Aesculus hippocastanum	3	1	1	1
Aesculus octandra	3	1	1	1
Aesculus parviflora	3	1	1	1
Aesculus x carnea	3	1	1	1
Ailanthus altissima	1	3	1	1
Albizia julibrissin	3	1	1	1
Amelanchier canadensis	1	2	1	1
Betula lenta	3	2	1	1
Betula nigra	3	1	1	1
Betula papyrifera	3	2	1	1
Carya glabra	1	2	1	1
Carya ovata	1	2	1	1
Celtis occidentalis	2	1	1	1
Cercidiphyllum japonicum	2	1	1	1
Cornus kousa	1	3	1	1
Cornus spp.	1	2	1	1
Fraxinus americana	2	2	1	1
Fraxinus pennsylvanica	2	1	1	1
Hibiscus syriacus	2	2	1	1
Juglans cinerea	1	3	1	3
Juglans nigra	1	2	1	3
Koelreuteria paniculata	3	1	1	1
Liriodendron tulipifera	1	2	1	1
Maackia amurensis	1	2	1	1

Magnolia Kobus	1	2	1	1
Malus hybrids	2	1	1	1
Malus spp.	2	3	1	1
Morus alba	2	2	1	1
Morus rubra	2	1	1	1
Nyssa sylvatica	1	3	1	1
Phellodendron amurense	1	3	1	1
Pinus densiflora	1	2	1	1
Pinus strobus	1	2	1	1
Platanus occidentalis	3	2	1	1
Platanus x acerifolia	3	1	1	1
Populus deltoids	2	1	1	1
Prunus avium	2	1	1	1
Prunus mume	2	3	1	1
Prunus serotine	2	2	1	1
Prunus serrulata	2	2	1	1
Prunus spp.	2	1	1	1
Prunus subhirtella	2	1	1	1
Prunus x hillieri	2	1	1	1
Prunus x yedoensis	2	2	1	1
Prunus x incamp	2	1	1	1
Prunus yedoensis	2	1	1	1
Pyrus calleryana	2	2	1	1
Pyrus communis	2	1	1	1
Quercus acutissima	2	2	3	1
Quercus alba	2	1	2	1

Quercus bicolor	2	1	2	1
Quercus coccinea	2	1	3	1
Quercus falcate	2	1	3	1
Quercus imbricaria	2	1	3	1
Quercus laurifolia	2	1	3	1
Quercus lyrata	2	1	2	1
Quercus macrocarpa	2	1	2	1
Quercus michauxii	2	1	2	1
Quercus nigra	2	1	3	1
Quercus pagoda	2	1	3	1
Quercus palustris	2	1	3	1
Quercus phellos	2	1	3	1
Quercus prinus	2	1	2	1
Quercus robur	2	1	2	1
Quercus rubra	2	1	3	1
Quercus serrata	2	1	2	1
Quercus shumardii	2	1	3	1
Quercus spp.	2	1	1	1
Quercus stellate	2	1	2	1
Quercus velutina	2	1	3	1
Robinia pseudoacacia	2	3	1	1
Salix babylonica	3	1	1	1
Salix nigra	3	1	1	1
Sassafras albidum	1	2	1	1
Styrax japonica	1	2	1	1
Tilia Americana	2	2	1	1

Tilia cordata	2	1	1	1
Tilia tomentosa	2	1	1	1
Ulmus Americana	3	1	1	1
Ulmus japonica	3	1	1	1
Ulmus parvifolia	3	1	1	1
Ulmus pumila	3	1	1	1
Ulmus rubra	3	2	1	1
Ulmus spp.	3	1	1	1
Ulmus x	3	1	1	1
Zelkova serrata	1	2	1	1

* Risk value assignment is as follows: 1 = species not susceptible, 2 = species moderately susceptible, 3 = species highly susceptible

Risk Equation

A crucial component of risk analyses is risk valuation. It is often obtained by developing an equation that considers factors or independent relationships that evaluate risk. For this project, the goal is to develop a risk equation that will produce a park pest risk value (PPRV) for each pest and park. This equation is based on a literature review of various pest risk assessments and the resulting determination that applying measures of host availability and habitat diversity is a common way to obtain a location-specific risk prediction. To produce a risk-prediction for a specific pest, the representation of host biomass available to the pest needs to be incorporated into the risk equation. This requirement is based on the host concentration hypothesis, which states that risk is assigned based on the proportion of trees that are host species in an area (Guyot et al., 2015).

A simple way to estimate available host cover is to use the diameter of all host trees at breast height (DBH) as a proportional measure of the tree's basal area (Woodbury and Weinstein, 2010). Since pests can infect tree species at different rates, it is important to also consider the differential susceptibility of tree species (Davies et al., 2017 and Woodbury and Weinstein, 2010). For example, in a pathway assessment of TCD it was determined that the *Juglans* and *Carya* genera are differently susceptible to *Geosmithia morbida* (Table 2) (USDA APHIS). To consider different host susceptibilities, risk factor values (RFVs) for each pest ranging from 1-3 (1 = not susceptible, 2 = susceptible, 3 = very susceptible) were applied to all inventoried tree species. The RFVs were then multiplied with the DBH of each individual tree to produce their weighted DBH values (DBH'). With these values, an accurate weighted percent basal (WBC) cover of host species can be produced by dividing the sum of the DBH' for all host species (host

DBH') by the cumulative DBH of all trees in the park (total DBH). To ensure risk values adequately reflect the ecological community being evaluated, it is important to include additional measures of risk, such as an area' diversity.

Table 2. Susceptibility of selected species within Juglandaceae to thousand cankers disease

Species	Status/Distribution	Uses	Susceptibility
Juglans californica (California walnut)	Native / Natural range restricted to southern California	Native tree	Susceptible (Utley et al., 2009)
J. cinerea (butternut)	Native / Natural range throughout NE U.S. and into Southern Appalachian region	Nuts, ornamental, timber	Nil (preliminary) (Utley et al., 2009)
J. hindsii (Hinds walnut or northern California walnut)	Native / Natural range from northern CA into OR	Timber, rootstock for English walnut (*J. regia*)	Susceptible (Utley et al., 2009)
J. major (Arizona walnut)	Native / Natural range AZ, NM, Mexico (Chihuahua)	Native tree	Resistant (tolerant)
J. mandshurica (Manshurian walnut)	Exotic	Ornamental	Susceptible (Utley et al., 2009)
J. microcarpa (little walnut)	Native / Natural range restricted to scattered populations in NM, TX, OK and KS	Ornamental, nuts (not commercial), rootstock in TX for non-native *Juglans* species	Susceptible (Utley et al., 2009)
J. nigra (black walnut)	Native / Natural range extends throughout eastern U.S. and into Kansas and Nebraska; planted throughout U.S.	Timber, nut and ornamental tree; used as rootstock for English walnut grafts	Highly susceptible (Tisserat et al., 2009;Utley et al., 2009)
J. regia (English walnut)	Exotic / Planted in commercial groves throughout U.S., particularly in CA (264,517 acres) and OR (1,460 acres)	Nut production – 99% of U.S. production of walnuts from CA English walnuts	Susceptible (Lauterback, 2007; Seybold and Leslie, 2009; Ford, 2009)
Carya illinoinensis (pecan)	Native / Natural range through the central U.S.; widely planted throughout U.S.	Nut production; ornamental	Nil (preliminary) (Utley et al., 2009)

Habitat diversity, including both population and community diversity, is an important variable to consider when assessing an area's potential for disturbance, which is a measure of ecosystem resilience (Folke et al., 2014). Also, standard indicators of diversity, such as species richness and Shannon's index, are widely used in conservation biology to provide useful information on the state of the ecological community (Juanatre et al., 2013). Specifically in relation to pest risk, an American Planning Association memo states that an area high in diversity of tree species is less likely to suffer catastrophic losses from diseases or pests (Gulick 2014). In a study testing this theory with chestnut gall, Guyot (et al., 2015) found that chestnut damage was significantly lower in stands with higher tree diversity.

To quantify diversity in the context of this project, a baseline value of tree diversity in urban parkland areas is needed. Established urban tree diversity goals within the literature state that any area should consist of no more than 10% of any species, no more than 20% of any genus, and no more than 30% of any family (Santamour, 2002). Using these values as a baseline, it was found that averaging the top three occuring tree species would most accurately represent the diversity of the parks as a whole, which is represented as the park diversity value (PDV).

This method was chosen because many park areas have a maximum of only three inventoried species. In addition, extrapolating the inventoried data as a way to represent the entire area of some parks was not possible due to the incomplete sampling of the trees within the parks. To ensure the PDV would be of significance, a Spearman's rank correlation analysis was done on the relationship between the PDVs and the number of species per park. This produced the expected results of the variables being negatively correlated ($\rho = -0.88$, $p < 0.001$) (Figure 3), since the PDV of parks with a greater number of species should be lower than parks with few species. This parameter also fits well in the equation since higher species diversities will result in lower PDVs, which ultimately will result in lower PPRVs. Overall, this supports the assumption that areas with higher diversity are more resilient in the face of disturbances, and therefore are less at risk. Therefore, the PDV used in this equation is well supported and will contribute to meaningful PPRVs. It can then be multiplied by the WBC variable to produce a significant PPRV (Spearman's rank correlation between WBC and PPRV: $\rho_{ALB} = 0.72$, $p < 0.001$; $\rho_{SLF} = 0.89$, $p < 0.001$; $\rho_{OW} = 0.96$, $p < 0.001$; $\rho_{TCD} = 0.99$, $p < 0.001$) (Figure 18) that is meaningful to park managers (E1).

E1.

Park Pest Risk Value (PPRV) = Park Diversity Value (PDV)*Weighted % Basal Cover of Host Species (WBC)

PDV: (% cover of species1 + % cover of species2 + % cover of species3) / 3

WBC: sum of weighted diameter at breast height (DBH) for all host species (host DBH')/cumulative DBH of all trees in the park (total DBH)

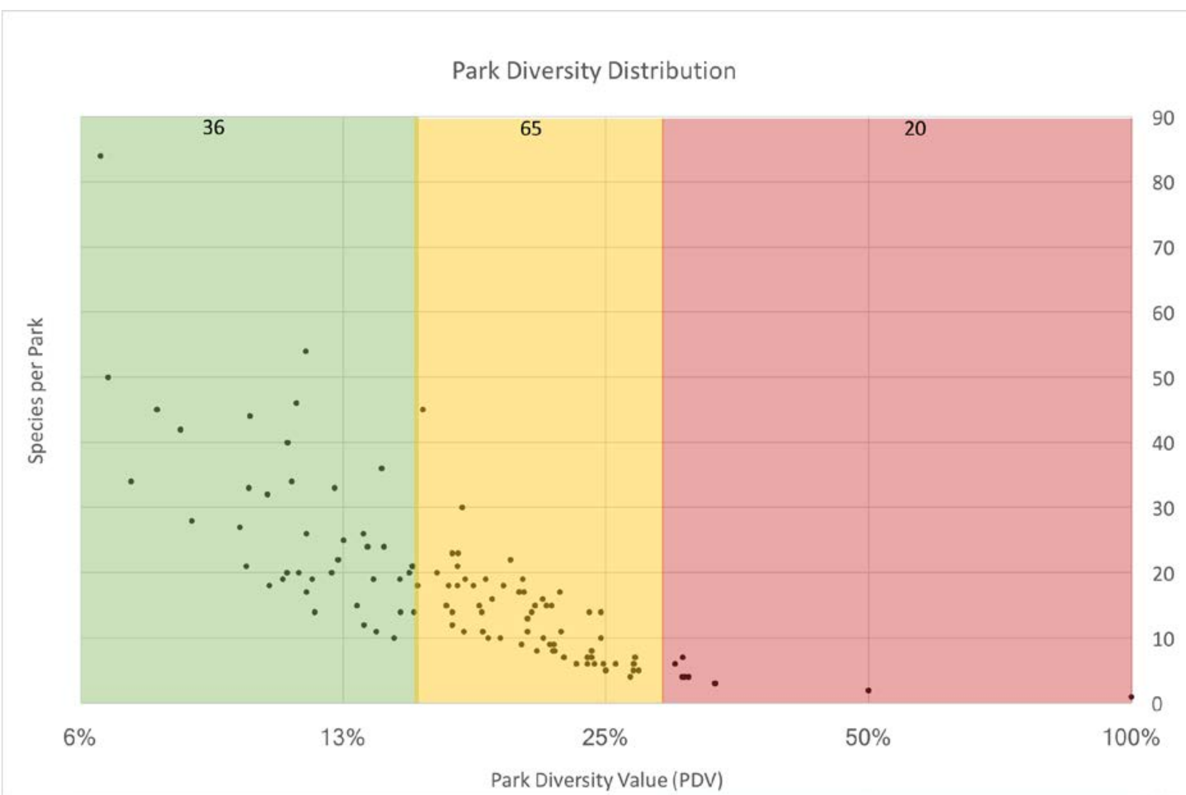


Figure 3**.** This graph shows the relationship between the number of species in a park and its respective Park Diversity Value (PDV). It conveys the expected result of parks with a large number of species having lower PDVs than those with only a few species ($\rho = -0.88$, $p < 2.2e-16$), which supports the use of this

variable as an accurate representation of park diversity. High diversity park values, which are low-risk, are less 15% of park tree inventory, medium diversity is 15-30%, and low diversity is greater than 30% of the park tree inventory.

ArcGIS Methods and Map Creation

(for a detailed outline of the ArcGIS approach see Appendix I)

Modeling the spread of invasive pests using spatial analysis and Geographical Information System (GIS) methods can provide valuable insight to park management in Montgomery County. The development of a tree risk susceptibility model based on specific attributes will allow for quantitative analysis leading to effective and timely mitigation strategies. In this section, understanding creation methods of this unique GIS model will allow for increased accuracy of susceptibility projections.

Creating an accurate spatial model to project park tree risk throughout all 120 managed park lands within Montgomery County requires extensive data sources with several detailed tree attributes. Tree inventory provided by Montgomery Parks was processed and refined to meet Parks requirements. This process removed blank cells, missing tree attributes, and incorrectly tagged trees. Using the equation (E1) mentioned in the previous section, two factors (PDV & WBC) were used to quantify park and tree risk within Montgomery Parks inventory data. Identifying these components before spatial analysis defines which type of GIS approach to perform. Selecting a basic susceptibility analysis method known as Risk Terrain Modeling (RTM) shown in Figure 4, GIS approaches can be modified to suit the application requirements. The basis of RTM constructs analysis values from a determined set of criteria (tree inventory) and variable weights. These values can be used to quantify park diversity and park risk for each pest, which can then be displayed on an interactive map of Montgomery Parks for in-depth evaluation of managed park lands.

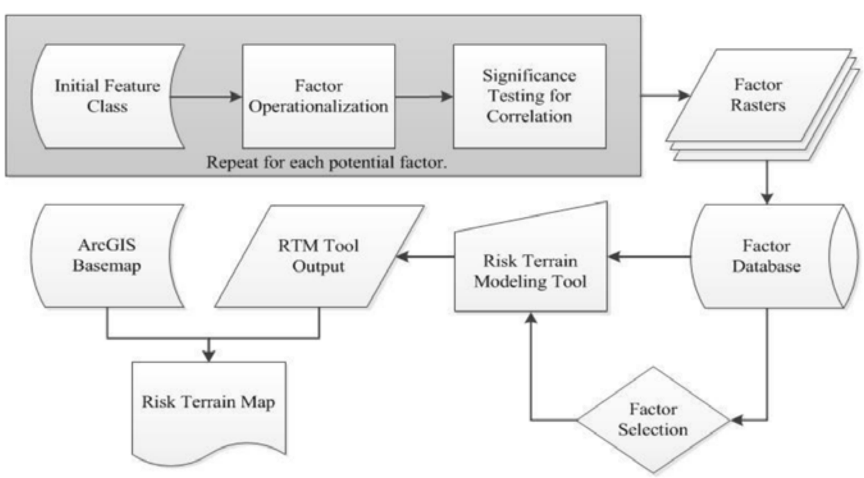


Figure 4. ArcGIS Tool Implementation of Risk Terrain Modeling, as illustrated by Goetz (2012).

ArcGIS: Park Diversity Value (PDV)

Based on the common 10-20-30 rule to maintain adequate biodiversity in case of pest infestation, no more than 10% of the trees are recommended to be the same species, no more than 20% same genera, and 30% same family within a park (Santamour, 2002). This project focuses solely on species diversity, which suggests high park diversity with no more than 10% of the same species. Due to the limitations and data uncertainty, the diversity scale of parks was expanded to account for any urban park inconsistencies. This project identifies park diversity by averaging the top three most abundant species per park to generate a consistent and accurate value. Once all Montgomery Parks were assigned park diversity values, data can be plotted following the scale below. Understanding park diversity can provide insight to which areas may be more prone to pests and that may require maintenance or preventive strategies.

Montgomery Parks Diversity Scale

Average percentage of top 3 occurring species:

Less than 15% of park tree inventory → **High Diversity**

15%-30% of park tree inventory → **Moderate Diversity**

Greater than 30% of park tree inventory → **Low Diversity**

(Can be broken into more quantiles based on preferences)

C	E	F	G
PARK_NAME	SPECIES	PERCENT_SPECIES	Average Top 3 Occuring Specie
Amity Drive Neighborhood Park	Laegerstroemia indica	33.33%	24.07%
Amity Drive Neighborhood Park	Quercus phellos	22.22%	
Amity Drive Neighborhood Park	Cercidiphyllum japonicum	16.67%	
Amity Drive Neighborhood Park	Cercis canadensis	11.11%	
Amity Drive Neighborhood Park	Acer rubrum	5.56%	
Amity Drive Neighborhood Park	Prunus subhirtella	5.56%	
Amity Drive Neighborhood Park	Prunus yedoensis	5.56%	

Figure 5. Sample Calculation for Amity Drive Neighborhood Park: (33.33% + 22.22% + 16.67%)/3 = 24.07% (Moderate Diversity)

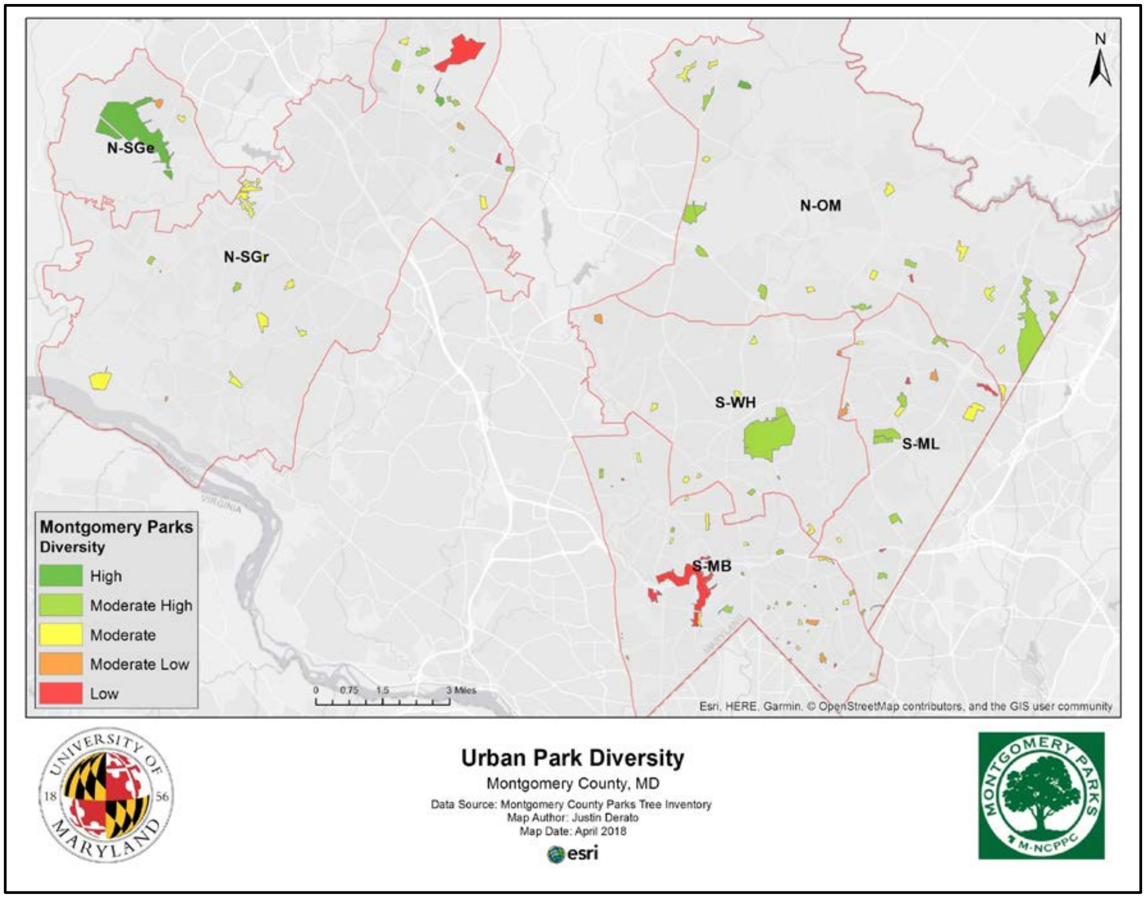


Figure 6. Montgomery Parks Diversity

ArcGIS Total Park Risk

To complete the Risk Terrain Model (RTM) for Montgomery Parks, the PDV and WBC were multiplied to create a general risk susceptibility for each park. Risk values use the unique factors outlined in E1, creating an effective and accurate projection for each pest considered in this report. These susceptibility values can be classified into quantiles and labeled from low to high risk.

ArcGIS Total Risk Sample: Asian longhorned beetle (ALB)

The final procedure for creating a GIS analysis of pest susceptibility is mapping quantitative risk values for each County park. Using the georeferenced data supplied by the client, unique risk and diversity values were calculated and joined with existing data. For each pest risk value, data was organized into five classes based on the frequency distribution. This infers each pest risk value is labeled (High/Low Risk) based solely on the assortment of all risk susceptibility values per pest. While this may be a limitation for determining which pest presents the greatest potential risk, it provides insight to which parks are the most at risk for each pest. The following figures represent total park risk values for Asian Longhorned Beetle (ALB) in Nolte Local Park. Maps identify total park risk based on color as well as host tree susceptibility outlined with colored markers. These sample images of Nolte Park provide a snapshot of the ArcGIS online application that contain the more than 120 Montgomery Parks along with all pest risks. These visuals aid in forming effective management strategies and urban forest management. The completed maps for all pests are in in Appendix II.

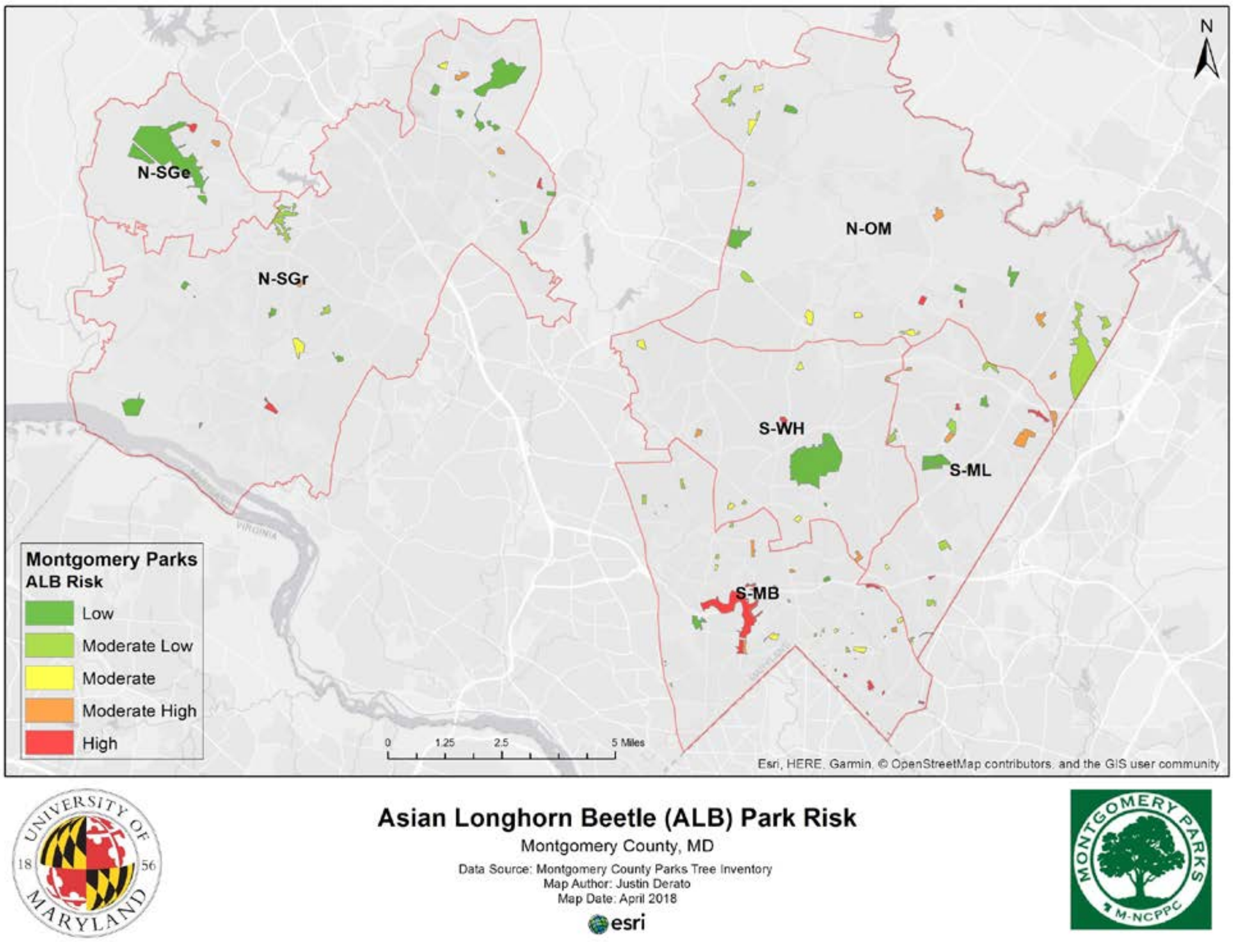


Figure 7. Asian longhorned beetle (ALB) Park Risk Map for six management regions of Montgomery Parks: Meadowbrook (S-MB), Wheaton (S-WH), Shady Grove (N-SGr), South Olney Manor (N-OM), South Germantown (N-SGe), and Martin Luther (S-ML).

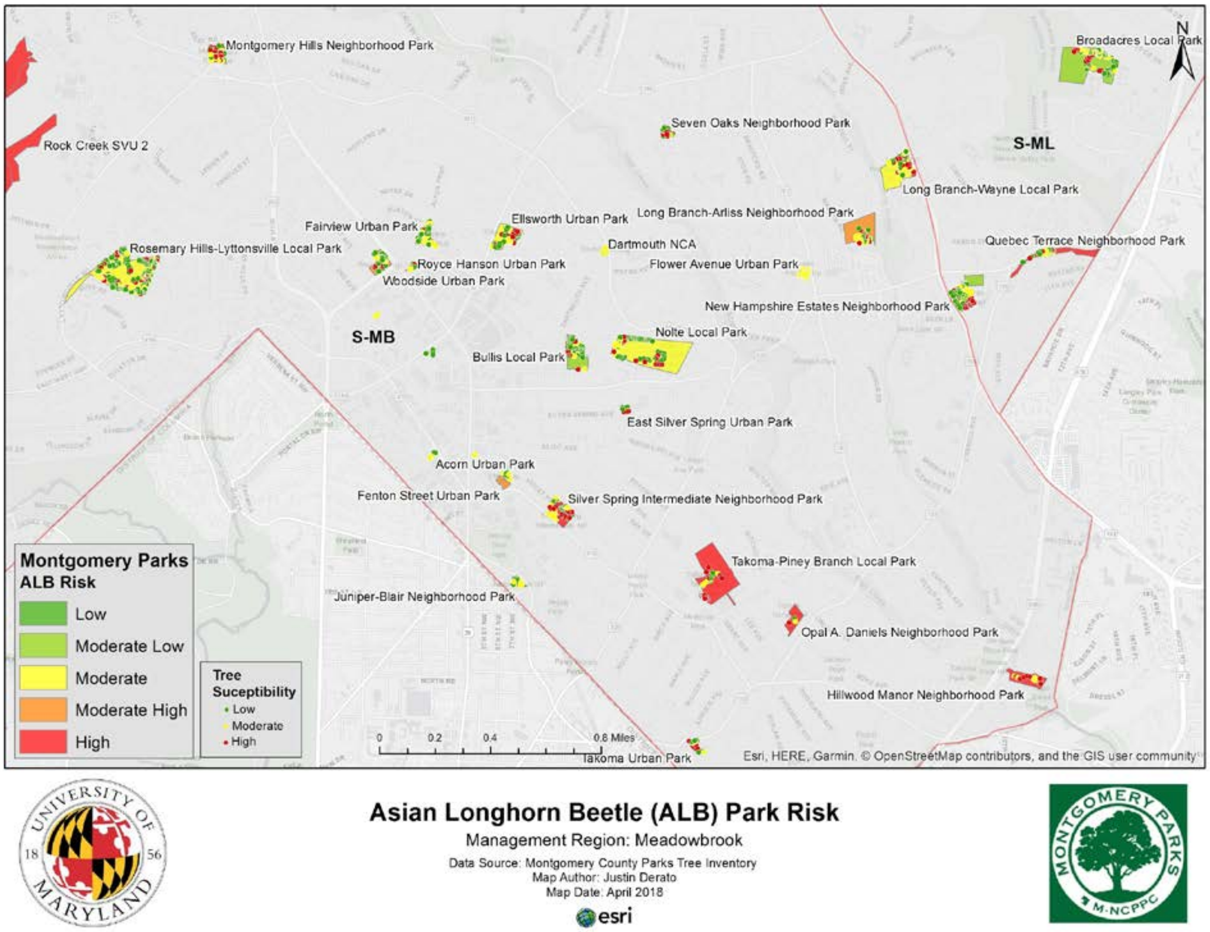


Figure 8. Meadowbrook Management Region Asian longhorned beetle (ALB) Park Risk

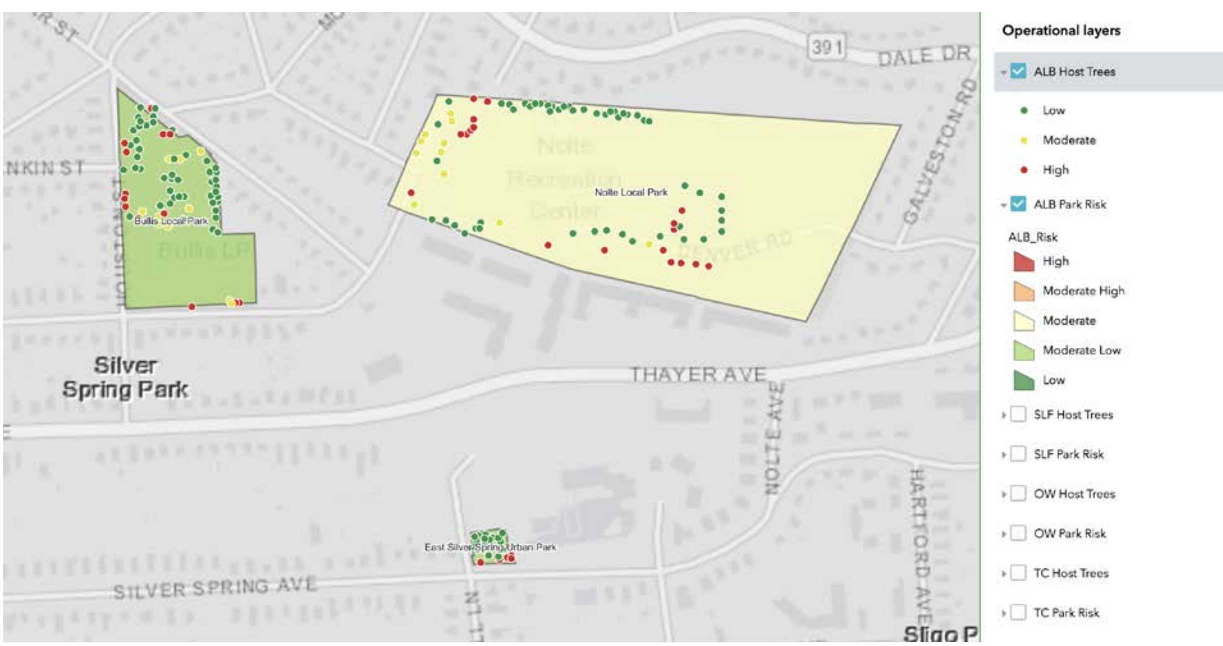


Figure 9. Nolte Local Park Asian longhorned beetle (ALB) Risk Map

Montgomery Parks Online Web Application

The product for this project is an online mapping application, hosted by ArcGIS Online, that allows users to view the tree inventory data across Montgomery Parks management regions. This tool provides a unique aspect for Montgomery Parks to determine Host Trees for each pest as well as a Park Risk layer to identify areas with a potential for high infestation. Various features can allow management to determine the location of high risk trees to implement mitigation strategies. More information about the intended use, limitation, and a detailed summary can be found in Appendix I.

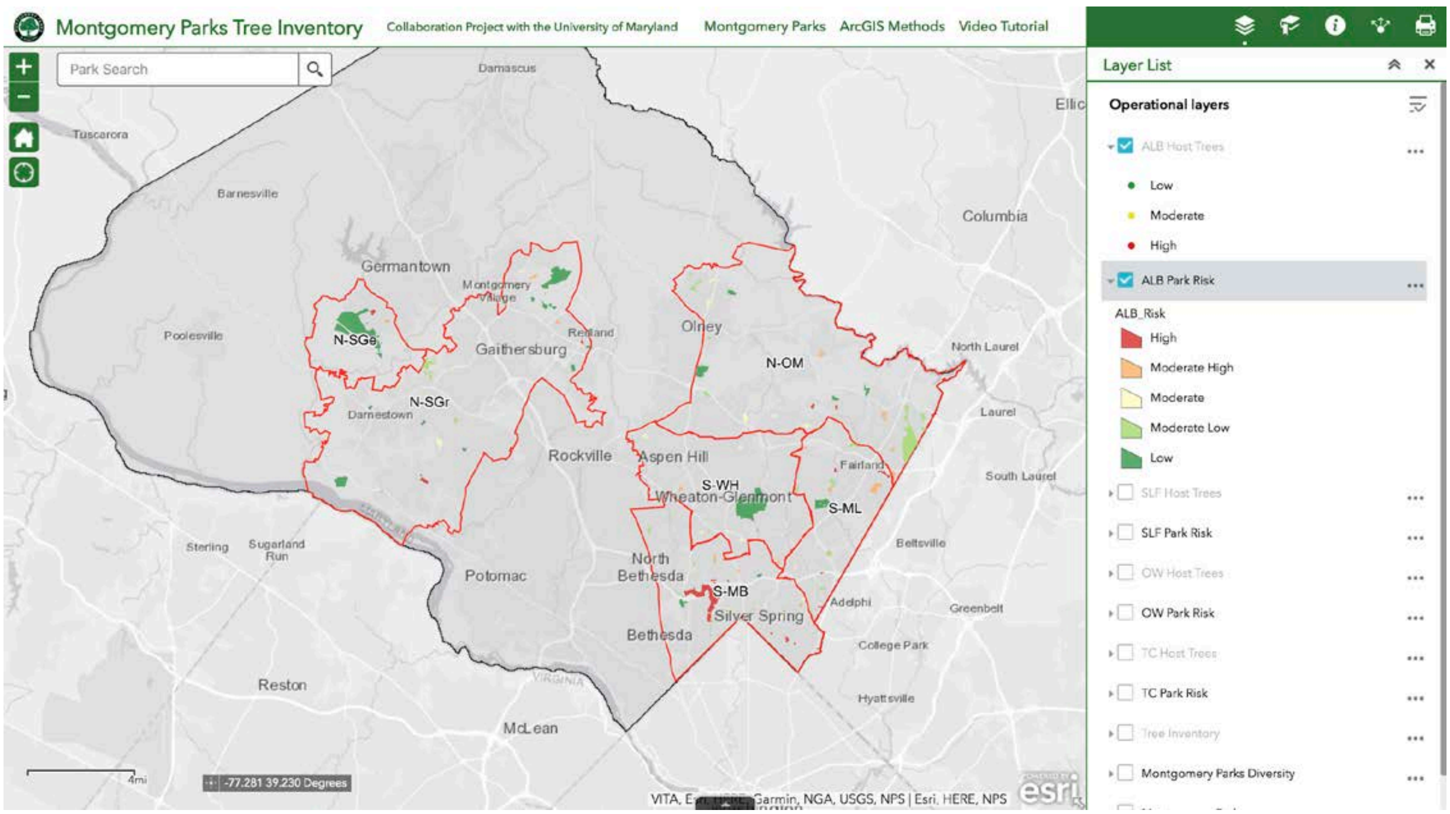
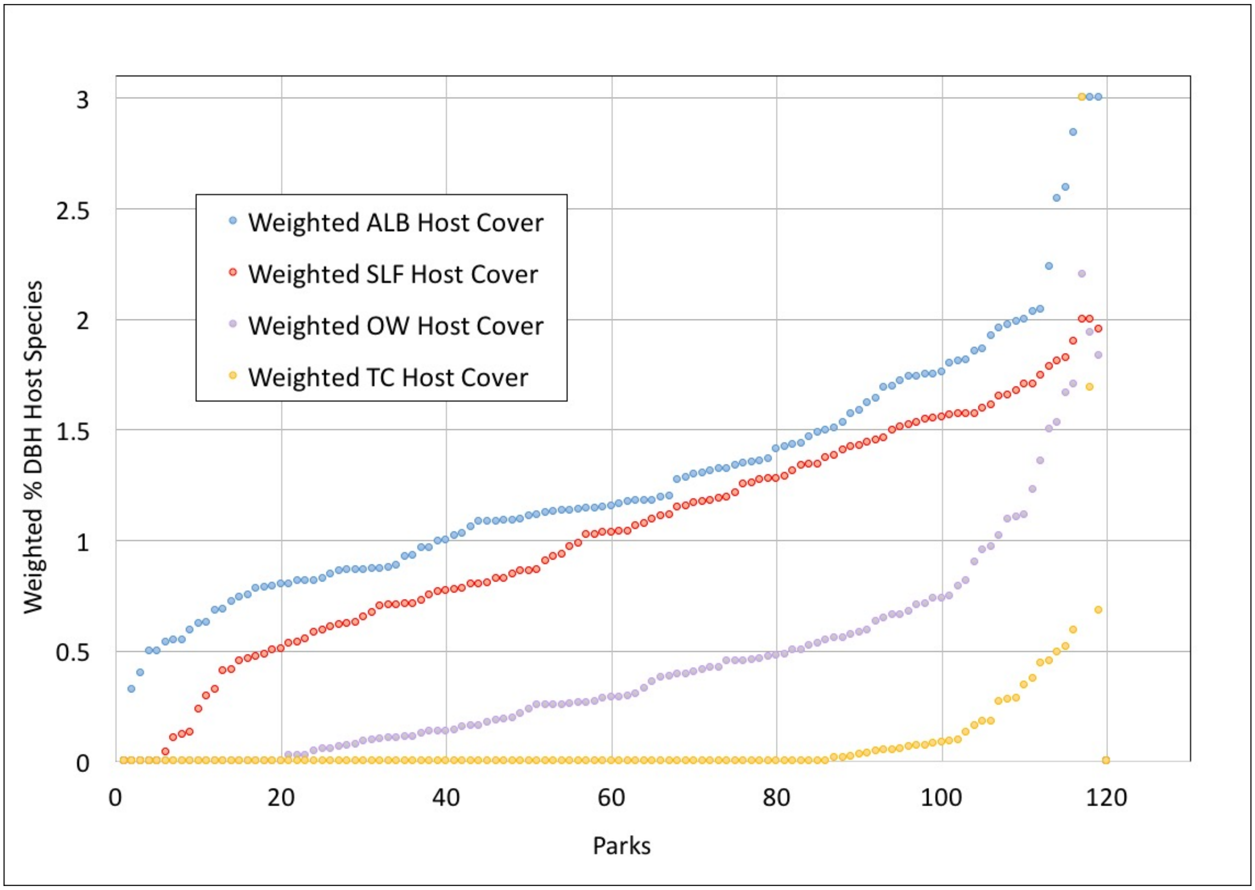


Figure 10. Screenshot of Montgomery Parks Interactive Tree Inventory**.** Link to completed ArcGIS Online Map: https://arcg.is/50yur

Risk Analysis Results

The spatial representations of tree inventory data in the previous section are valuable to park managers, but they do not present an aggregate picture of risk throughout all County parks. The tables and figures in this section provide a profile of the four pests of interest. An explanation of how the tables and figures relate to the risk assessment is also provided, and can be found in the captions of the tables and figures. The most substantial findings are included within this section.



*Each marker represents 1 park

Figure 11. This graph compares the distribution, from smallest to largest, of weighted host cover (available biomass) in all Montgomery parks for each pest, Asian longhorned beetle (ALB), spotted lanternfly (SLF), oak wilt (OW), and thousand cankers disease (TCD). Asian Longhorn Beetle (ALB) has the highest weighted host cover values when compared to other pests inferring a greater risk (host trees) for this particular pest.

Average weighted DBH:
ALB = 1.17
SLF = 1.03
OW = 0.42
TC = 0.05

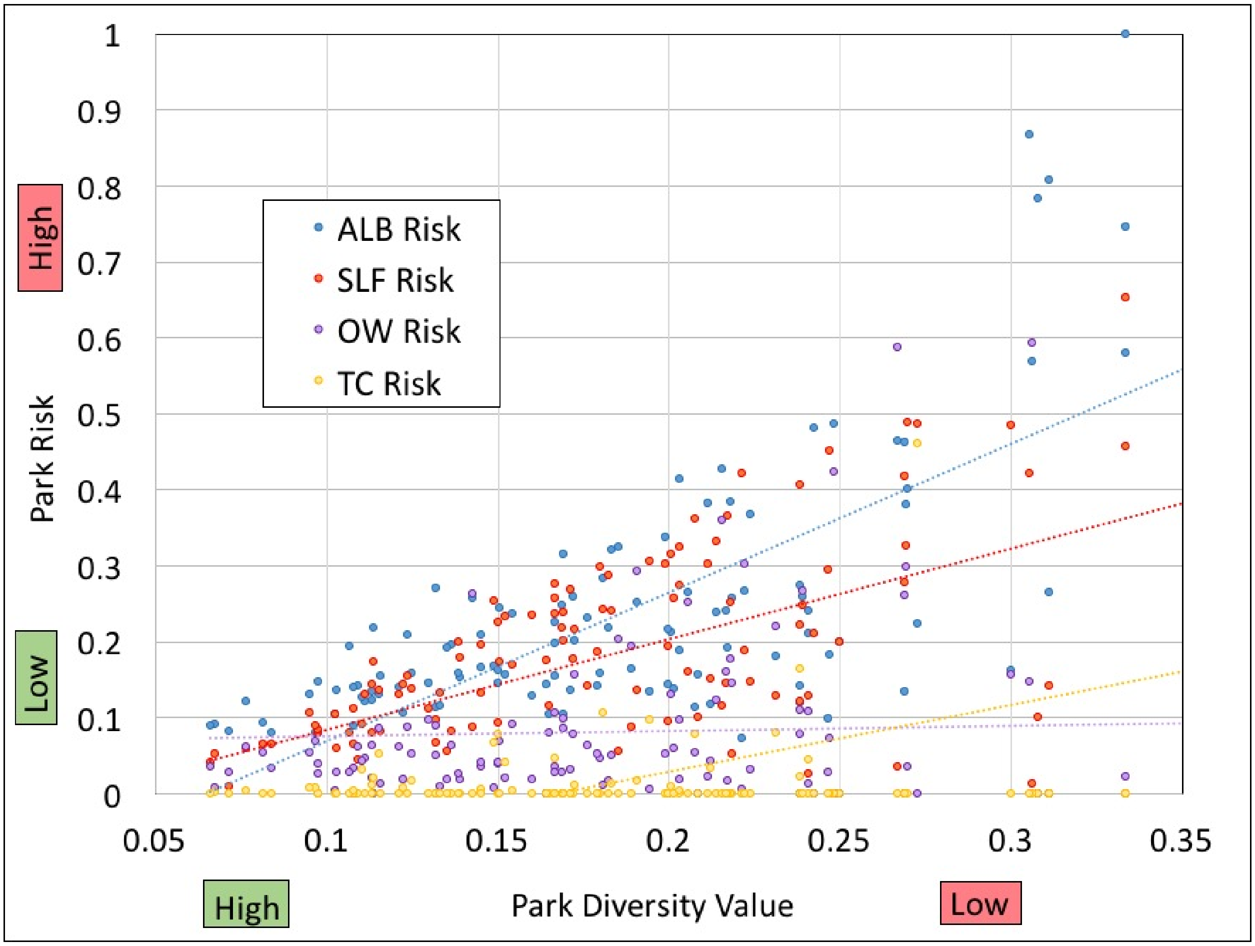


Figure 12. The graph displays the correlation between park diversity and park risk for each of the four pests, Asian longhorned beetle (ALB), spotted lanternfly (SLF), oak wilt (OW), and thousand cankers disease (TCD), in Montgomery parks. Park diversity values are inversely proportional, where high park diversity is indicated by lower values and low diversity by higher risk values. While the variables are not statistically significant (ALB R^2= 0.544, SLF R^2 = 0.433, OW R^2= 0.228, TCD R^2= 0.007), the graphs shows an overall trend that lower park diversity is weakly correlated with high park risk. This trend is more prevalent with ALB and SLF.

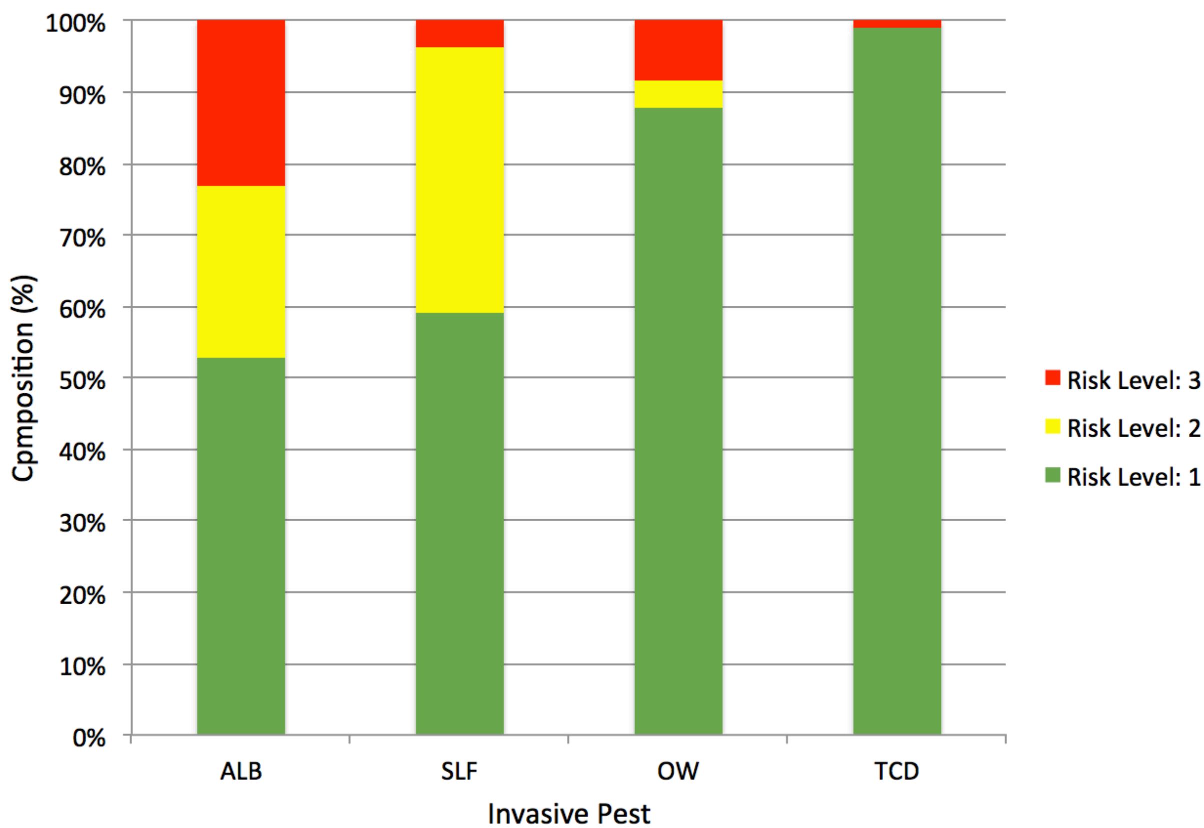


Figure 13. The percent composition of all host trees in Montgomery County parks for each invasive pest, classified by susceptibility level. The percent composition of host species, risk level 2 and 3 inclusive, for Asian longhorned beetle (ALB), spotted lanternfly (SLF), oak wilt (OW), and thousand cankers disease (TCD) are 47.2%, 40.9%, 12.3%, and 1.05%, respectively.

Table 3: The top five at-risk parks in Montgomery County, ranked by the Park Pest Risk Value calculated, for Asian longhorned beetle (ALB), spotted lanternfly (SLF), oak wilt (OW), and thousand cankers disease (TCD).

	ALB	**SLF**	**OW**	**TCD**
1	Brookview Local Park	Brookview Local Park	Juniper-Blair Neighborhood Park	Lois Y. Green CP
2	Goshen Elm Conservation Park	Lois Y. Green CP	Flower Avenue Urban Park	Royce Hanson Urban Park
3	Hopefield Neighborhood Park	North Chevy Chase Local Park	Acorn Urban Park	Tobytown Neighborhood Park

4	Rock Creek SVU 2	Tamarack Neighborhood Park	Hoyles Mill Village Local Park	General Getty Neighborhood Park
5	Mill Creek Towne Local Park	Seven Oaks Neighborhood Park	Takoma Urban Park	Kensington Heights Neighborhood Park

Economic Risk Analysis

A key component of risk assessment is to consider the economic benefits that would be compromised as a result of a disturbance such as invasive pest infestation. Using the Montgomery Parks tree inventory, i-Tree Eco v6 generated a summary of the services provided by managed trees. I-Tree Eco v6 is an online ecosystem services calculator that takes into account individual characteristics such as tree species, height, DBH, basal cover, etc. For example, when calculating carbon storage of all managed trees, it considers the crown health, trunk health, DBH + crown area, and crown: trunk ratio (Table 4).

Table 4. Ecosystem service quantities and cost analysis provided by i-Tree Eco v6 using Montgomery Parks tree inventory data. The values i-Tree Eco v6 provides are based on the 11,435 surveyed trees in the Montgomery Parks inventory. The true costs of losing all host trees in Montgomery parks are likely much higher given that the surveyed trees represent only a fraction of the total number of trees within the parks.

Ecosystem Service	**Quantity Lost**	**Dollars Lost**
Carbon Sequestration	137.5 tons/year	$17.8 thousand/year
Carbon Storage	7.762 thousand tons	$1.01 million
Avoided Runoff	81.89 thousand ft^3/ft	$5.84 thousand/year

Additionally, i-Tree Eco v6 highlighted dominant species within Montgomery parks, many of which are highly susceptible host species to Asian longhorned beetle and oak wilt (Table 5). Weighted Value (Percent of Population + Percent of Leaf Area) indicates species dominance, where species with a higher Weighted Value are more dominant within the managed trees in Montgomery parks.

Table 5. Dominant tree species in Montgomery parks according to i-Tree Eco v6. Dominant trees (highlighted) are high risk host species. Of those species, the red maple, sugar maple, and river birch are species are at a high risk for Asian longhorned beetle (ALB), and Willow oak and Northern red oak are at a high risk of infestation by oak wilt.

Species Name		*Percent Population*	*Percent Leaf Area*	Weighted Value
Eastern white pine		13.7	21.4	35.1
Red maple	High risk for ALB	8.3	10.6	18.9
Tulip tree		3.1	6.6	9.7
Sugar maple	High risk for ALB	3.4	3.5	6.9
Norway spruce		3.2	3.5	6.7
Willow oak	High risk for oak wilt	3.1	3.3	6.3
Northern red oak	High risk for oak wilt	3.0	3.2	6.2
River birch	High risk for ALB	2.9	2.4	5.3
White oak		2.3	2.4	4.7
Japanese zelkova		2.6	1.8	4.4

As i-Tree Eco v6 is only able to analyze tree data on a county-wide scale, The National Tree Benefit Calculator was used to conduct a species specific cost analysis. Similar to i-Tree Eco v6, the National Tree Benefit Calculator is an online program that considers location, mean DBH (in), and land use type to generate an overall dollar value for each species. Furthermore, raw species data of only the high risk (Risk Level: 3) host species were used to determine the mean dollars lost per each high risk species for each pest (Table 6). The total dollar value considers monetary value of stormwater runoff, electricity conserved, air quality retained, property value, CO_2 sequestered, and natural gas reduction of each individual tree species.

Table 6. Total cost to manage all trees according to species, mean DBH, and abundance in Montgomery County parks. Values obtained from The National Tree Benefit Calculator

Trees	**Mean DBH (in)**	**Cost Per Individual Tree ($)/year**	**Number of Trees in County**	**Total Cost ($)**
Acer buergerianum	6.00	6	10	60
Acer campestre	8.00	34	25	850
Acer ginnala	5.83	10	6	60
Acer griseum	10.02	19	53	1007
Acer negundo	16.61	85	33	2805
Acer nigrum	24.00	148	1	148

Acer palmatum	11.50	24	12	288
Acer platanoides	20.09	114	53	6042
Acer pseudoplatanus	7.00	25	4	100
Acer rubrum	17.87	115	861	99015
Acer saccharinum	29.47	170	35	5950
Acer x freemanii	14.83	74	30	2220
Aesculus hippocastanum	20.75	120	4	480
Aesculus octandra	11.00	49	8	392
Ailanthus altissima	15.63	80	25	2000
Albizia julibrissin	4.67	12	3	36
Betula lenta	75.00	140	1	140
Betula nigra	11.99	57	335	19095
Betula papyrifera	7.83	33	7	231
Cornus kousa	7.89	14	114	1596
Juglans cinerea	33.50	235	18	4230
Juglans nigra	25.73	163	116	18908
Koelreuteria paniculata	10.79	22	39	858
Nyssa sylvatica	12.31	59	126	7434
Phellodendron amurense	13.82	68	28	1904
Platanus occidentalis	13.22	64	165	10560
Platanus x acerifolia	7.90	30	145	4350
Prunus mume	22.00	69	4	276
Quercus acutissima	22.98	126	119	14994
Quercus coccinea	25.00	157	18	2826
Quercus falcata	28.29	187	17	3179
Quercus imbricaria	13.45	66	22	1452
Quercus nigra	15.60	89	1	89
Quercus palustris	22.44	134	96	12864
Quercus phellos	19.61	111	331	36741
Quercus rubra	17.81	93	312	29016
Quercus shumardii	20.84	120	24	2880

Quercus velutina	33.41	234	43	10062
Robinia pseudoacacia	17.27	89	118	10502
Salix babylonica	15.13	75	8	600
Salix nigra	12.67	61	3	183
Ulmus americana	16.00	83	65	5395
Ulmus parvifolia	8.63	37	134	4958
Ulmus pumila	28.00	184	2	368
Ulmus rubra	13.10	64	10	640
Ulmus spp.	11.05	50	223	11150

Table 7. Potential cost for each invasive species, Asian longhorned beetle (ALB), spotted lanternfly (SLF), oak wilt (OW), and thousand cankers disease (TCD), in monetary value based on The National Tree Benefit Calculator

Potential Cost	**ALB**	**SLF**	**OW**	**TCD**
Total Potential Loss of Benefits ($)	177981	28230	114014	23138
Number of High Risk Trees in the County	2275	445	983	134
Mean Loss per Tree ($)	78.23	63.44	115.99	172.67

Table 7 illustrates the combined potential losses for each pest. Total potential losses represents the monetary value if all high risk host trees in Montgomery County parks were lost. The mean loss per tree shows the mean monetary value of a high risk host tree per each species. The results of this table should be considered in conjunction with the percent composition of host trees (Figure 19). It should be noted that ALB has the highest percent of high risk host species (23.1%), but shows the lowest mean value per tree ($78.23), while TCD has the lowest percent composition of high risk host species (1.05%), but has the highest mean value per tree ($127.67).

Final Recommendations

General Strategies for Montgomery Parks

For Montgomery Parks to apply this risk assessment effectively, it is important for managers to be aware of the current techniques available to control the pests of concern. To do this, managers should work to increase overall park diversity, work with governmental officials to implement quarantine zones and monitoring programs, and increase public outreach about each pest. Additionally, current distribution of pests should be monitored to predict their arrival. It is important to involve the public and educate individuals on the impact of artificial spread via the movement of firewood or other woody debris. Regarding the pests examined in this project, the transportation of leaves and wood have facilitated in their widespread distribution, and therefore should be minimized to reduce accidental introductions.

Mitigation strategies should focus on local control and eradication. One method of managing current populations is the use of pesticides, typically injected into the base of an infected tree. It is important to adopt aggressive pesticide practices, including but not limited to, treating tree stumps following removal of host species, and proactively spraying potential hosts in the area. The most effective eradication strategies include the total removal of all host trees near an infested tree. Following removal, it is imperative to replace host trees with non-host species. In addition to preventing further spread this will increase parks diversity, thereby improving resilience to future infestations. Along with these general guidelines, it is also valuable to have pest-specific management techniques available.

Pest Specific Management Strategies

Asian Longhorned Beetle (ALB)

Due to the nature of ALB, quarantines have been the most effective way of preventing further spread. Under such circumstances, surveying for ALB within an 800-meter radius of each infestation point is conducted. Wood should not be used, moved or disposed of without an inspection permit. State or federal personnel will inspect wood for free and dispose of any infested wood. It is also recommended that host trees be replaced with non-host species, frass holes be filled, and adults, eggs, and larvae should be removed when possible.

The Animal and Plant Health Inspection Service (APHIS) has also implemented regulations that require fumigation of Solid Wood Packaging Materials (SWPM) from China. In areas where ALB has been detected, infected trees are cut, thoroughly removed, including below-soil portions, and either chipped or incinerated (University of Vermont "ALB Infestations").

Trunk or soil injections of imidacloprid, an insecticide, can be applied to each potential host tree within the 800-meter radius from the infestation point. A study on the effectiveness of this pesticide in controlling ALB found that imidacloprid, paired with other management efforts, such as biological control through fungal pathogens, is more effective at controlling beetle populations than tree injections of the pesticide alone (Ugine, 2011). *Metarhizium anisopliae* is an example of a fungus that is used for biological control of ALB in the US (Hu et al., 2009).

Spotted Lanternfly (SLF)

There are numerous physical and chemical methods to mitigate the damage and spread of SLF. Physical methods include scraping egg masses off of surfaces or the base of trees, which can prevent new hatchlings from disturbing the immediate area and can be performed by an individual without the use of external tools or technology. Another management tactic is banding trees. Wrapping a sticky brown tape around the base of host trees is an effective and environmentally-friendly way to catch SLF nymphs (PDA, 2018; Pitts, 2018). The Pennsylvania Department of Agriculture reported over 1 million nymphs have been killed by tree bands. SLF are reliant on the movement of nymphs to increase establishment and spread, however the sticky surface of the bands stops nymphs from climbing up trees and sucking sap, and they eventually starve to death (PDA, 2018).

The use of chemical and physical methods has proven highly successful for local eradication of SLF (Parra et al., 2017). If host species exists on a plot of land, about 90% of the host population should be cut down and herbicide should be added to the tree stump, as removing the tree is not sufficient. The remaining 10% of host trees on the property should be chemically treated with a systemic insecticide, specifically a chemical containing Dinotefuran. The removal of 90% of host trees forces SLF to congregate on the remaining trees where they feed on the chemically treated plants and die. A study conducted by Shin and colleagues (2015) reported SLF to be highly susceptible to broad-spectrum pyrethroids, organophosphate and neonicotinoid insecticides. Additionally, host trees killed should be female, seed producing trees if applicable to prevent reintroduction of host species, specifically where *A. altissima* is concerned (Parra et al., 2017).

Oak Wilt (OW)

There are several strategies used to manage oak wilt, including pruning alteration, wound dressing, tree removal, sanitation, root disruption, and fungicide treatment. Host trees should not be pruned during spring or summer due to the activity of insect vectors. Montgomery Parks should not prune managed trees from April 1st to October 1st. This reduces the likelihood of disease transfer by nitulid beetles because no wound will be intentionally created while the insects are active. A wound cover, such as paint, shellac, or pruning sealer, should be added when a tree is wounded from pruning or limb loss during a storm. This treatment deters the beetles from landing on the wound and provides a protective layer, separating the beetles from open xylem. These coverings will increase the healing time of the tree.

Once a tree is infected it must be removed, along with all host trees within a root grafting distance. Once removed, infected wood must be sanitized by burning, debarking, girdling, chipping, covering with plastic, or chemical treatment. Root disruption is used to break up root grafts and prevent underground spread. Trench inserts should be placed after root disruption to prevent re-grafting. Root disruption may be used preemptively in areas with close groupings of red oaks to prevent future spread of the disease. Fungicide treatment, such as propiconazole, may also be used on high-value white oaks. It is injected into white oaks to delay symptom progression and mortality. It does not prevent oak wilt spread or cure the disease (Koch et al., 2010; Juzwik et al., 2011, O'Brien et al., 2011).

Thousand Cankers Disease (TCD)

Monitoring schemes to track TCD are crucial to preventative management. Priority should be given to walnut trees growing near facilities such as walnut veneer or sawmills. *Juglans* found to have thinning crowns and that display signs of drought should be evaluated for the walnut twig beetle (WTB) and TCD in early to mid-summer. If suspected, a wood sample and installed with a pheromone baited trap can capture WTB near the site; specific trapping regimes can be found in the USDA Thousand Cankers Disease Survey Guidelines for 2018. If a lab confirms TCD, notification of the State Secretary of Agriculture and State Forester should follow (Daniels et al., 2016). A quarantine will then be established.

To mitigate spread after introduction, infected trees may be removed. The bark and wood of the tree should be burned or kiln-dried (Mayfield III et al., 2014). Alternatively, sanitation chipping can make wood too small to support the beetle. Tree removal may slow but not stop the spread due to the lag time between WTB infestation and expression of symptoms (United States Forest Service, 2011). Aggressive removal may increase efficacy, but removal should not replace consistent monitoring.

Some common bark beetle insecticides (e.g., carbaryl, various pyrethroids) can be used to treat high value walnut trees. WTB tends to colonize large areas and stay active for much of the year, so coverage is costly to maintain. Additionally, G. morbida will likely continue to grow on infected trees even if WTB are eliminated (United States Forest Service, 2011). Preliminary studies have found improvement and TCD dormancy in trees treated with high water and nutrient availability (Griffin, 2015).

Project Limitation Recommendations

For future applications of risk models, we recommend several improvements to the current model. The assessment of risk in this report was solely based on the limited tree inventory data supplied by Montgomery Parks. It is important to note that not every tree was surveyed in each park, and several parks in the inventory consisted of only a few trees because those are the only ones Montgomery Parks actively manage. The risk evaluation for this limited number of park trees may not represent the true risk of a park—therefore, a more accurate risk model requires a larger, more comprehensive inventory.

Along with limiting accurate representations of the park risk, sparse tree data restricted the ability to assess park diversity by only considering species richness rather than number of families. Additional assumptions also had to be made about only using tree data to assess risk to the four invasive pests; we had to assume each park had equal climate suitability, probability of introduction, and rate of spread for each pest. Ideally, a risk model would factor in comprehensive parameters to more accurately assess risk, for example, proximity to likely sites of potential introductions, park soil conditions, likely paths of dispersal, and wind patterns.

Despite these assumptions, this assessment is still highly relevant to the county's urban park areas, where a large percentage of the trees are actively managed. As Montgomery Parks expands their tree inventory, the risk assessment will become increasingly accurate. In the future, urban park managers in other regions may find value in applying our methods of risk assessment to their parks. Ultimately, any region where a reliable tree inventory can be collected can be analyzed using our methods.

Conclusion

Risk assessment is a process used to identify areas that are extremely vulnerable to the invasion of given plant pests, and thus are crucial for effective management. The assessment presented here identifies the susceptibility to Asian longhorned beetle (ALB), spotted lanternfly (SLF), oak wilt (OW), and thousand cankers disease (TCD) invasion for Montgomery Parks' managed areas.

The model was designed to use provided tree inventory data to consider relative host susceptibility and current diversity states of park areas as measures for invasion risk. As a result, it was determined that numerous park areas are at high risk of invasion from ALB, SLF, and OW, and only a few are at moderate risk of invasion from TCD. A significant portion (67.5%) of parks were also found to be below the standard tree diversity goal for urban areas, which here is defined as any park area with a PDV of 0.15 and above. When combined with a benefit analysis of annual ecosystem service provisions from high risk (RFV = 3) host species, it is clear that management should prioritize efforts toward ALB and OW.

To ensure effective management toward all four pests, preventative strategies, with a focus on public education, should be implemented. Local community members are the first line of defense against invasive plant pests. If informed, they can provide early warning sightings for multiple pests, avoiding significant inevitable damage to the county's trees and removing the need for substantial management expenses.

Despite the limitations of applying only one source of data to a risk assessment, the park risk values presented here are nevertheless statistically significant and can be applied to inform effective pest management. Overall, this pest risk assessment provides Montgomery Parks' managers with a valuable interactive web toolkit that identifies potential areas of interest for management and engages local community members' pest eradication efforts.

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