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Geospatial analysis of invasive plant species and their threats to ecological functionality at the VCU Rice Rivers Center

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

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Abstract

GEOSPATIAL ANALYSIS OF INVASIVE PLANT SPECIES AND THEIR THREATS TO ECOLOGICAL FUNCTIONALITY AT THE VCU RICE RIVERS CENTER

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

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Invasive plants are a significant threat to native ecosystems and are considered one of the most significant threats to biodiversity. Invasive plants are often strong competitors and utilize a variety of techniques to outcompete native plants. Because they have the potential to be destructive, it is important to control or remove invasive plants to facilitate the restoration of native ecosystems. We used GPS technology coupled with field surveying techniques adapted from the U.S. Fish and Wildlife Service (USF&W) to locate and identify invasive plants present within VCU's Rice Rivers Center. On the GPS receiver, we digitally overlaid a 50-meter x 50-meter grid system over VCU's Rice Rivers Center property boundary. In the field in each grid cell we recorded visual estimations of invasive plant coverage sorted into modified Daubenmire cover classes to inventory present invasive plants across the property. We used ArcGIS applications to create maps detailing both location and coverage information of the identified invasive plants. To evaluate the influence of anthropogenic disturbance on invasive plant species distribution, we created a 50-meter wide buffer zone around each disturbance to determine whether the presence of a disturbance (roads, construction sites, buildings, bike trail, etc.) influenced the presence and average coverage of invasive plant species found. Across the entire property, we found 25 unique invasive plant species, 16 herbaceous, 4 vines, and 5 woody

species. At least one invasive plant was found in 93% of the grid cells across the property. The highest count of unique individual invasive species found within a single grid cell was 7. The presence and coverage of unique invasive plant species was greater within the disturbance buffer zone compared to intact forest (non-buffered zone). *Microstegium vimineum, Lonicera japonica,* and *Ligustrum sinense* were the most common and widely distributed species within the terrestrial habitats. *Murdannia keisak* was the most widely distributed invasive plant in the restored wetland. A spatial distribution map of *M. vimineum* generated by Rice Rivers Center researchers in 2004 was compared to the data of our current 2017 survey. Between 2004 and 2017 *M. vimineum* spread from 40% of the grid cells in 2004 to 76% of the grid cells in 2017. The spatial maps we have created will be an important foundation to an integrated invasive species management program for the Rice Rivers Center and will assist with management and control efforts within terrestrial and aquatic ecosystem restoration efforts onsite.

Introduction

Invasive species are one of the most significant global threats to biodiversity. Invasive species are defined by Federal Order 13112 of the United States Department of Agriculture (USDA) (1999) as species that are non-native to the area under consideration, and whose introduction/presence is likely to cause harm to the environment, the economy, or to human health. With advancements in technology, specifically advancements in transportation, humans are directly facilitating the spread of invasive species across the globe. Many invasive plants were introduced to the United States from overseas within ballast water in ships, as packaging materials, for erosion control purposes, and from the horticultural and nursery industries (Cassey et al. 2005). Invasive plant species are generally able to outcompete the other species for resources, and therefore have the potential to destroy native plant communities. Invasive plants utilize a diverse variety of methods to gain competitive advantages, such as higher levels of water use and nitrogen use efficiency, allelopathy, improved seed dispersal mechanics, rapid vegetative growth compared to native species, and others. In their introduced environments, there is a lack of native herbivores and pathogens to naturally control populations of invasive plant species. There are an estimated 50,000 non-native species in the United States (Pimentel et al. 2004), with ~4,300 of these non-natives being considered invasive species (Corn et al. 1999).

Removal of already established invasive species is often both logistically difficult and expensive. According to the Virginia Invasive Species Working Group (VISWG) the Commonwealth of Virginia spends an estimated $1 billion annually on invasive species damage control, with the entire country spending approximately $120 billion. Invasive species damage crops, pasture and forestlands, and have detrimental impacts on urban trees. It is generally accepted that areas most susceptible to invasion are those that have been recently disturbed –

either by natural disaster or by human intervention. Historic land use practices generally lead to degraded environmental conditions and therefore low native species richness (Surette & Brewer 2008). Removal of native species by human intervention releases areas for invasive species to inhabit, as well as increasing their access to resources. Invasive species alter ecosystem functionality by changing hydrology, altering erosion and sedimentation rates, and by changing biogeochemistry. Invasive plants further disrupt biodiversity by disrupting native communities and food webs. Research by Tallamy (2009) revealed that by eliminating and displacing native plants, invasive plants create "protein deserts", where native lepidopterans do not use the invasive plants either as a nursery or as a food source. As a result, lepidopterans move to a more suitable habitat. This eliminates a food source for many bird species. Invasive species also prevent the natural regeneration of native ecosystems by blocking succession and by outcompeting and potentially extirpating native species. Simberloff and von Holle (1999) proposed the concept of an "invasional meltdown" – a concept in which invasive species interact with one another on a mutually beneficial level resulting in a dramatic increase in the competitive abilities of both species. While this is still a relatively new and untested theory, the implications of such mutually beneficial relationships between invasive species could be hugely damaging for native ecosystems.

In the National Invasive Species Council's 2016-2018 Management Plan, four general approaches to minimize the effects of invasive species are listed:

1. Prevention (of invasive species entering a new ecosystem)
2. Eradication (of non-native populations)
3. Control (minimize the spread of invasive species into new environments to further minimize impact)

4. Ecosystem restoration (build resistance/resilience to future invasions by restoring healthy native communities)

Developing an integrated invasive plant species management program using the approaches listed above is a critical step in restoring healthy native communities at VCU's Rice Rivers Center.

The Rice Rivers Center currently has no invasive species management program and, as a result, currently houses substantial invasive plant communities. Invasive plant species are detrimental to terrestrial wetland and aquatic habitats at VCU's Rice River Center, as invasive plant species are preventing native plant establishment and growth on this property. Given the Rice River Center's role as a model for restoration efforts and land management in the Mid-Atlantic region, invasive plant species on-site will require some type of management and control or else they will threaten the integrity of restoration efforts, native ecosystems, and alter ecosystem dynamics in profound ways. Invasive species may block regeneration niches within ecosystems and may replace individuals or entire populations of indigenous species indefinitely (Clewell & Aronson 2013).

Geographic Information Systems (GIS), in conjunction with Global Positioning Systems (GPS) and GPS receivers, provide valuable tools in constructing interactive maps and conducting spatial analyses. Using a combination of these tools, we were able to construct a series of interactive maps detailing the locations and estimated level of coverage of invasive plant species across the Rice Rivers Center property. These synthesized maps will assist in the development of an integrated invasive plant species management program for the Rice Rivers Center and provide a foundation baseline for evaluating management strategies and tracking the spread of invasive species into the future. Using a combination of the management approaches listed earlier will be

critical in managing the invasive plant populations currently present within the Rice Rivers Center terrestrial, aquatic, and wetland habitats.

Some of the more pervasive and pernicious invasive plant species present at VCU's Rice River Center were identified during a precursory ocular reconnaissance of terrestrial and aquatic habitats and include the following: Japanese stiltgrass (*Microstegium vimineum* Trin.), common reed (*Phragmites australis* Cav.), tree of heaven (*Ailanthus altissima* Mill.), marsh dayflower/dewflower (*Murdannia keisak* Hassk.), Chinese privet (*Ligustrum sinense* Lour.), Japanese honeysuckle (*Lonicera japonica* Thunb.), and garlic mustard (*Alliaria petiolata* Bieb.). These species pose significant threats to ecosystem functionality and restoration efforts and warranted increased evaluation.

Microstegium vimineum (Japanese stiltgrass), can be found in upland and wetland habitats. The Virginia Department of Conservation and Recreation (DCR) invasiveness rank for this species is "high" (Heffernan et al. 2014). *Microstegium vimineum* is a shade tolerant C4 grass that is capable of rapidly invading disturbed ecosystems (Fryers 2011). *Microstegium vimineum* is native to temperate and tropical Asia, and was first recorded in the US near Knoxville, Tennessee in 1919 (Miller 2003). It was likely introduced through international shipping, as it was commonly used as a packing material for fragile exports. *Microstegium vimineum* is slower to invade undisturbed vegetation, but once a site has been disturbed and native vegetation disrupted, *M. vimineum* is able to colonize and form monocultures rapidly (Fryers 2011). Experiments performed in forested floodplains in North Carolina showed *M. vimineum* is far more capable of invading shaded, mesic, disturbed sites than another common invasive plant *L. japonica* (Barden 1987). However, when placed in direct competition with *L. japonica*, the rate of invasion is drastically reduced. (Barden 1987)

Seeds of *M. vimineum* remain viable for at least 5 years and develop dense seed-banks (Gibson et al. 2002). The seeds are capable of quick germination to reestablish a cohort in the event that an existing cohort is disturbed (Gibson et al. 2002). *Microstegium vimineum's* cleistogamous reproduction further aids in its dispersal and rapid invasion (Fryers 2011). The presence of *M. vimineum* frequently leads to significantly lowered native species diversity (Adams 2009; Fryers 2011).

In areas with significant white-tailed deer populations, a combination of deer and *M. vimineum* alters species composition. Deer do not forage on the grass because it is unpalatable, so instead the deer heavily browse native woody species (Baiser et al. 2008). This, in turn, depletes native woody species populations and releases ground for *M. vimineum* to invade (Baiser et al. 2008). *Microstegium vimineum* then spreads and forms dense monotypic stands across the forest floor (Baiser et al. 2008). These dense stands provide enough shade to effectively shade out woody species seedlings and further prevent germination of woody species seeds (Adams 2009). This reduction in woody species leads to a further decrease in bird species that rely on ground and mid-story nesting sites (Baiser et al. 2008; Griggs et al. 2006).

Phragmites australis (Common reed), can be found in aquatic, wetland, and upland habitats. The DCR invasiveness rank for this species is "high" (Heffernan et al. 2014). The invasive common reed is a tall wetland grass species native to Europe. It was likely introduced in the late 1700s or early 1800s in contaminated ballast water (Swearingen et al. 2010). A native haplotype does exist in the United States. There is a nonnative haplotype that has invaded the United States (Saltonstall 2003). The presence of *P. australis* in marshlands has been linked to decreases in biodiversity of native plant communities, as well as decreases in native fish and invertebrate habitat (Swearingen et al. 2010). *Phragmites australis* also leads to increased

sediment accretion in marshlands. Monotypic stands of *P. australis* provide substantially less cover and therefore practical use to birds and mammals (Gucker 2008). Presence of *P. australis* has reportedly reduced suitable habitat area for state-listed endangered, threatened, and special concern bird species in Connecticut (Gucker 2008). *Phragmites australis* is also allelopathic. It exudes gallic acid from the roots that will degrade the structural components, specifically tubulin, of native plant species root networks (Bryant 2007).

Ailanthus altissima (Tree of heaven) can be found in upland and wetland habitats. The DCR invasiveness rank for this species is "high" (Heffernan et al. 2014). *Ailanthus altissima* was initially introduced in the United States as an ornamental species from China in 1748 by a gardener in Pennsylvania (Swearingen et al. 2010). It was made commercially available in 1840 (Swearingen et al. 2010) *Ailanthus altissima* grows rapidly and has a high water-use efficiency, meaning it can easily overtake native plant growth and consequently shade the native plants out (Swearingen et al. 2010). *Ailanthus altissima* develops large and intricate root networks that also competitively exclude native plant belowground biomass (Swearingen et al. 2010; Kowarik 1995). Some reports suggest that *A. altissima* is also allelopathic (Swearingen et al. 2010; Lawrence et al. 1991). The chemical substances it exudes below ground can prevent establishment, germination, and growth of native species (Lawrence et al. 1991). The young leaves of *A. altissima* are toxic to birds and mammals and are therefore unpalatable (Fryer 2010). The pollen of *A. altissima* is known to cause allergic reaction in some humans, and the sap of the plant causes skin irritations (Fryer 2010). Prolonged exposure to sap on broken skin can lead to more serious health impacts, including elevated heart rate and chest pains severe enough to cause hospitalization (Fryer 2010).

Murdannia keisak (Marsh dayflower/dewflower) can be found in aquatic and wetland habitats. The DCR invasiveness rank for this species is "high" (Heffernan et al. 2014). *Murdannia keisak* is a member of the spiderwort family found in freshwater marshes and along the edges of ponds and streams (Swearingen et al. 2002). *Murdannia keisak* was most likely introduced to the United States in contaminated rice imported for crop production. It was first recorded in 1935 in South Carolina rice paddies (Swearingen et al. 2002). The seeds of *M. keisak* are a food source for waterfowl, and it is likely that waterfowl play a significant role in the dispersal of *M. keisak* (Dunn & Sharitz 1990). Not much literature has been published regarding *M. keisak* and its invasiveness; however, following the precursory ocular reconnaissance, it is evident that the dense mats of vegetation formed by *M. keisak* monotypic stands have the potential to prevent native plant species from establishing. Management of this species in particular is critical in protecting wetlands restoration efforts at the Rice Rivers Center.

Ligustrum sinense (Chinese privet) can be found in upland habitats and along riparian corridors. The DCR invasiveness rank for this species is "high" (Heffernan et al. 2014). *Ligustrum sinense* is native to Southeast Asia and was introduced in the United States in the 1950s. *Ligustrum sinense* was initially introduced as an ornamental plant in urban areas, because it is tolerant of pollution and degraded conditions (Munger 2003). The shrub is still often used as hedges in gardens and yards, where it is typically free to escape containment (Swearingen et al. 2010). *Ligustrum sinense* is a partially shade tolerant shrub, and its seedlings are more shade tolerant than mature plants. *Ligustrum sinense* forms dense monotypic stands that shade out native herbaceous plant species (Swearingen et al. 2010). This then prevents regeneration of native hardwood communities, as the rapidly growing *L. sinense* stems shade out the seedlings of

native hardwoods (Munger 2003). The leaves of L. sinense contain phenolic compounds that protect it from herbivory by native insects (Swearingen et al. 2010).

Lonicera japonica (Japanese Honeysuckle) can be found in upland and riparian habitats. The DCR invasiveness rank for this species is "high" (Heffernan et al. 2014). *L. japonica* is native to Eastern Asia and was introduced in the United States as an ornamental species and for erosion control in 1806 in Long Island, New York (Swearingen et al. 2010). Its presence has been reported across the majority of the United States, including the entirety of the East Coast with the exception of Vermont (Munger 2002). *Lonicera japonica* is a trailing, twining, evergreen vine. It is predominately pollinated by insects and hummingbirds, and its seeds are typically dispersed by frugivorous birds and small mammals (Hardt 1986). Indirect evidence suggests that there is low probability of *L. japonica* producing seedbanks (Munger 2002). The seeds require cold stratification to germinate, are more efficient when exposed to high light, and will typically germinate in spring following dispersal (Leatherman 1955). *Lonicera japonica* is susceptible to droughts and shading. It struggles to compete with grass species such as *M. vimineum* but remains capable of forming dense monotypic stands given the right conditions (Williams & Timmins 1999). *Lonicera japonica* is capable of producing 30 feet of stem growth in a year and has been found twining as high as 50 feet upwards in New Zealand (Williams & Timmins 1999). *Lonicera japonica* is a choice browse for white tailed deer, particularly in the winter, and the fruit is also preferred by a variety of birds and insects (Munger 2002). However, *L. japonica* directly and negatively impacts native plants through light competition.

The vines form dense canopies in forests and often eventually kill the host species they use to twine upwards (Hardt 1986; Thomas 1980). Host plants are often forced into allocating more resources to underground biomass production to support the additional weight of the *L.*

japonica vines (Munger 2002). This results in fewer resources available for leaf production, thereby reducing the photosynthetic capabilities of the host plant. *Lonicera japonica* also alters forest composition by shading out herbaceous species and other species found on the forest floor (Munger 2002). This includes saplings and young tree species. In particular, *L. japonica* is often found to constrain oak forest regeneration (Munger 2002). Since it is an evergreen vine, it also begins growth nearly two months before its deciduous counterparts (Hardt 1986). The vine also reproduces both vegetatively as well as sexually, allowing for more means of spreading across a forest (Munger 2002).

     Alliaria petiolata (garlic mustard) can be found in upland habitats. The DCR invasiveness rank for this species is "high" (Heffernan 2014). *Alliaria petiolata* is native to Europe and Asia and was first reported in the United States in 1868 on Long Island, New York (Nuzzo 1993). Since its introduction to the United States, it has reportedly spread across most of the country with the exception of the south-western states over to California and the deep south (Swearingen et al. 2010). *Alliaria petiolata* prefers mesic upland deciduous forests on the east coast (Cavers et al. 1979). It is a cool-season, herbaceous biennial (Cavers et al. 1979). Biomass production is strongly influenced by exposure to light (Munger 2001), and the plant produces seeds contained within siliques (Cavers et al. 1979).

     Alliaria petiolata is a prolific seed producer and is capable of self-pollination (Cruden & McClain 1996). *Alliaria petiolata* is most prolific in seed production in shaded, moist environments where it is capable of producing up to 100,000 seeds per square meter (Cavers et al. 1979). Seeds are dispersed through ballistic expulsion from the siliques, and dispersal is accelerated along river corridors (Nuzzo 1993). Humans are another significant vector of dispersal for *Alliaria petiolata*, as the seeds stick to clothing or on mud-caked vehicles (Nuzo

1993). White tailed deer forage on *Alliaria petiolata*, and in doing so create favorable conditions for seed germination as well as assisting in seed dispersal (Munger 2001).

Seeds typically require cold stratification to germinate, and the plant forms seedbanks to compensate for the low overall success rate of seed germination (Munger 2001). The seedlings emerge in early spring and establish rapidly under areas of high light availability (Munger 2001). Because *Alliaria petiolata* is not capable of vegetative reproduction, seeds are required for dispersal.

Alliaria petiolata is very tolerant of environmental extremes, including both low and high levels of light, flooding, and a variety of soil characteristics (Byers & Quinn 1998). In areas of low light in particular, garlic mustard will form dense monotypic stands (Nuzzo 1993). The presence of *Alliaria petiolata* has been heavily linked to areas of disturbance, more specifically anthropogenic disturbances such as roadways, hiking and biking trails, railways, and more (Byers & Quinn 1998).

The presence of *A. petiolata* has substantial negative impacts on native communities. While it is a forage species for white tailed deer, it is exceptionally harmful to threatened butterfly species (Cavers et al. 1979). *Alliaria petiolata* displaces toothwort plants that butterflies use as a host plant and the leaves of *Alliaria petiolata* contain compounds that are toxic to the larvae. *Alliaria petiolata* also exudes chemicals in the soil that are detrimental to native mycorrhizal communities (Swearingen et al. 2010). It also dominates the herbaceous layer of forests, preventing the establishment of native plant species as well as blocking regeneration of hardwood forests (Munger 2001).

Objectives

The purpose of this project was to conduct a spatial analysis of invasive plant species present at the VCU Rice Rivers Center, and to examine the spread of *M. vimineum* over the past 15 years. We surveyed the property, recording visual estimates of percent coverage of invasive plant species present. Using this data, we developed interactive maps using ArcGIS software detailing coverage and spatial location information of invasive plants. These maps are intended to serve as a tool in the development of an integrated invasive plant species management program for the Rice Rivers Center. Managing invasive plants is a crucial step in facilitating the restoration and renewal of native communities and ecosystems. Using our collected spatial information on invasive plants, we evaluated the impacts of anthropogenic disturbances on the number of unique invasive plant species present within grid cells determined to be within close proximity to identified disturbances, as well as evaluated the coverage of selected invasive plants within close proximity to these disturbances. Because we have access to spatial data collected from a 2004 survey of *M. vimineum* at the Rice Rivers Center, we also determined the spread of this invasive grass species across the property over the last 15 years. To facilitate the analysis of collected data, we applied a number of statistical approaches using the following hypotheses:

A. The number of unique invasive species present within each individual grid cell will be higher on average within grid cells in close proximity to identified disturbances.

B. The average cover class observed in grid cells within close proximity to identified disturbances will be higher than the average cover class of grid cells that are not determined to be within close proximity to disturbance for the following species: *Microstegium vimineum, Lonicera japonica, Ligustrum sinense,* and *Ailanthus altissima.*

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C. The spatial distribution of *M. vimineum* has increased across the Rice Rivers Center property between 2004 and 2017.

Methods

This study took place at the Rice Rivers Center in Charles City County, Virginia. This ~142-hectare parcel consists of a ~28-hectare wetland and stream restoration site as well as about 101-hectares of upland habitat, including a planted pine forest as well as deciduous forest. This property contains an additional 12-hectares of tidal and non-tidal forested wetlands. The entire Rice River Center property was evaluated in this study. We digitally overlaid a 50-meter x 50-meter grid layer to a map of the Rice Rivers Center property (Figure 1).

Following protocol established by U.S. Fish and Wildlife Service (USF&W), we systematically processed each individual grid cell and identified the invasive plant species present, using a handheld GPS (Trimble Navigator Geo-7 series receiver with a Zephyr Model 2 antenna mounted on a monopod) to ensure accurate location information within each cell. The GPS receiver was used to locate our position in the field and to georeference the center point of each grid cell. When the researcher operating the handheld GPS reached the center of each grid cell, 25 point measurements were collected at the center point of the grid cell. The more points collected, the more accurate the location information produced by the GPS receiver will be. We chose to collect 25 individual measurements due to logistics and efficiency.

In order to effectively survey invasive plants in each grid cell, we used a combination of techniques: We used the "V-formation" technique developed by USF&W personnel when we only had access to two field surveyors. Surveyors utilizing the V-formation technique walk in a V shape across the cell, starting in the top left corner, proceeding down to the midpoint of the

bottom boundary, and then continuing back up to the top right corner of the cell. Alternatively, when three field surveyors were available, grid cells were assessed by simply walking through the cell with each surveyor spread approximately 12 meters from one another in a trident formation. We progressed through the grid cell from one end to the other, with the surveyor in the central position stopping in the middle of the grid cell to collect a GPS point using the handheld GPS receiver. Researchers that were not in control of the GPS unit were equipped with Nikon Forestry Pro Hypsometer/range finders to accurately determine distance away from the researcher controlling the GPS receiver.

Total number of invasive plant species present within each grid cell were recorded and visual estimations of individual invasive plant coverage for each grid cell. For herbaceous and vine species we recorded percent coverage, and for the woody species *Ligustrum sinense* and *Ailanthus altissima* we recorded individual stem counts. The results were then sorted into modified Daubenmire cover classes. We slightly modified the Daubenmire cover classes to differentiate presence and absence of invasive plants by adding a "zero" no-cover class. We also sorted the *L. sinense* and *A. altissima* stem counts into stem count "bins" to simplify construction of maps in ArcMap.

Our modified Daubenmire cover classes were as follows:

Cover Class	Range of Coverage
0	0%
1	1 to 5%
2	6 to 25%
3	26 to 50%
4	51 to 75%
5	76 to 95%
6	96 to 100%

The selected bin ranges for the invasive shrub *L. sinense* are as follows:

Stem Count Bin	Range of Stems in Bins
0	0
1	1 to 10
2	11 to 50
3	51 to 100
4	101 to 200
5	201 to 300
6	More than 300

The selected bin ranges for the woody invasive *A. altissima* are as follows:

Stem Count Bin	Range of Stems in Bins
0	0
1	1
2	2 to 4
3	5 to 10
4	11 to 15
5	15 to 25
6	More than 26

After all grid cells had been surveyed and the center points collected in the GPS receiver, the GPS points were post-processed and differentially corrected using Trimble Pathfinder software. The points were first transferred from the GPS receiver unit onto a computer using Trimble Pathfinder. After the points had been differentially corrected, they were exported into a shapefile to incorporate into ArcGIS. Efficiently correcting all GPS points required creating individual shapefiles for each rover file created by the GPS unit and then merging the results into one master shapefile using the merge tool in ArcMap.

To test our hypotheses that invasive plant species are more likely to occur in both higher frequency and higher density in closer proximity to disturbed sites (roads, construction sites, buildings, parking lots, lake edge), a 50-meter buffer was constructed and applied to identified

disturbed areas within the Rice Rivers Center (Figure 2). This was achieved by creating a new shapefile in ArcMap and using the hand draw tool to trace roads, construction sites, buildings, parking lots, and any other areas identified and classified as "disturbed" on the property. The buffer tool in ArcMap was used to apply a 50-meter buffer to the created line segment shapefile (Figure 2). The intersect tool in ArcMap was then used to determine which center points fell within the 50-meter buffer zone. The grid cell numbers of the points that intersected with the buffer were recorded and separated in an Excel table. In total, 315 out of 596 grid cell center points fell within the buffered zone, and 281 grid cell center points fell outside of the buffered zone.

To construct maps highlighting invasive plant spatial information, a tabular join was performed in ArcMap using a CSV file of invasive plant data by grid cell and the master shapefile of GPS points. The table was joined by copying the FID column created by ArcMap for the GPS points shapefile and pasting it to the CSV file of invasive plant data. We then edited the symbology of the shapefile to display desired invasive plant species. For data visualization, a hot to cold color ramp was used to visualize cover classes of invasive plant species, with blue colors representing low cover classes, red colors representing high cover classes, and black representing the maximum coverage (Cover class 6: 96-100% coverage). The maps produced give insight into the coverage and spatial information of invasive plant species present across the entirety of the Rice Rivers Center property. We also constructed a map illustrating the total number of unique invasive plant species present in each grid cell using a similar color ramp as previously mentioned. At the end of this process, we created 15 unique maps, with the ability to construct presence/absence and cover class maps for all 25 individual invasive plant species we discovered

on the Rice Rivers Center property, with the exception of *Ligustrum sinense* and *Ailanthus altissima* for which we collected stem count data rather than cover class data.

To determine the spread of *Microstegium vimineum* across the Rice Rivers Center property, we acquired polygon and point-data collected by Dr. Crawford and his students, Stephen Baker and Ryan Freidburg in 2004. We overlaid the same 50-meter x 50-meter grid system on top of the polygons and points they generated in 2004, and then visually estimated the percent coverage of *M. vimineum* in each grid cell based on what percentage of each grid cell was covered by a polygon or point. Points were determined to represent patches of *M. vimineum* approximately 1-meter x 1-meter and were therefore recorded as 2% coverage of a grid cell each. The estimated coverages were then sorted into the modified Daubenmire cover classes. This process resulted in cover class data of *M. vimineum* from 2004 per grid cell. The difference in cover classes were calculated by subtracting the 2004 data from the 2017 data. By editing symbology in ArcMap, we created a map visualizing areas of the Rice Rivers Center where *M. vimineum* coverage increased from 2004 to 2017 as well as areas where coverage decreased.

A Mann-Whitney U test was used to compare the difference in the cover classes of *Microstegium vimineum* and *Lonicera japonica* in grid cells that fell within the 50-meter disturbance buffer to grid cells that did not fall within the 50-meter buffered zone. The Mann-Whitney U test was also used to compare the difference in stem counts of *Ligustrum sinense* and *Ailanthus altissima* as well as the count of unique invasive plant species present in grid cells that fell within the 50-meter disturbance buffer to grid cells that did not fall within the buffered zone. A Wilcoxon signed-rank test was used to compare the difference in *Microstegium vimineum* over classes in 2004 to *Microstegium vimineum* cover classes in 2017. All tests were performed using an alpha level of 0.05. We adopted a null hypothesis of there being no significant statistical

difference in the invasive count or cover classes between the sampled populations of grid cells falling within the 50-meter buffered zone and grid cells falling outside the 50-meter buffer zone. To statistically analyze results, the data were separated based on whether or not the corresponding point fell within the 50-meter buffered zone. We selected *Microstegium vimineum*, *Lonicera japonica*, *Ligustrum sinense*, and *Ailanthus altissima* because these specific species were found to be some of the more pervasive and abundant across the Rice Rivers Center property, and present higher threats to native plant biodiversity and ecosystem recovery and function. We have also included spatial distribution maps for *Vinca minor, Hedera helix,* and *Rosa multiflora.* The former two species are typically associated with homesteads, and the latter probably arrived at the Rice Rivers Center on its own.

Results

Spatial Survey Results

The survey of the Rice Rivers Center property resulted in the identification of 25 unique invasive plant species (Table 1). We found 16 herbaceous invasive plant species, 4 vines, and 5 woody species. At least one invasive plant was found in 552 of the 596 grid cells, meaning approximately 93% of the grid cells house some type of invasive plant (Figure 3). The highest count of unique invasive plants found in a single grid cell was seven (Figure 4). *M. vimineum* and *L. japonica* occurred in the largest percentage of the 596 grid cells – 445 and 411 respectively (Figures 5 and 9). *M. vimineum* was found in both upland and wetland habitats and *L. japonica* was found in predominantly upland habitats. *L. sinense* had the third highest spatial coverage in terms of presence in grid cells at 270 out of 596 (Figure 10) and was found in mainly

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upland habitats and along riparian corridors. *Ailanthus altissima* was located in ~3% of the total grid cells (Figure 11) and was also found in only uplands. *Murdannia keisak* was found in 15.63% of the total grid cells, occurring predominately in the wetland habitats (Figure 12). *Phragmites australis* was found in ~1% of the total grid cells and was located in both wetlands and along upland borders (Figure 13). *Alliaria petiolata* was found in just 3 grid cells just east of the education center, present in 0.50% of the total grid cells (Figure 14). *Rosa multiflora* was found in ~1.68% of the total grid cells (Figure 15). *Hedera helix* and *Vinca minor* were found in 1.34% and 1.51% of the total grid cells respectively and occurred in upland habitats near the former grounds of an old hunting lodge (Figures 16 and 17 respectively).

Statistical Results

The number of unique invasive plant species found within the disturbance buffer was significantly greater than within intact forested areas (Mann-Whitney U test, p = < 0.0001) (Table 2). The average cover class of *M. vimineum* found within the disturbance buffer was significantly greater than within the non-buffered intact forested areas (Mann-Whitney U test, p = < 0.0001) (Table 2). The average cover class of *L. japonica* found within the disturbed buffer was not significantly greater than within the non-buffered intact forested area (Mann-Whitney U test, p = 0.7717) (Table 2). The average stem count of *L. sinense* was significantly greater within the disturbed buffer area than within the non-buffered intact forested area (Mann-Whitney U test, p = 0.0085) (Table 2). The average stem count of *A. altissima* was significantly greater within the disturbed buffer area than within the non-buffered intact forested areas (Mann-Whitney U test, p = 0.0018) (Table 2). The average cover class of *M. vimineum* significantly increased from 2004 to 2017 (Wilcoxon signed rank test, p = < 0.0001) (Table 2).

Discussion

The primary objectives of this research were to identify, geospatially locate, and create distribution maps of invasive plant species within the Rice Rivers Center property and quantify the rate of spread of *Microstegium vimineum* over a 15-year period across the Rice Rivers Center property. Secondary objectives were to provide support for restoration and management efforts across the property. The purpose of creating species distribution and coverage maps was to identify areas of the Rice Rivers Center that currently host invasive species, determine their amount of cover and provide a framework for implementing management strategies relative to their level of infestation and the ecological threat they pose to Rice Rivers Center ecosystems.

The total number of unique invasive plant species was higher for plots that fell within the buffered disturbance zone. *Ailanthus altissima* and *L. sinense* had higher stem counts on average in plots that fell within the buffered zone. *Microstegium vimineum* had higher cover classes on average in plots that fell within the buffered zone, while *L. japonica* showed no statistical difference in average cover class between grid cells within the buffer and grid cells outside of the buffer. This suggests, with the exception of *L. japonica*, that proximity to disturbances such as roadways and construction sites has a significant impact on the presence and coverage of the selected invasive plant species. In a meta-analysis conducted by Lozon and MacIsaac (1997), it was determined that 86% (402 unique invasive plant species) required disturbance to establish. These results highlight the importance of monitoring and controlling for invasive plant species near areas of new and existing disturbance. The Rice Center is currently in a development phase, and with the construction of future research facilities, it will be very important to pay special attention to preventing the establishment of invasive plants near any new construction areas. It

has been documented that invasive plant species establish more effectively in areas of disturbance.

Interestingly, *L. japonica* did not occur in higher percent coverages between the buffered and non-buffered populations. A possible explanation for this could be that *L. japonica* is quite capable of persisting in the low light environments of dense forests. The *L. japonica* plants occurring towards the interior of the eastern half of the Rice Rivers Center, where many of the grid cells were farther away from roadway or construction sourced disturbances, could have potentially established years ago and simply persisted in the interior of the property. Vertical structure disturbances, such as treefalls or other spontaneous gaps, are significant events in aiding the spread of *L. japonica* (Thomas 1980). While mature plants are capable of succeeding in low light environments, the seeds typically require open conditions to germinate and succeed (Hardt 1986). Heavy grass cover prevents *L. japonica* seeds from fully germinating as the shade produced prevents sunlight from reaching the seeds, and the seeds themselves possess little in the way of stored nutrients, meaning *L. japonica* must reach sunlight quickly in the developmental stages to establish effectively (Hardt 1986). The eastern uplands of the Rice Rivers Center were also clear-cut in the mid-1970s and a pine forest was planted. Removal of a substantial number of trees will have aided the germination of *L. japonica* seeds by providing access to adequate sunlight. This type of disturbance could have contributed to the spread of *L. japonica* through the forest interior. *Lonicera japonica* is also able to resist the spread of *M. vimineum*, so pre-existing stands of *L. japonica* could have prevented an even more aggressive spread of *M. vimineum* into the interior of the forest as well (Barden 1987).

According to Swearingen et al., (2010), there are no known biological control methods for *L. japonica.* It is a forage species for some animals, but not in significant enough quantities to

remove existing communities (Nyboer 1992). Removal typically requires mechanical methods. Hand pulling smaller vines (less than 2 years old) is an effective means of removal, however older vines have much more extensive root networks making hand pulling very difficult (Evans 1982). According to Evans (1982), mowing in open areas is an effective means of removal, however in the case of the Rice Rivers Center, it is probably difficult to get mowers or other heavy machinery deeper into the forest interiors. Light brush trimmers could be a more viable option, since it would be easier to maneuver through the forest. Chemical removal is effective, and glyphosate is reportedly the most effective chemical (Nyboer 1992). Glyphosate is an indiscriminate herbicide, so it is difficult to prevent collateral damage to native herbaceous species. Applying foliar herbicides during winter months where *L. japonica* is one of the few evergreen species present could be an effective way to minimize damage to native plant communities (Nyboer 1992).

Ligustrum sinense's average stem count in grid cells within the buffer zone was significantly greater compared to the average stem count in grid cells outside of the buffer zone. Like many invasive plant species, *L. sinense* occurs in greater numbers near disturbance. Studies in western Tennessee found that *L. sinense* is shade tolerant enough to persist in controlled environments with sun levels as low as 10%, but the plant performs with greater efficiency when it is exposed to higher levels of light (Brown & Pezeshki 2000). The seedlings are reportedly more shade tolerant, suggesting that *L. sinense'*s ability to move from forest edge deeper into the interior is highly likely (Fryer 2010).

Ligustrum sinense can be difficult to control, because the fruits are dispersed by birds and mammals and the plant is a prolific fruit producer (Westoby et al. 1983). Mechanical means of removal are often ineffective because the plant will sprout from stumps of severed stems. The

most effective means of removal for privet appears to be applying herbicide to the severed stems by "painting" the stem (DCR 2003). *Ligustrum sinense* has a strong root network, so hand pulling is typically an ineffective method unless one can be sure that the entire root network is removed. (DCR 2003) There appears to be no effective means of biological control for privet, outside of allowing goats to roam the infested area and browse (Batcher 2000). However, this requires the targeted privet species to be at browsing level (Batcher 2000). Larger stems will ultimately be unaffected. Typically, herbicides are effective in the removal and destruction of privet populations, but the herbicides are often indiscriminate in what they destroy, so native herbaceous species will also be at risk (Batcher 2000).

Ailanthus altissima is similar to *L. sinense* in that stem counts were higher on average near areas of disturbance. It is often argued that the most cost effective and efficient method of preventing the establishment and invasion of *Ailanthus altissima* communities is to simply maintain a healthy and strong native hardwood community within a forest (Sheley et al. 1999). Fryer (2010) suggests to simply avoid building roadways through forested areas to decrease the creation of disturbance and edge habitat.

Ailanthus altissima is another invasive plant that is effective at invading newly disturbed sites (Figure 11). Unfortunately, one of the most common and effective methods of opening up new territory for invasion is by removing a preexisting invasive species. This makes complete monitoring and controlling for invasive plant species time consuming and labor intensive project for restoration practitioners. Maintaining a healthy grass layer on the floor of a forest is another effective method at preventing the establishment of tree of heaven seedlings. The shade provided by a thick grass layer, preferably consisting of native species, aids in the prevention of germination by *Ailanthus altissima* seedlings (Hoshovsky 1988).

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Mechanical means of control include hand-pulling of smaller seedlings, and mowing of smaller established communities. Stem girdling is another effective method of destroying larger *A. altissima* individuals. This is achieved by disrupting the xylem and phloem, thereby depriving the plant of pathways used to transport nutrients. *Ailanthus altissima* is another plant species that is capable of sprouting directly from the root systems of previously destroyed plants, so destroying the stems without fully removing the root networks is not typically advised (Hoshovsky 1988). Chemical means of control are typically required to fully counter *A. altissima* infestations. There appear to be no current native means to biologically control *A. altissima* infestations. There are several insect species native to China that naturally forage on *A. altissima*, but it is generally inadvisable to introduce another non-native species to counter an invasive (Herrick et al. 2009). Chemical means of control are currently the most effective method of controlling *A. altissima*. Chemical compounds such as glyphosate kill belowground biomass as well as above ground biomass, suggesting that it is no longer necessary to fully physically destroy extensive root networks (Hoshovsky 1988).

Alliaria petiolata and *Phragmites australis* are two high concern invasive species currently present on the Rice Rivers Center property. *Alliaria petiolata* is only found within three grid cells very near the eastern side of the education building (Figure 14). *Phragmites australis* is found in several areas within the restored wetland (Figure 13). Special attention must be given to these two species in order to prevent a more significant and destructive infestation.

For *A. petiolata,* deterrence is considered to be one of the more effective means of control and prevention (Munger 2001). *Alliaria petiolata* creates seedbanks that can remain viable for up to six years, making total eradication difficult (Munger 2001). Very similar to *M. vimineum,* once *A. petiolata* has established itself, management practices should focus on prevention of seed

dispersal. Removing plants before they are capable of producing seeds is an effective tactic (Munger 2001). Unfortunately, a method for destroying the seedbank of seeds that are under the soil has yet to be determined or discovered (Munger 2001). Hand pulling is generally considered to be one of the more effective methods of controlling smaller populations of *A. petiolata*, particularly in areas that have only recently been infested (McCarthy 1997). Cutting is yet another effective means of preventing spread, as long as it is conducted during the second growing season while the flowering stem is elongating (Nuzzo 1991). It was determined that cutting the plant as close to ground level as possible can result in up to 99% mortality rates in *A. petiolata* plants (Nuzzo 1991). Mowing in general is not advised, as it can potentially distribute seeds and result in larger afflicted areas (Nuzzo 1991). Applying glyphosate appears to be the most effective means of control, however, glyphosate is indiscriminate and will negatively affect native plant communities as well (Nuzzo 1996).

While not overly abundant on Rice Rivers Center property, *Phragmites australis* is a potentially damaging invasive wetland plant. Controlling *P. australis* is difficult. It appears as if some of the more effective means of prevention include nurturing and influencing strong, healthy native plant communities in areas that could be invaded by *P. australis*, and by attempting to decrease the available nutrient loads to the site (Minchinton & Bertness 2003). Existing stands of *Phragmites* can be eradicated by chemical means, however collateral damage is always a concern when using herbicides such as glyphosate (Warren et al. 2001). Mechanical means of removal such as mowing can also be effective, but potentially not worth the intensive labor required if the stands are large enough and are located in inconvenient locations. *Phragmites australis* primarily spreads through vegetative reproduction, so mechanical removal efforts could cause more harm than good by encouraging a more pernicious spread of the reed (Uva 1997). It

is particularly important to monitor the current stands of *Phragmites* in the Rice Rivers Center wetland, as it alters hydrology, sedimentation rates, and leaves the wetland more susceptible to fire (Swearingen et al. 2010). *Phragmites* also crowds out native plants and, by forming dense monotypic stands, reduces the amount of suitable habitat available for native fauna (Swearingen et al. 2010). *Phragmites* is also allelopathic -- it exudes gallic acid from its root system. Gallic acid disintegrates the structural components of competitor species' root networks (Bryant 2007). Fortunately, management efforts for the *P. australis* infestations present at the Rice Rivers Center are being conducted by TNC contractors.

Rosa multiflora is another invasive plant species discovered on the Rice Rivers Center property that poses a legitimate threat to ecosystem functionality. While it did not appear in great abundance, it has established itself in the recently acquired Harris Creek as well as in the north end of Kimages Creek wetlands. Mechanical control for *Rosa multiflora* through mowing is possible, but it requires consistent attention (multiple treatments) throughout a year (Hindal & Wong 1988). Herbicides such as glyphosate are also effective. There is also a pathogen, Rose Rosette Disease (RRD) that can potentially eliminate up to 90% of existing *Rosa multiflora* plants within 5 years of introduction (Epstein & Hill 1999). The pathogen reportedly has little impact on other plant species. Both *Hedera helix* and *Vinca minor* are also present on the Rice Rivers Center property. These two vines were likely introduced as ornamental species when the land was owned and operated by the YMCA. *Hedera helix* can be removed mechanically by cutting the stems and then by pulling the vines down by hand. *Vinca minor* can be effectively removed by mowing.

Microstegium vimineum is a potent invader of disturbed sites. As a C4 plant, *M. vimineum* is a much more efficient photosynthesizer compared to typical C3 understory plants

because it experiences decreased levels of photorespiration. It is also more efficient in water usage and Nitrogen usage, meaning it is physically advantaged when these resources are limited (Fryer 2011). *Microstegium vimineum* is shade tolerant as well, further increasing its environmental tolerance. *Microstegium vimineum* seeds germinate with much higher rates of success when placed in open areas. Studies have shown that *M. vimineum* is well adapted to shade as well as full sunlight, with the plant producing similar levels of above ground biomass when exposed from 18% - 100% full sunlight (Winter et al. 1982). This means that while the seeds typically require more sunlight to germinate effectively, existing plants are capable of full efficiency in substantially shaded environments. Following a disturbance such as building a road or clearing land for construction, open areas are produced creating ideal habitat for *M. vimineum*. The plant produces mass quantities of seeds that are easily dispersed, as a result, expansion of *M. vimineum* coverage is essentially inevitable once it has room to establish a cohort (Huebner 2011). In Huebner's 2011 analysis of *M. vimineum* spread into a closed-canopy forest, it was suggested that *M. vimineum*'s spread into forest interiors is especially likely if there are roadsides nearby that are already infested with *M. vimineum*. Huebner asserts that this is likely due to the plant's prolific seed production – the quantity of which give *M. vimineum* advantage over native plants (Huebner 2011).

Controlling *M. vimineum* is difficult once it has established. Since the grass is most likely and most effective at establishing and invading newly disturbed sites and along forest edges, controlling the spread alongside roadways is one of the more efficient means of preventing the spread of *M. vimineum* into forest interiors (Huebner 2007). Following studies on biomass production and reproductive capabilities of *M. vimineum* in varying light treatments, Cheplick & Fox (2011) determined that *M. vimineum* is most effective at establishing in edge habitat with

access to ample amounts of direct sunlight and low densities of competitors. This would indicate that anthropogenic disturbances create not only suitable, but favorable habitat for *M. vimineum* invasion. Because the Rice Rivers Center is in the final phases of development, careful monitoring of new land disturbance should be conducted to prevent and control new infestations of *M. vimineum. Microstegium vimineum* produces extensive seedbanks, so persistent control must be exercised to deplete and exhaust the seedbank once established (Gibson et al. 2002). Another effective method in preventing infestations is to maintain a strong, healthy native plant community (Sheley et al.1999). *Microstegium vimineum* is an effective invader of disturbed areas, but it does struggle to move into pre-existing plant communities (Sheley et al. 1999).

Hand pulling existing stands of *M. vimineum* can be an effective method of removal for smaller populations but can quickly become a labor-intensive task once a seedbank has been developed. In wetland restoration efforts in North Carolina, it was found that newly developing streambanks are a means of dispersal for *M. vimineum* seeds and hand pulling the *Microstegium vimineum* in these areas will require near indefinite treatments (Fryer 2011). Mowing *M. vimineum* is not a particularly viable method of mechanical removal, as the mower tends to disperse seeds and makes the infestation problem bigger (Fryer 2011). There are no known means of biological control for *M. vimineum*, either predators or pathogens (Claridge & Franklin 2002). It has been determined, however, that quickly establishing a native plant community immediately following the removal of an invasive plant community is an effective method of preventing future infestations of invasive plants such as *M. vimineum* (Osland 2009). Chemical prevention and control are effective on existing stands of *M. vimineum*, but like most chemical control methods, it does not make the invaded environment any less desirable and suitable for invasive plants. Studies conducted by University of Tennessee researchers determined that

imazameth in particular is a good herbicide to use as it did not appear to negatively affect native herbaceous plant species unlike glyphosate, which is an indiscriminate herbicide (Tu 2000). It appears as if a combination of control methods is most effective in preventing the spread of *M. vimineum*. Chemical means are most effective for large infestations, where hand pulling is the most effective way of eliminating small, new infestations that have not had enough time to develop a seedbank (Fryer 2011).

Microstegium vimineum greatly expanded across the Rice Rivers Center property between 2004 and 2017. In 2004, 238 out of the 596 grid cells contained *M. vimineum* for a total of 40% (Figure 6). In 2017, 445 of 596 grid cells contained *M. vimineum* for a total of 75% (Figure 5). This increase in coverage across the property is likely influenced by both the expansion of facilities present on the Rice Center (education center, overnight lodge, Capital City Trail/bike path, dam removal etc.) coupled with a lack of invasive plant management. The draining of Lake Charles released a minor amount of new habitat for *M. vimineum* to invade. The combined coverage map of 2004 *M. vimineum* coverage and 2017 *M. vimineum* coverage shows expansion of the grass down into some grid cells that would have been "underwater" in 2004 (Figure 7). There also exists a substantial white-tailed deer population across the Rice Rivers Center property. Since deer are a significant vector of dispersal for *M. vimineum* seeds, it is highly likely that burgeoning deer population enabled existing stands of *M. vimineum* to spread and disperse from 2004 to 2017.

Ongoing restoration efforts taking place in the Rice Rivers Center wetlands are currently threatened by the presence of invasive plants. *Murdannia keisak, Phragmites australis,* and *Microstegium vimineum* all present significant threats to native plant communities, and ecosystem functionality at the Rice Rivers Center. *Murdannia keisak* and *Phragmites australis*

both form dense monospecific mats of vegetation in wetland environments that crowd out native plants and disrupt trophic systems by altering habitat structures and food availability for native species. Special considerations need to be accounted for when controlling invasive plant species in wetland environments. Because wetlands are a protected ecosystem, caution must be exercised to prevent damage from introduced substances such as herbicides. The structure of wetland environments also makes utilizing heavy machinery for mechanical removal difficult. Invasive plants in upland environments are likely easier to access. Depending on the targeted species, mechanical methods of removal and control could be a more viable option. Herbicides likely should be used sparingly to prevent collateral damage to native plants, and to prevent harmful run-off into the wetland.

These anthropogenic disturbances (roads, construction sites, buildings, etc.) present at the Rice Rivers Center potentially played an important role in the coverage and spatial distribution of the identified invasive plant species. It is especially important to bring attention to control and removal methods of invasive plants. There are three general categories of invasive plant removal/control. These are mechanical removal (hand pulling, mowing, bush hogging, etc.), biological control/removal (introducing a native or non-native species that counters the invasive plant – could be a pathogen, predator, or strong competitor), and chemical control (spraying herbicides to kill the invasive plant). A combination of these techniques is typically required to fully combat invasive plant infestations. Such combinations of techniques are referred to as integrated control methods (Buckley 2008). Adapting an integrated approach to invasive plant control is typically required.

Conclusion

VCU's Rice Rivers Center's current management strategy of "no management" is creating issues with invasive plant species. It is important to remove, control, and monitor invasive plant species as they are detrimental to native communities – both floral and faunal. Invasive plant species are also hazardous to restoration efforts occurring across the property. We have identified the invasive plants present, estimated their coverage, and documented their spatial extent. The next logical step is to use the information and data we have gathered to form an integrated invasive plant species management program for the property. Developing such a management plan would require determining required permit and licensing details, cost analysis, equipment requirements, available labor pools – both professional and volunteer, and developing a species management hierarchy based on spatial extent, coverage, and potential harmful effects of each species.

In addition to serving as the foundation for the development of an integrated invasive plant species management program, this research will also serve as the foundation for future invasive plant species research to take place on the Rice Rivers Center property. Replicating this research in the future would provide insight into the spread of the identified invasive plant species across the property as well as to the efficacy and efficiency of management actions. If a management plan is implemented to counter the spread of invasive plants across the property and current infestations are controlled, replication of this study could document the reductions in invasive plant coverage.

The author of this thesis sincerely hopes that such a management plan could be developed in the future to help better protect the beauty and uniqueness of the Rice Rivers Center.

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Vita

Erik William Kellogg was born April 16, 1993 in Richmond, Virginia. He attended Patrick Henry High School in Ashland, Virginia and graduated in 2011. He then attended Hampden-Sydney College, where he received his Bachelor of Science degree in Biology in 2015. During his four years at Hampden-Sydney, Erik conducted research projects focusing on the growth characteristics of the invasive plant *Centaurea stoebe* when grown in different substrates, as well as field studies on the distributions of the invasive weed along the Highbridge Trail in Farmville, Virginia. His research at Hampden-Sydney sparked his interest in studying invasive plants and led him to the research project detailed in this thesis.

Table 1: Invasive species found in 2017 survey across all habitats at the Rice Rivers Center and methods of seed dispersal. Z = Zoochory; A = Avichory; H = Hydrochory; W = Wind

Species	Common name	Presence in percentage of grid cells	Dispersal Method
Herbaceous			
Alliaria petiolate (M. Bieb,) Cavara & Grande	Garlic mustard	0.50%	Z, H
Arctium minus Bernh.	Common burdock	0.17%	Z
Arthraxon hispidus Thunb. Makino	Small carpetgrass	0.34%	Z, A, H
Cardamine hirsute L.	Hairy bittercress	2.52%	Z
Convolvulus arvensis L.	Morning glory	0.34%	Z
Hydrilla verticillate (L. f.) Royle	Waterthyme	0.34%	Z, A, H
Iris pseudacorus L.	Yellow flag iris	1.68%	H
Lespedeza cuneate (Dum. Cours.) G. Don	Chinese bushclover	6.39%	Z
Microstegium vimineum (Trin.) A. Camus	Japanese stiltgrass	74.79%	Z, A, H
Murdannia keisak (Hassk.) Hand.-Maz.	Marsh dayflower	15.63%	H, A
Narcissus spp.	Daffodils	1.34%	Z
Nasturtium palustre (L.) DC.	N/A	0.84%	Z, H
Oxalis stricta L.	Yellow woodsorrel	0.17%	Z
Panicum capillare L.	Witchgrass	0.17%	H
Persicaria maculosa L.	Lady's thumb	0.34%	Z, H
Phragmites australis (Cav.) Trin. ex Steud.	Common reed	1.01%	A, H
Vines			

Clematis terniflora DC.	Sweet autumn clematis	1.18%	Z
Hedera helix L.	English ivy	1.34%	Z, A
Lonicera japonica Thunb.	Japanese honeysuckle	69.08%	Z, A
Vinca minor L.	Dwarf periwinkle	1.51%	Z
Woody			
Ailanthus altissima (Mill.) Swingle	Tree of Heaven	3.03%	W
Ligustrum sinense Lour.	Chinese privet	45.38%	Z, A
Nandina domestica Thunb.	Sacred bamboo	0.34%	Z, A
Paulownia tomentosa (Thunb.) Siebold & Zucc. ex Steud.	Princess tree	0.34%	Z
Rosa multiflora Thunb.	Japanese rose	1.68%	Z, A

Table 2. Results of Statistical Analyses using nonparametric statistical tests

Species	Test	Level	Measurement Type	*n*	DF	p-value
M. vimineum	Mann-Whitney U	50-meter Buffer Intersect	Cover Class	315	1	<0.0001
		Outside Buffer		281		
L. japonica	Mann-Whitney U	50-meter Buffer Intersect	Cover Class	315	1	0.7717
		Outside Buffer		281		
L. sinense	Mann-Whitney U	50-meter Buffer Intersect	Stem Count	315	1	0.0085
		Outside Buffer		281		
A. altissima	Mann-Whitney U	50-meter Buffer Intersect	Stem Count	315	1	0.0018
		Outside Buffer		281		
All Invasives	Mann-Whitney U	50-meter Buffer Intersect	Count	315	1	<0.0001
		Outside Buffer		281		
M. vimineum 2004-2017	Wilcoxon signed rank	2004 data	Cover Class	596	595	<0.0001
		2017 data		596		
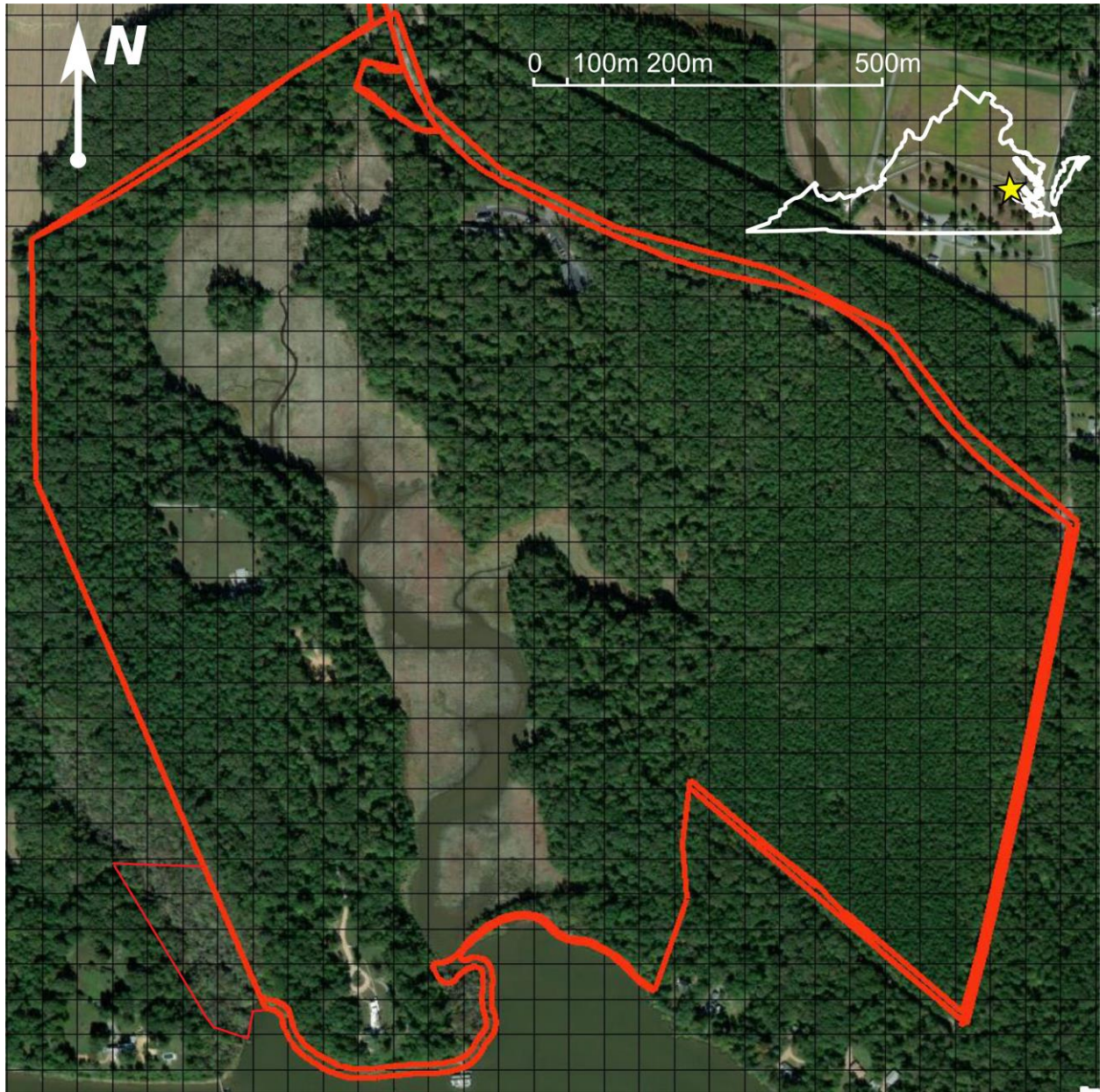
Figure 1. The Rice Rivers Center property boundary.
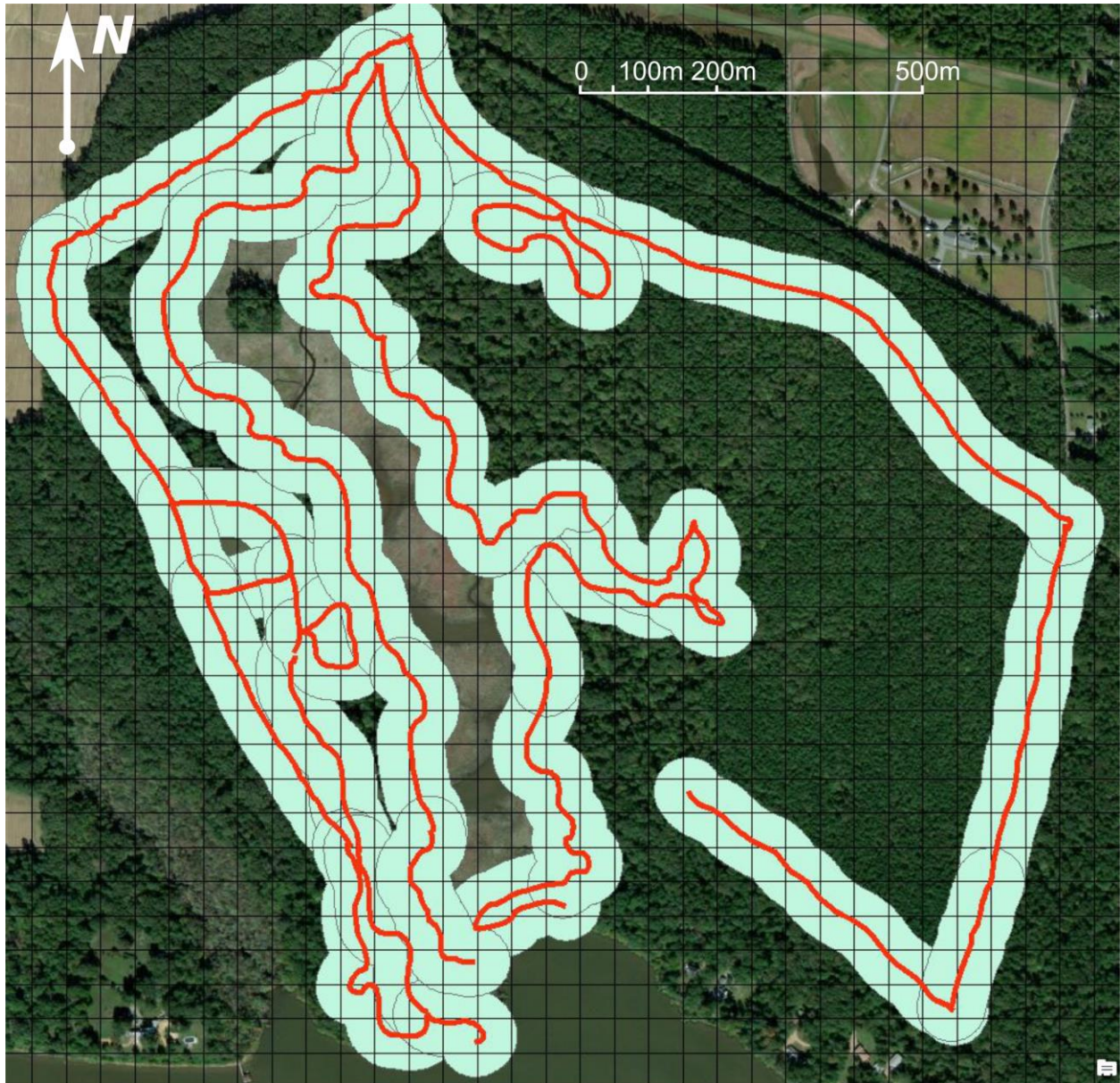
Figure 2. Spatial distribution of identified disturbances across the Rice Rivers Center with the 50-meter disturbance buffer.
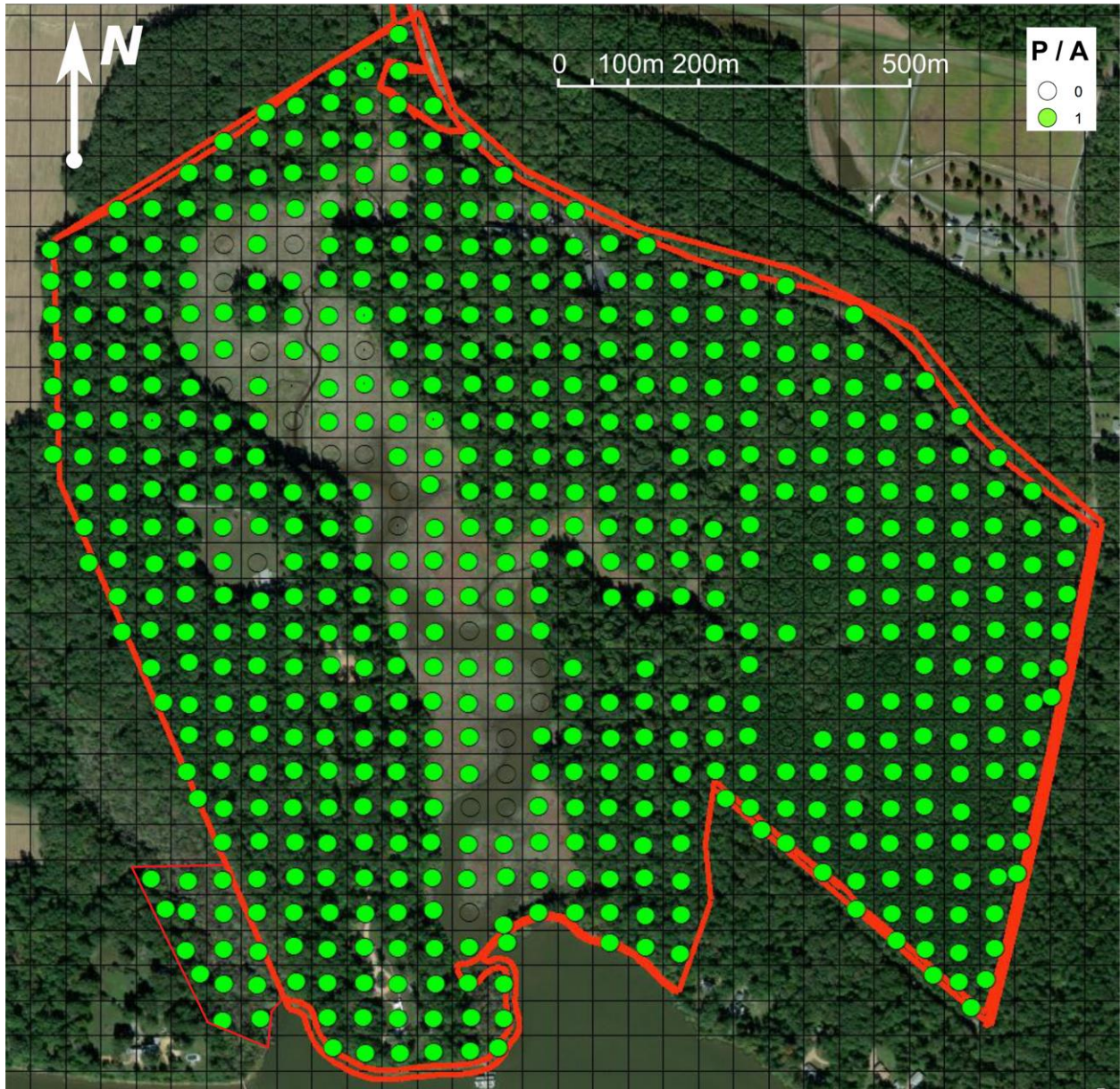
Figure 3. Spatial distribution of the presence of invasive plant species across the Rice Rivers Center property. Clear circles indicate absence, green circles indicate presence.
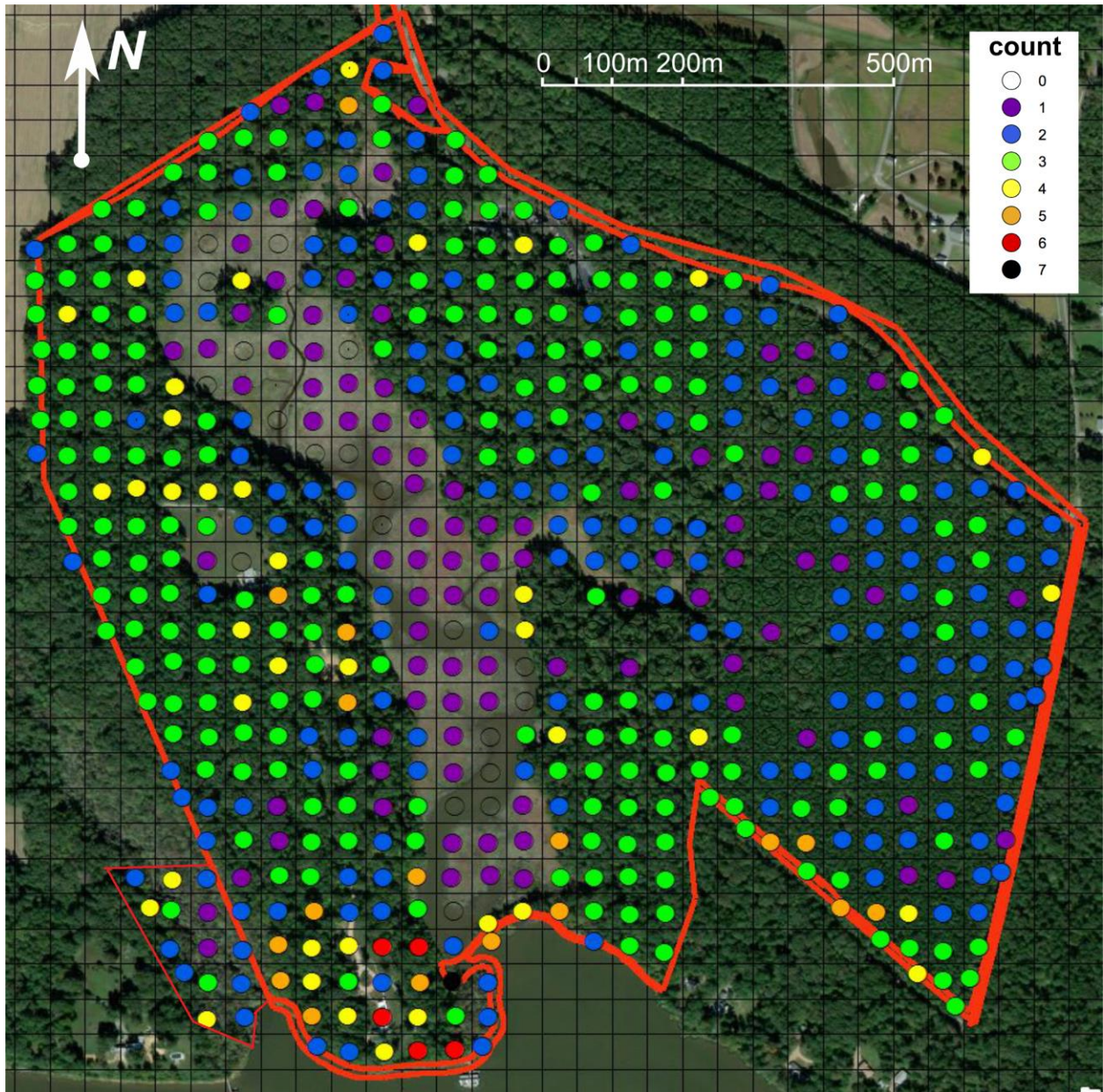
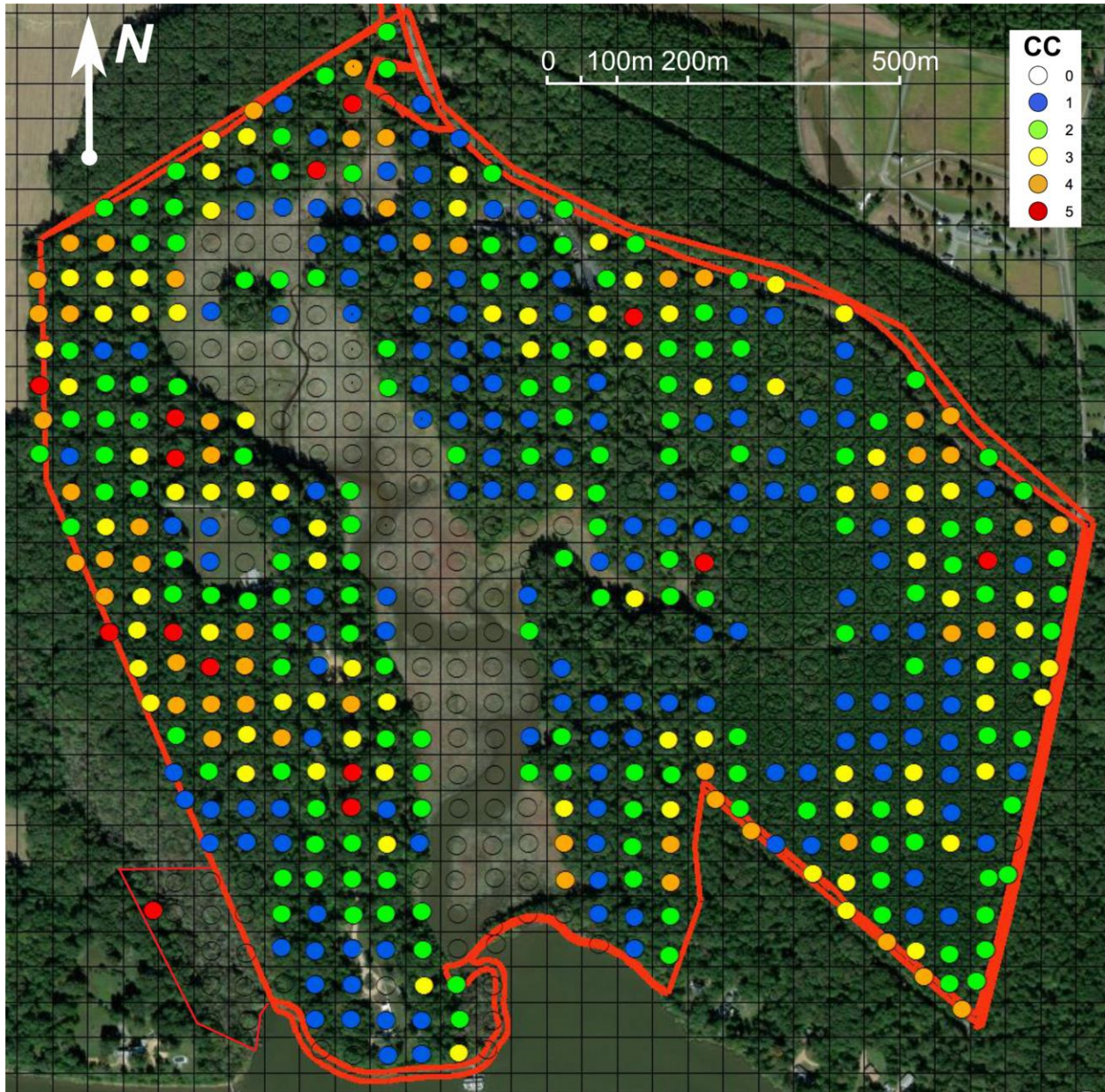Figure 4. Number of invasive plant species per grid cell across the Rice Rivers Center property.

Figure 5. Modified Daubenmire cover classes for *Microstegium vimineum* in each grid cell (2017) across the Rice Rivers Center. A clear circle indicates cover class 0, blue indicates cover class 1, green cover class 2, yellow cover class 3, orange cover class 4, red cover class 5. Refer to text for percentage ranges. Cover classes are as follows: 0 – 0% coverage, 1 – 1-5%; 2 - 6-25%; 3 - 26-50%; 4 – 51-75%; 5 – 76-95%; 6 – 96-100%
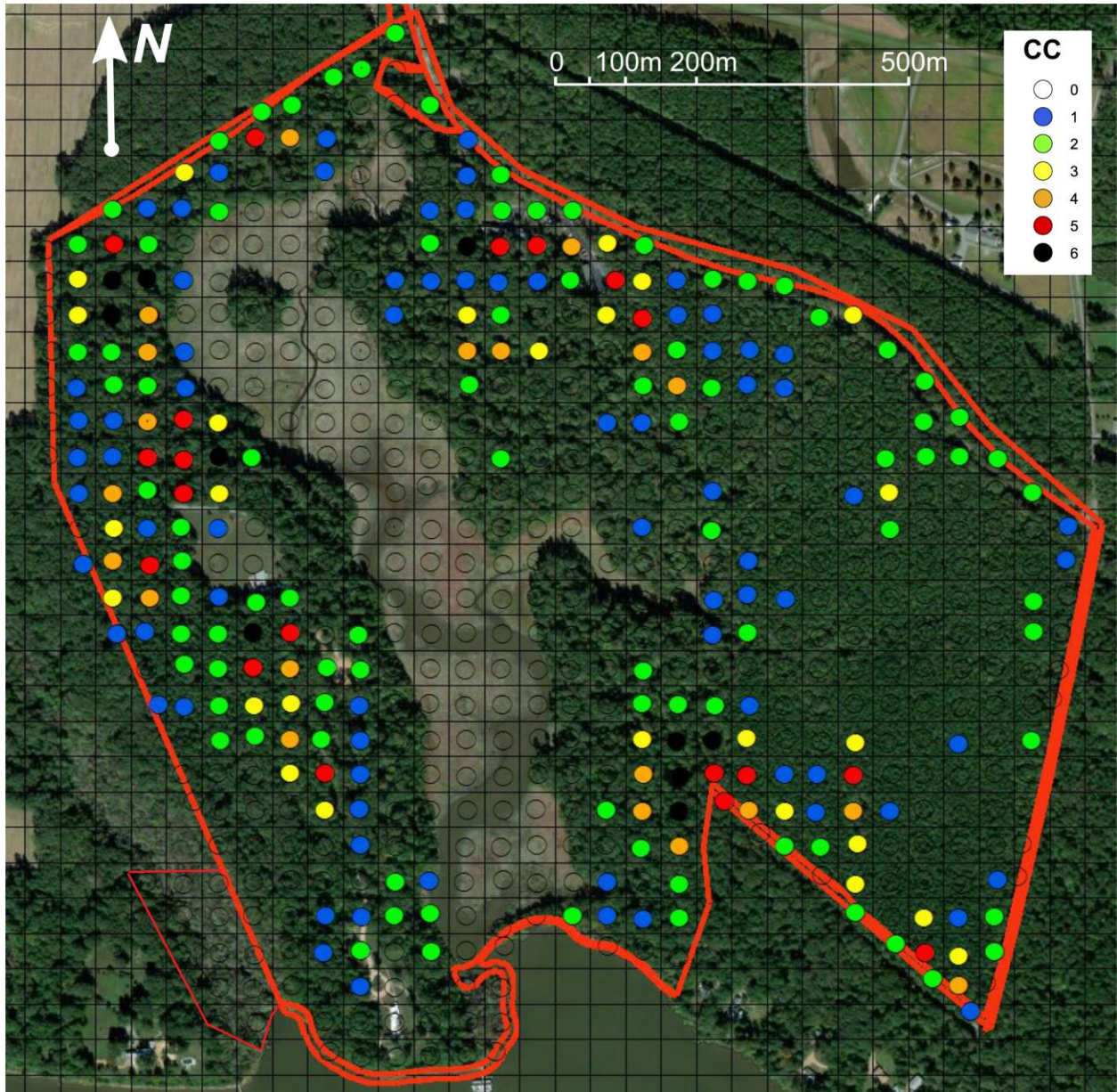
Figure 6. Modified Daubenmire cover classes for *Microstegium vimineum* in each grid cell (2004) across the Rice Rivers Center property. Cover classes are as follows: 0 – 0% coverage, 1 – 1-5%; 2 - 6-25%; 3 - 26-50%; 4 – 51-75%; 5 – 76-95%; 6 – 96-100%
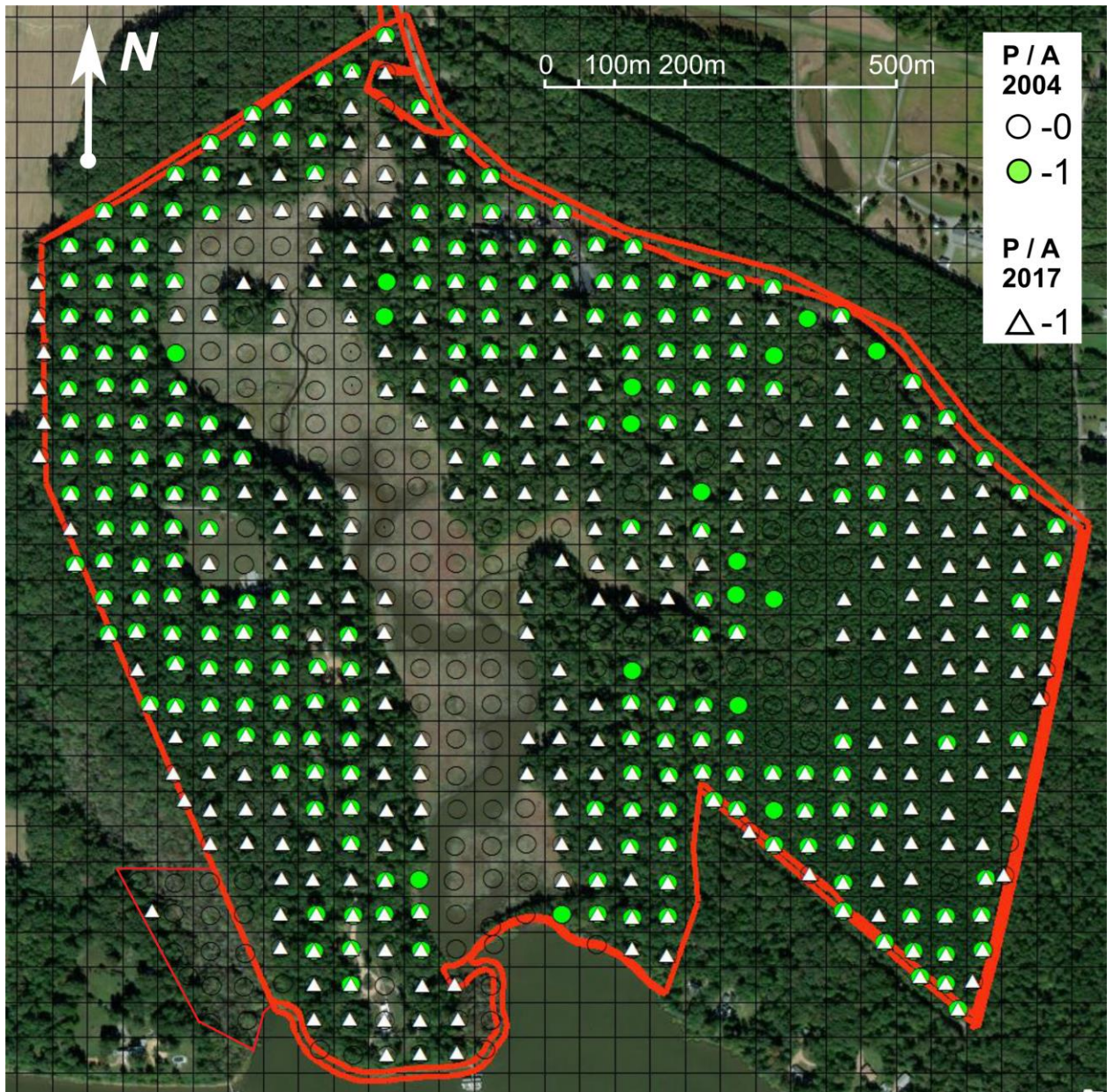
Figure 7. Combined presence/absence of *Microstegium vimineum* in each grid cell for 2004 and 2017 data at the Rice Rivers Center.
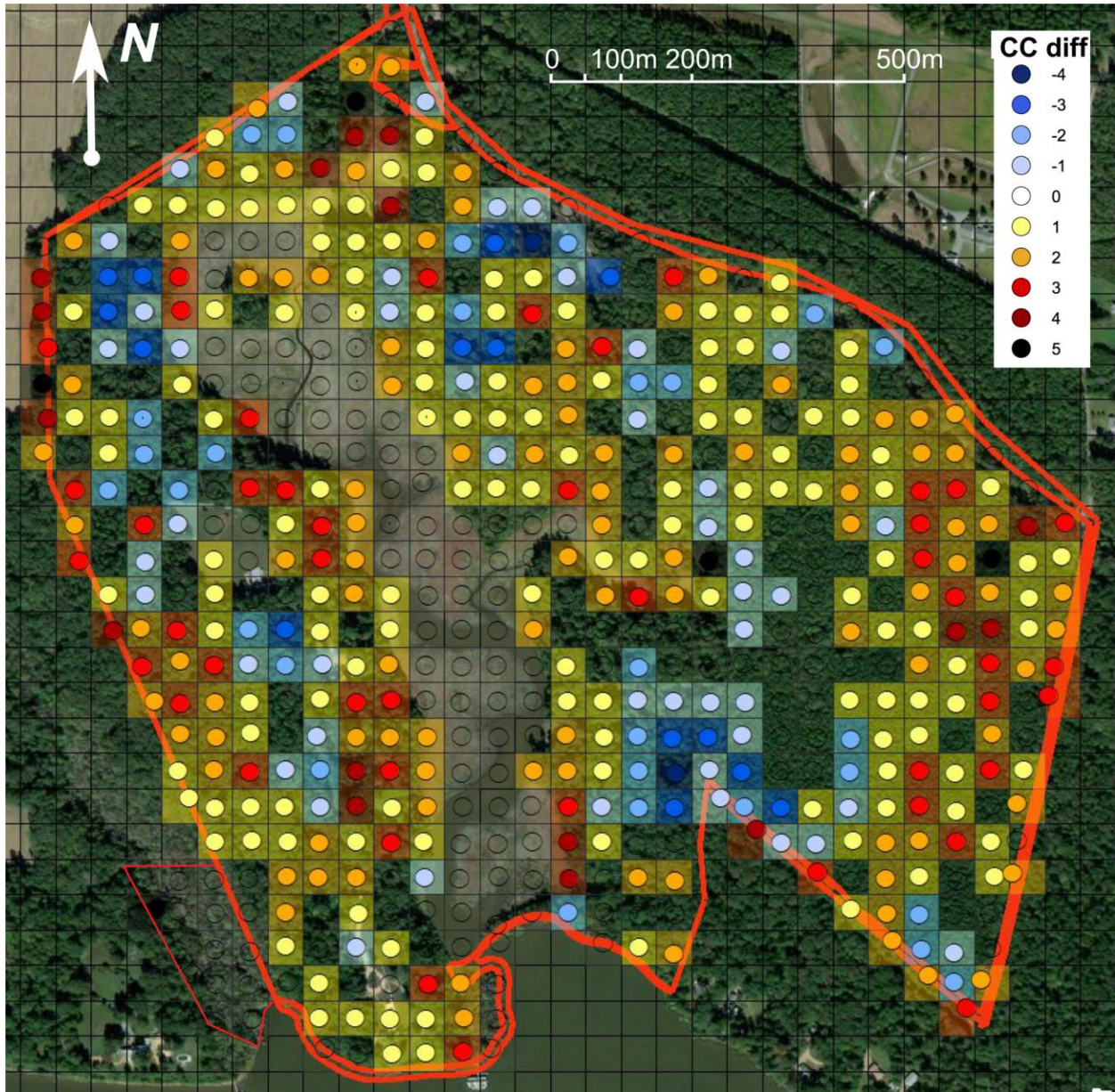
Figure 8. Change in *Microstegium vimineum* cover classes from 2004-2017 across the VCU Rice Rivers Center. Negative values (blue colors) indicate a reduction in *M. vimineum* cover class from 2004 to 2017, so coverage was lost. Positive values (yellow-red colors) indicate where *M. vimineum* coverage increased from 2004 to 2017. Clear circles indicate where no change in cover class was experienced.
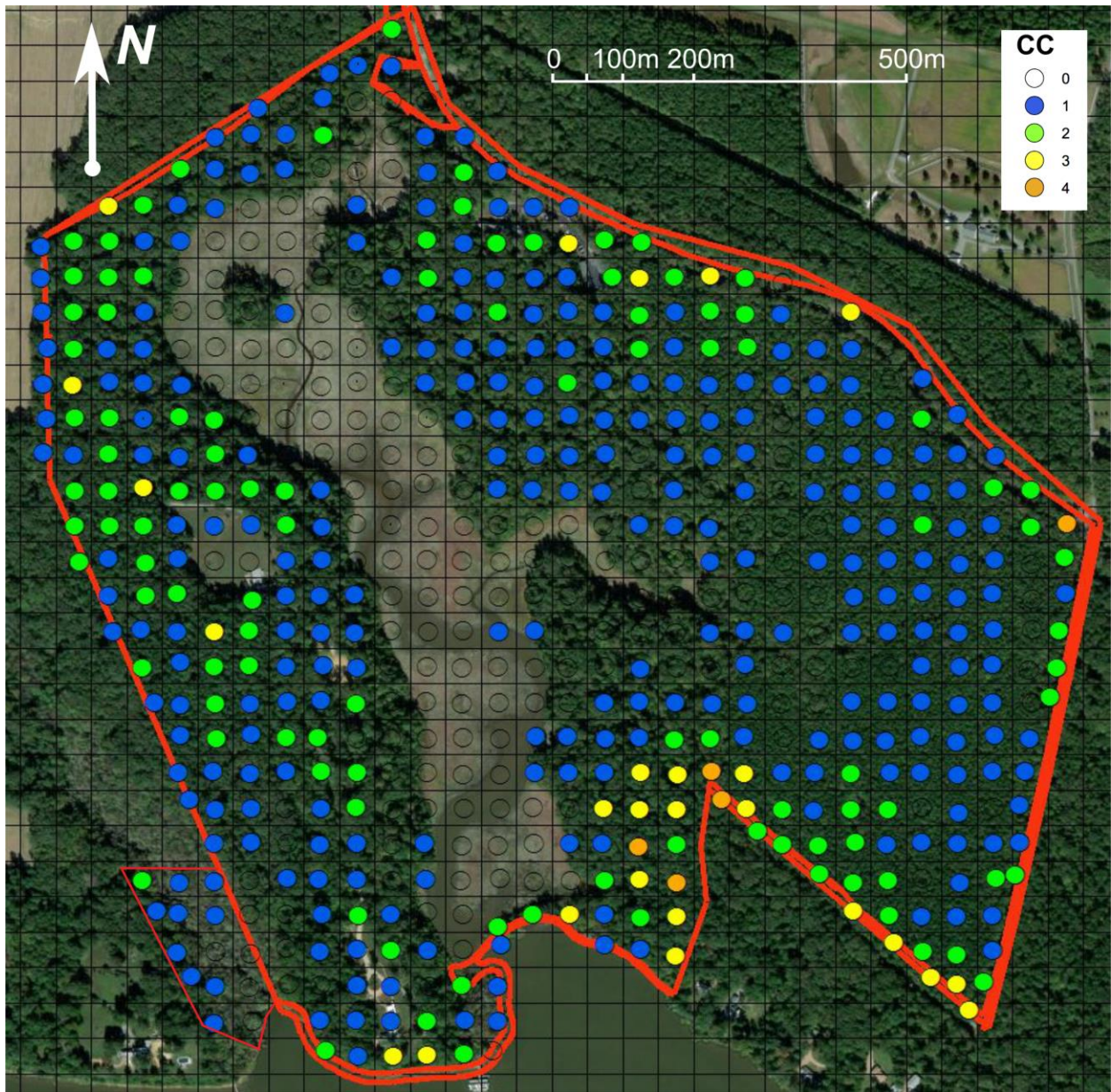
Figure 9. Spatial distribution and modified Daubenmire cover classes of *L. japonica* in each grid cell across the Rice Rivers Center property. Cover classes are as follows: 0 – 0% coverage, 1 – 1-5%; 2 - 6-25%; 3 - 26-50%; 4 – 51-75%; 5 – 76-95%; 6 – 96-100%
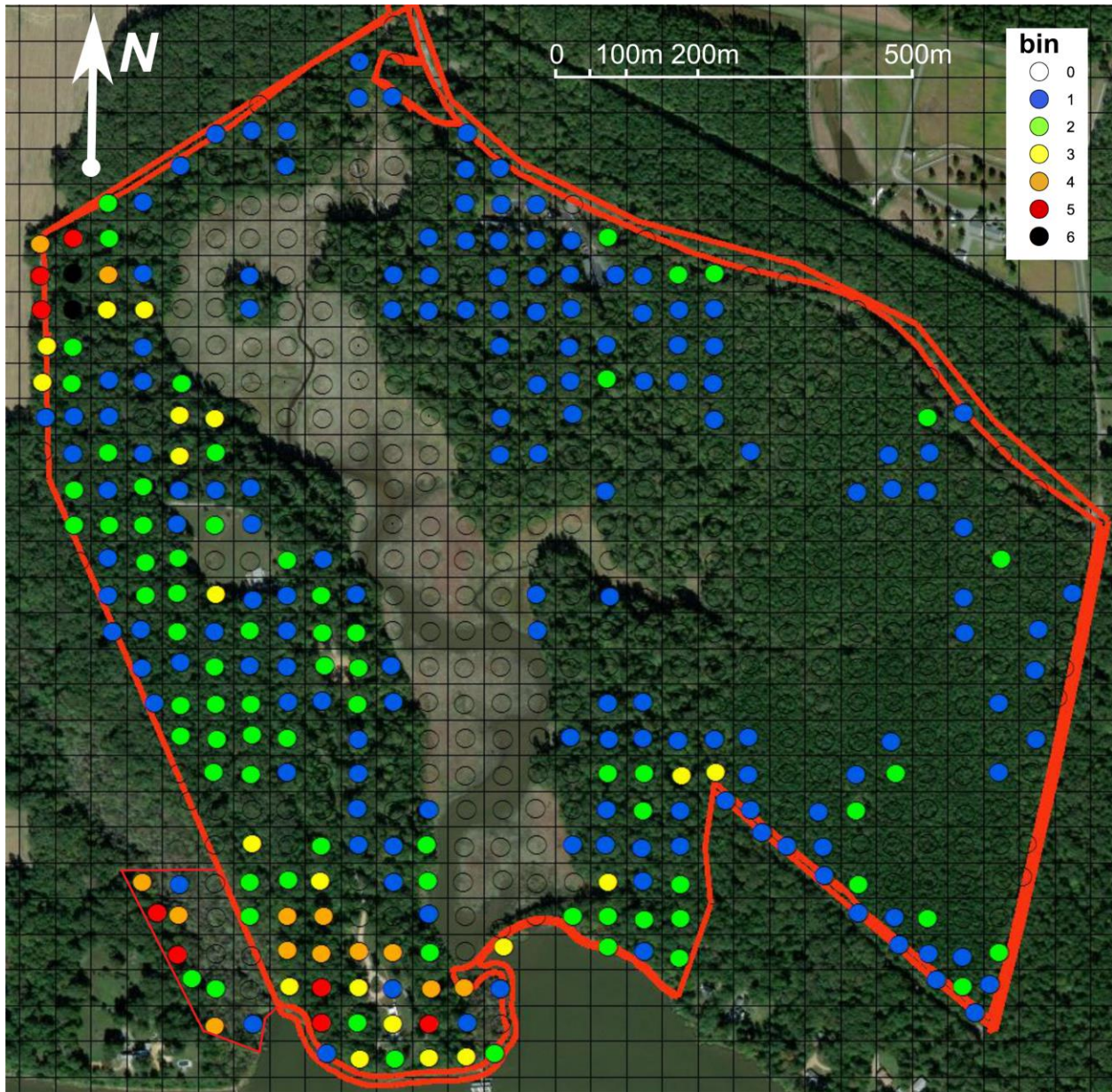
Figure 10. Spatial distribution and stem-count bins of *Ligustrum sinense* across the Rice Rivers Center property. The stem count bin ranges are as follows: 0 – 0 stems; 1 – 1-10; 2 – 11-50; 3 – 51-100; 4 – 101-200; 5 – 201-300; 6 – 300+
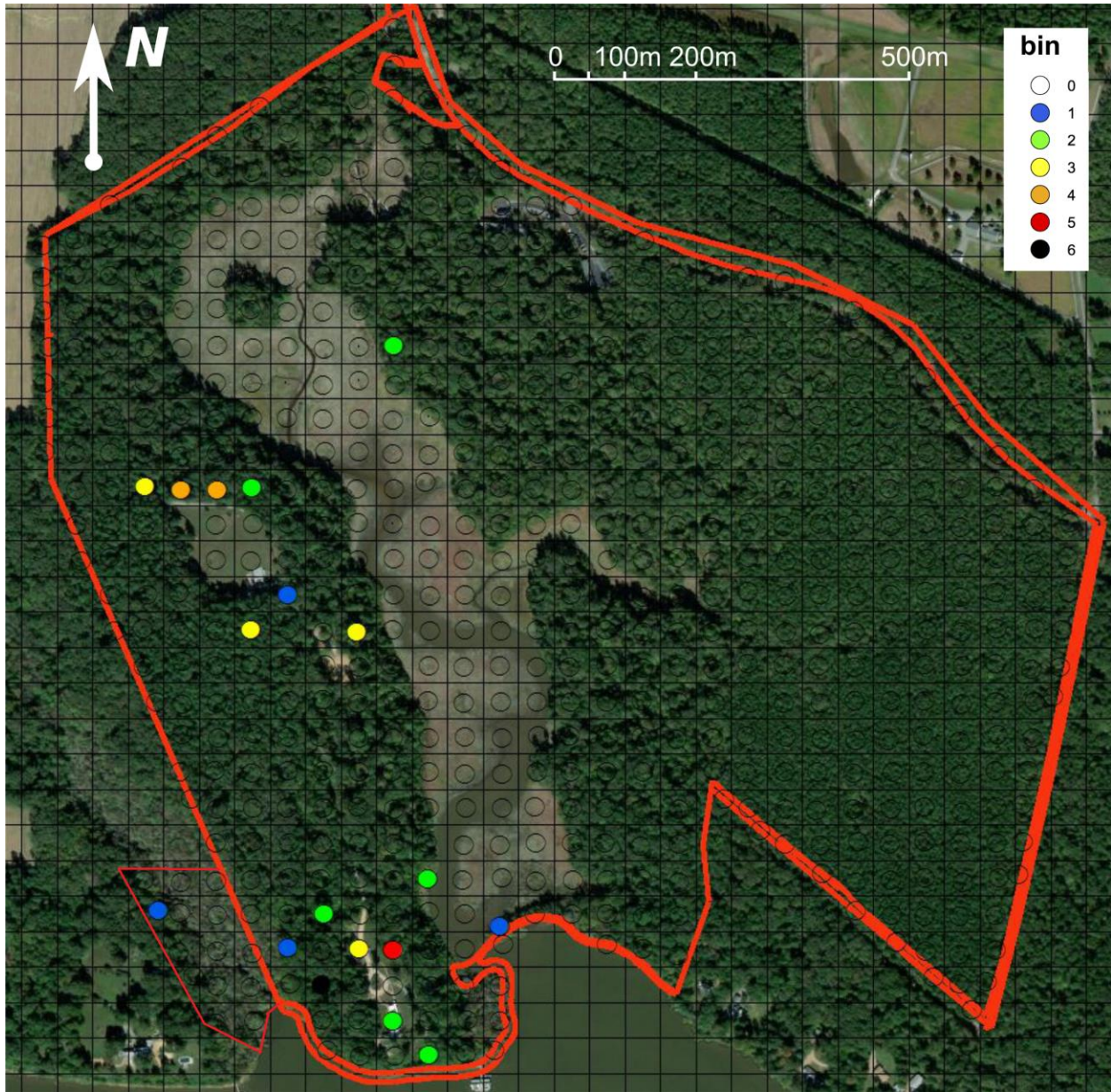
Figure 11. Spatial distribution of stem counts for *Ailanthus altissima* across the Rice Rivers Center property. Stem count bin ranges are as follows: 0 – 0 stems; 1 – 1; 2 – 2-4; 3 – 5-10; 4 – 11-15; 5 – 15-25; 6 – 26+
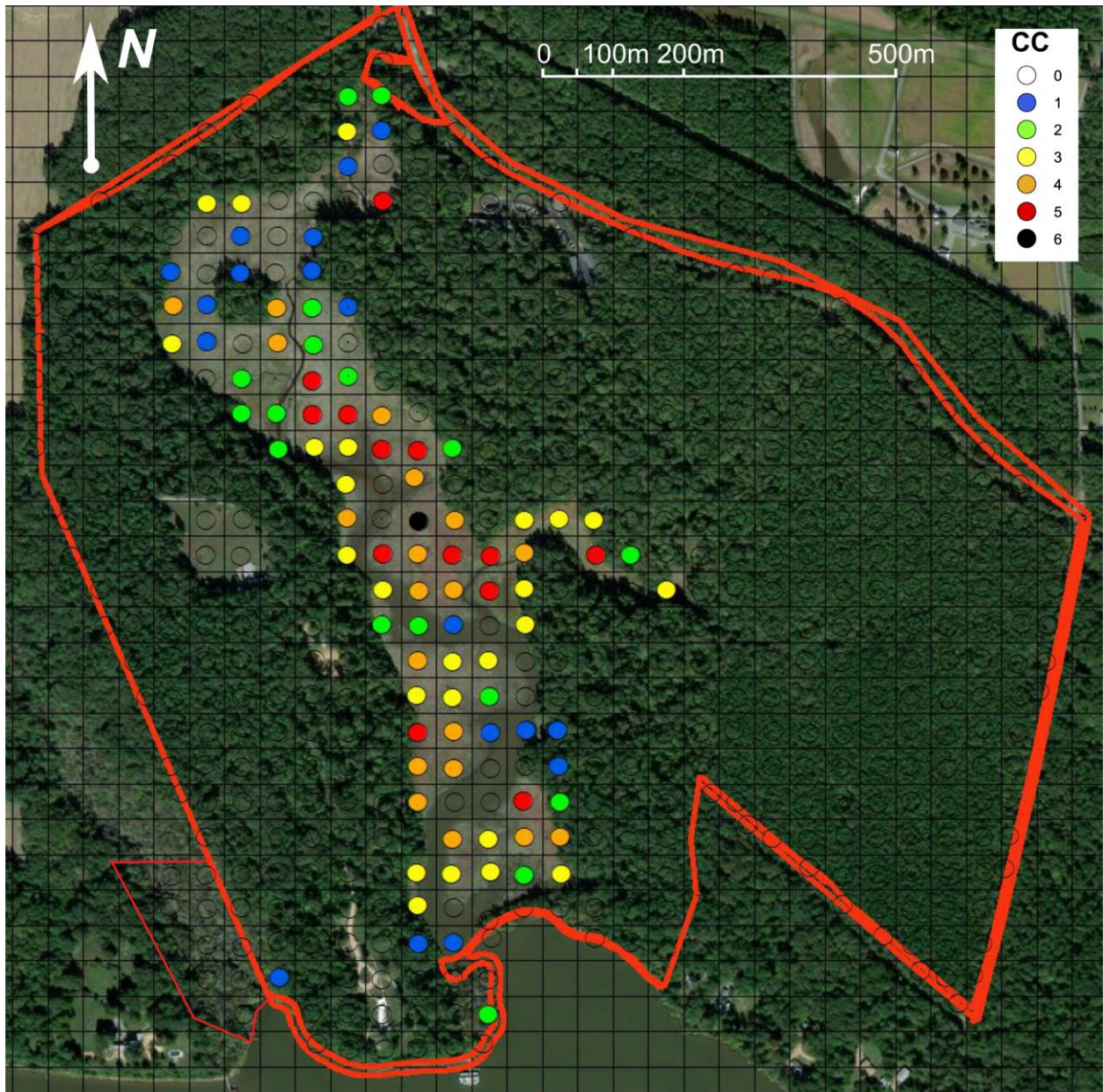
Figure 12. Spatial distribution and modified Daubenmire cover classes for *M. keisak* in each grid cell across the Rice Rivers Center property. Cover classes are as follows: 0 – 0% coverage, 1 – 1-5%; 2 - 6-25%; 3 - 26-50%; 4 – 51-75%; 5 – 76-95%; 6 – 96-100%

Figure 13. Spatial distribution of cover classes of *Phragmites australis* in each grid cell across the Rice Rivers Center property. Cover classes are as follows: 0 – 0% coverage, 1 – 1-5%; 2 - 6-25%; 3 - 26-50%; 4 – 51-75%; 5 – 76-95%; 6 – 96-100%

Figure 14. Spatial distribution and cover classes of *Alliaria petiolata* in each grid cell across the Rice Rivers Center property. Cover classes are as follows: 0 – 0% coverage, 1 – 1-5%; 2 - 6-25%; 3 - 26-50%; 4 – 51-75%; 5 – 76-95%; 6 – 96-100%
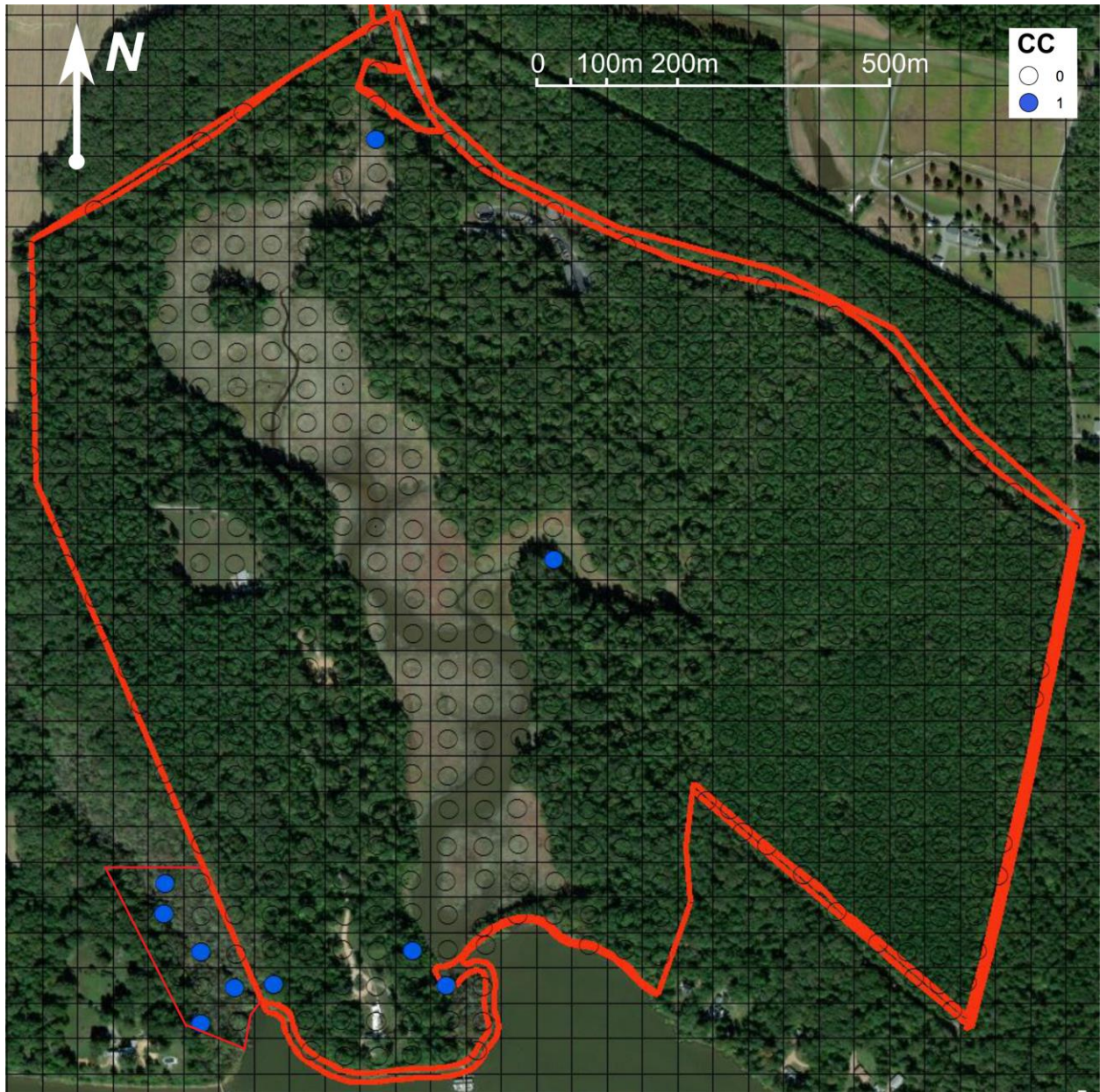
Figure 15. Spatial distribution and cover classes of *Rosa multiflora* in each grid cell across the Rice Rivers Center property. Cover classes are as follows: 0 – 0% coverage, 1 – 1-5%; 2 - 6-25%; 3 - 26-50%; 4 – 51-75%; 5 – 76-95%; 6 – 96-100%
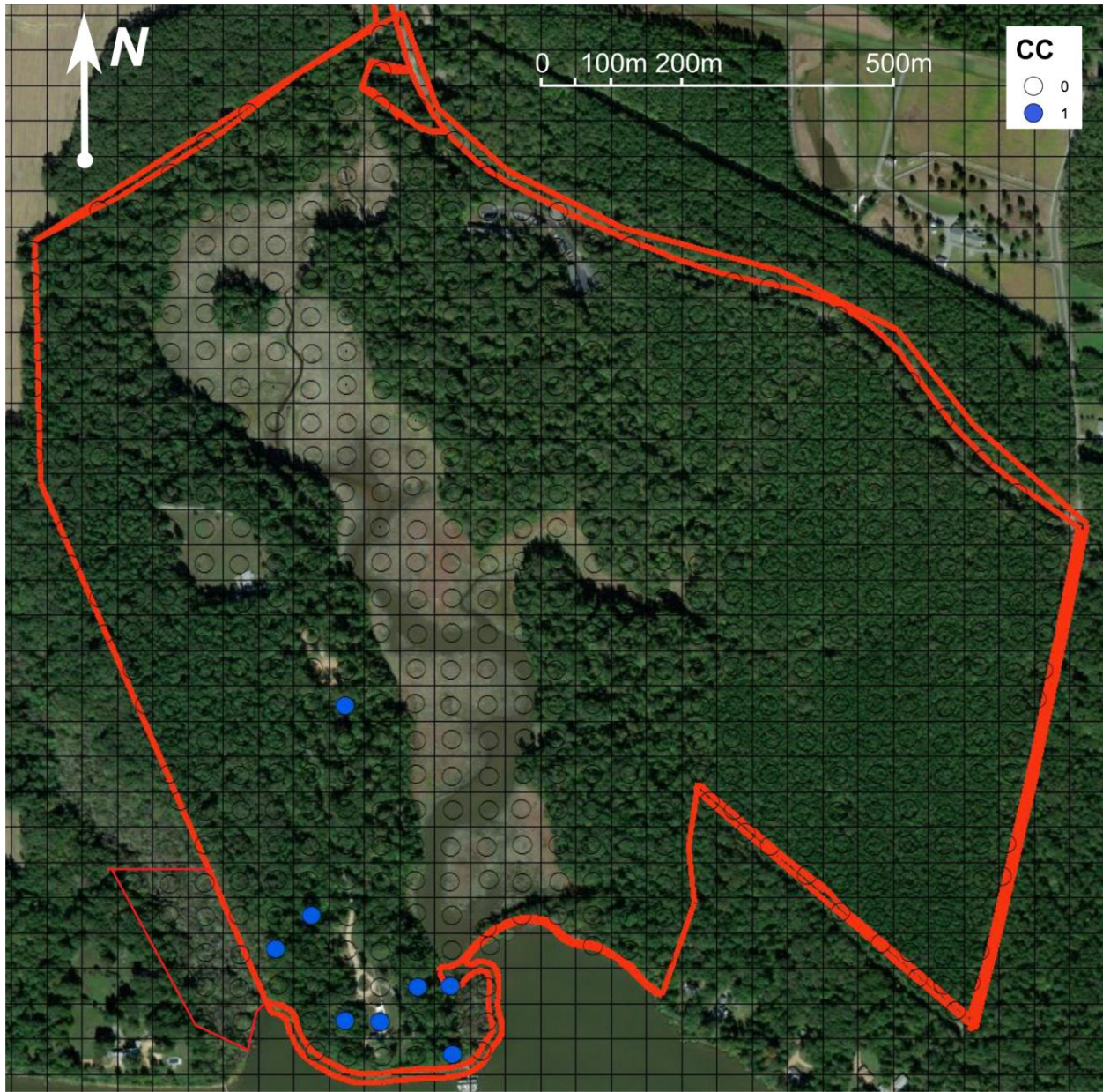
Figure 16. Spatial distribution and cover classes of *Hedera helix* in each grid cell across the Rice Rivers Center property. Cover classes are as follows: 0 – 0% coverage, 1 – 1-5%; 2 - 6-25%; 3 - 26-50%; 4 – 51-75%; 5 – 76-95%; 6 – 96-100%
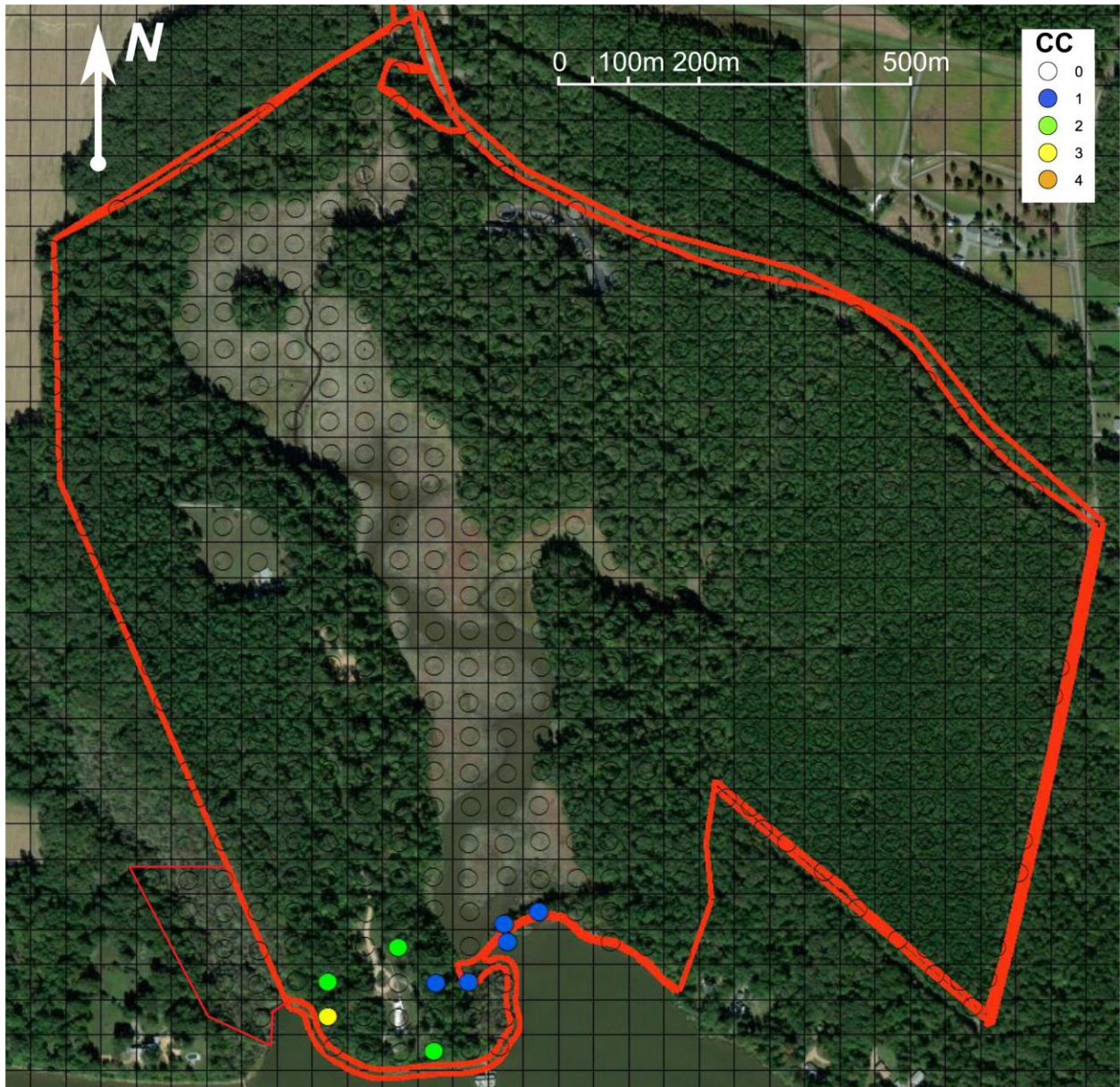
Figure 17. Spatial distribution and cover classes of *Vinca minor* in each grid cell across the Rice Rivers Center property. Cover classes are as follows: 0 – 0% coverage, 1 – 1-5%; 2 - 6-25%; 3 - 26-50%; 4 – 51-75%; 5 – 76-95%; 6 – 96-100%