ABSTRACT

Title of Thesis:	INVASIVE LIANA *HEDERA HELIX* (ENGLISH IVY) IMPACTS ON ECOLOGICAL CHARACTERISTICS AND NUTRIENT CYCLING IN BALTIMORE FOREST PATCHES
	Elad Shdaimah, Master of Science, 2023
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The effects of invasive plants on forest ecology and nutrient cycling are highly variable and poorly understood. Many studies have found that species and location make each plant invasion unique. Thus, studying invasive plants on the species and local level is necessary to understand how they impact ecosystems and how to manage them. Ninety-four percent of forest patches in Baltimore contain invasive plants. *Hedera helix* is one of the most prominent. My study explores how different characteristics and intensities of *H. helix* invasion impact ecology and nutrient cycling in Baltimore forest patches. I analyzed canopy structure, litter properties, soil properties, and steps of C and N cycling in forest patch plots. I compared findings across the invasion characteristics: presence, canopy invasion intensity, and ground cover presence. My study revealed that invasion characteristics and location strongly influence the impact of *H. helix* on Baltimore forest patch plots. The presence of ground cover appeared to be dictated by soil hydrology, which varied by location. Invaded plots with ground cover had significantly altered soil properties, increased soil

respiration rates (2.86 times greater than control plots, $p = 0.047$), and may have increased decomposition rates. These differences in C cycling metrics appear to be driven by altered soil temperature, structure, and chemistry (i.e., 1.62 times more TN than control plots, $p = 0.022$). Canopy invasions may have caused tree loss and altered canopy structure, which indicate potentially negative consequences for forest patch ecology in the future. pH may have been higher in the presence of *H. helix* (1.17 times higher pH than control plots, $p = 0.090$). Several ecological characteristics and nutrient cycling variables may have also been more variable in the presence of *H. helix*. No significant differences were detected in N cycling due to invasion. These findings can help Baltimore forest patch managers to assess problematic *H. helix* invasions and allocate resources to control it when necessary. They also lay out further groundwork for plant invasion research, demonstrating the necessity of species-specific, location-specific studies.

INVASIVE LIANA *HEDERA HELIX* (ENGLISH IVY) IMPACTS ON ECOLOGICAL CHARACTERISTICS AND NUTRIENT CYCLING IN BALTIMORE FOREST PATCHES

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2023

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Dedication

This thesis is dedicated to my dear, late friend Alex Levy, a fellow environmentalist. His dreams will continue to drive my efforts to create greener, more ecologically sound urban environments.

Acknowledgements

I thank the Explorers Club Washington Group and USDA Forest Service for providing the necessary funds to complete my field and lab research. I thank the University of Maryland, Baltimore County and Baltimore Green Space, as well as the Baltimore Office of Sustainability and United States Forest Services, for laying the groundwork for this whole body of research in the Baltimore area and providing necessary data for my project (via Dr. Matthew Baker).

I thank my advisor and the principal investigator of our lab, Dr. Mitchell Pavao-Zuckerman, for his guidance, advice, and support. I also appreciate the rest of my committee, Drs. Matthew Baker and Stephanie Yarwood, for assistance with framing my thesis project and with other aspects of this study. I also thank my department, all the professors, and the Project Development Center for providing me with all the necessary resources to complete my project, as well as endless advice and support.

I appreciate Lorna Atkinson at the Riverbend Environmental Education Center for showing me the exigency of invasive species. I thank Dr. J.B. Moon at Murray State University for involving me in her research on invasive species at Lake Lacawac, PA and teaching me so much about the research process.

I appreciate Mairead for being a great peer through our shared program and excellent soundboard for everything. I also thank Qianyao Si, Sarah Ponte, Daylan Sears, Gabrielle Jarvis, and the rest of our lab and research assistants who helped with field and lab work, and paper and presentation review.

My family and friends volunteered their weekends to help with field work. This project could not have been completed without my friends Aaron Robinson, Aaron Marsh, Ben Robinson, Jonah Eisen, Katie Stahl, Michael Allman, Nick Held, Patrick Hogan, and Ted Getselman. My parents, Corey and Amichai Shdaimah, also served as field volunteers, driving to and from Philadelphia and Baltimore several times. My parents have always unequivocally supported my goals with love, patience, and guidance.

Finally, I acknowledge and honor the indigenous communities in Baltimore, on whose stolen land this research was conducted. Baltimore was built on the unceded land of the Piscataway and Susquehannock people.

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List of Abbreviations

Ammonia	NH_3
Ammonium	NH_4^+
Beam Fraction	$\frac{H_b}{H}$
Carbon	C
Cloudiness Index	K_t
Decay Rate	k (coefficient)
Deionized Water	DI water
Effective Leaf Area Index (0-60° zenith)	LAI_e
Gap Light Analyzer	GLA
Net Primary Productivity	NPP
Nitrate	NO_3^-
Nitrite	NO_2^-
Nitrogen	N
Soil Organic Matter	SOM
Spectral Fraction	$\frac{R_p}{R_s}$
Tea Bag Index	TBI
Total Carbon	TC
Total Nitrogen	TN
University of Maryland, Baltimore County	UMBC
University of Maryland, College Park	UMD

Chapter 1. Introduction & Background

1.1 Introduction

North America, as well as much of the world, is most densely populated in temperate deciduous forest regions (United Nations, 2013). Twenty percent of the United States population lives in these regions along the East Coast alone (United States Census Bureau, 2010). Large cities in these areas have completely altered the landscapes and ecosystems at the cost of cities being susceptible to stresses and perturbations. The provisioning and management of green spaces is a necessary part of making cities resilient, as is recognized by international programs and approaches such as the United Nation's Sustainable Development Goals (United Nations, 2015), EcoHealth (EcoHealth Alliance, n.d.), and One Health (World Health Organization, 2017).

Urban green spaces are subject to habitat fragmentation, invasive species, altered species diversity and community structure, as well as novel hydrology, nutrient dynamics, and energy dynamics (Biggerstaff & Beck, 2007; Johnson, Trammell, et al., 2020; Larocque, 1999; Pouyat et al., 2009; Trammell et al., 2021; Yesilonis et al., 2022). Within urban land-use contexts are urban forest patches, self-sustaining systems with continuous canopy areas (not over impervious surfaces) with an edge width of at least 15 m (M. Baker, personal communication, 2023). They contain regenerative forest vegetation and are the result of both environmental and anthropological factors (Avins, 2013; Johnson, Trammell, et al., 2020; Ogden et al., 2018). Four key factors (urbanization, global climate change, invasive species, and natural abiotic and biotic) influence their ecological structure, function, community, and the ecosystem services

they provide (Figure 1). Urban forest patches can provide a bounty of supporting, provisioning, regulating, and cultural ecosystem services (Avins, 2013; Bouma & van Beukering, 2015; Livesley et al., 2016; Sonti et al., 2021), though these may be negatively impacted by the human-derived influences illustrated in Figure 1 (Groffman et al., 2006; Johnson, Johnson, et al., 2020; Pouyat et al., 2008, 2009).

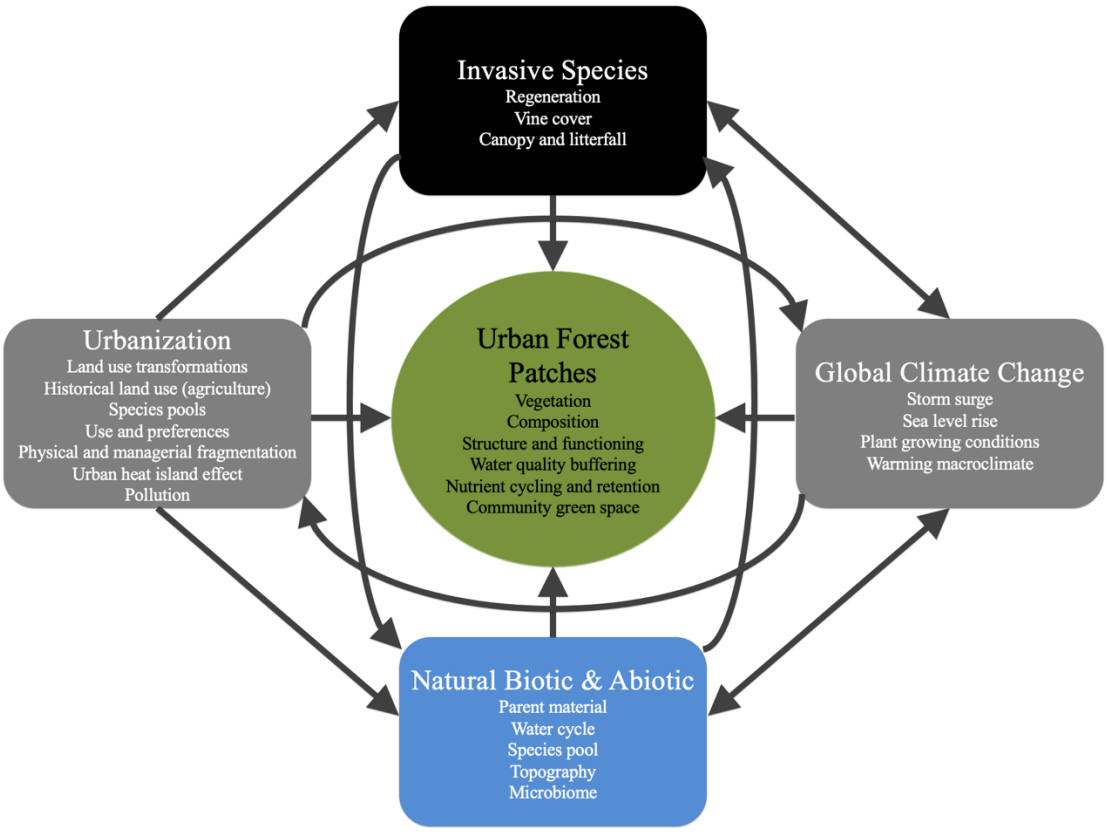


Figure 1. Conceptual model of major influences on urban forest patches. Arrows indicate directions of influence. Black and gray boxes are human-derived influences. 'Invasive Species' is emphasized because they are the focus of this project. Blue indicates natural influences, much of which is ultimately dictated by human activity. Inspired by Johnson, Johnson, et al. (2020) and Pouyat et al. (2009).

One critical dimension influencing the health of urban forest patches is invasive plants. Plant invasion is a human and urban-induced phenomenon wherein plants lacking their natural boundaries, such as consumers and other plant competition, can

grow and spread uncontrollably (Liebhold et al., 2017; Pyšek et al., 2020; Tassin & Kull, 2015). Most invasive species are non-native, and the interconnectedness of our world has created an excessive movement of species into new ecosystems, leading to an unprecedented takeover by invasive species.

Successful plant invaders are fast growers and tolerant to pressures which typically hinder the growth of native species, allowing them to proliferate and alter ecosystem ecology. Harsh growing conditions in urban areas, such as habitat fragmentation, are particularly favorable for these aggressive and adaptable plants (Johnson, Johnson, et al., 2020; Kang et al., 2019; Larocque, 1999; Pyšek et al., 2020; Rai & Singh, 2020). Generally, invasive plant species have direct and indirect impacts on nutrient cycling, canopy cover, litter and soil chemistry, water dynamics, and more (Ehrenfeld, 2003, 2010; Liao et al., 2008; Zhang et al., 2019). They have also been found to decrease plant community species diversity by smothering native species, outcompeting them for light and nutrients, and hindering seedbank regeneration, consequently altering the overall ecology of their environments (Biggerstaff & Beck, 2007; Ehrenfeld, 2003, 2010; Larocque, 1999; Levine et al., 2003; Liebhold et al., 2017; Pyšek et al., 2020; Rai & Singh, 2020).

The effects of invasive plants on forest health are highly variable (Ehrenfeld, 2003, 2010; Liao et al., 2008; Weidlich et al., 2020; Zhang et al., 2019). Some studies have found that invasive plants are not major drivers of urban forest patch health but are the indirect result of features such as fragmentation and nearby lawn fertilizer application, which create unique nutrient dynamics and settings for growth (Johnson,

Johnson, et al., 2020; Trammell et al., 2021; Yesilonis et al., 2022). Many studies have found that plant invasions impact ecosystems' ecological characteristics and nutrient cycling uniquely by species and location (Ashton et al., 2005; Ehrenfeld, 2003, 2010; Jo et al., 2016; Liao et al., 2008; Patil et al., 2020; Tassin & Kull, 2015; Ward et al., 2020; Zhang et al., 2019). The case-by-case basis for invasive plant impacts makes it so generalizations about invasive plants are suggestive but not practical from a management or control perspective (Ehrenfeld, 2003, 2010; Liebhold et al., 2017; Tassin & Kull, 2015; Ward et al., 2020; Zhang et al., 2019). Studies at the species level on a regional spatial scale are valuable in informing the revitalization and management of green spaces. Understanding the impacts of various invasion intensities and structures can also help managers decide when and where to assign resources.

I am primarily concerned with two components when it comes to the impacts of invasive plants on forest patches (Figure 2). The first is overall ecological characteristics, such as canopy structure, litter dynamics, and soil properties. The second is nutrient cycling and retention, particularly of nitrogen (N) and carbon (C), two of the most important nutrients in terrestrial environments. One dominant invasive plant in United States cities is the woody vine (liana) *Hedera helix* (English Ivy). This species is the focus of my study. The study was conducted in forest patches throughout Baltimore City, MD.

1.2 Background

1.2.1 Hedera helix

Hedera helix is an evergreen perennial liana in the Araliaceae family with over 400 cultivars (Strelau et al., 2018). It is native to Europe and goes by the common names English Ivy, Common Ivy, European Ivy, Ivy, Canary Island Ivy, and Algerian Ivy (Strelau et al., 2018). It can survive in temperatures as low as -25 °C and is shade tolerant (especially as a juvenile), though it grows best in full sun at warmer temperatures (Larocque, 1999; Metcalfe, 2005; Thomas, 1980). It prefers dry or moist soils and does not fare well in waterlogged soils (Metcalfe, 2005; Reichard, 2000; Thomas, 1980). It can grow in a wide range of pH levels (Reichard, 2000) but avoids soil with a pH below 4 (Metcalfe, 2005). Its leaves have three or five lobes (Reichard, 2000) and have a C:N ratio of about 10:1 (Badre et al., 1998; Lenaghan et al., 2013).

H. helix has two major growth stages. It grows for an average of eight years as a juvenile, where it can grow about 42 cm/m until about four m long, spreading across the forest floor and climbing up trees using an adhesive substance excreted from its rootlets. As an adult it can grow 22 cm/m until about 11 m long, typically growing vertically with larger leaves than when juvenile (Larocque, 1999; Strelau et al., 2018). Lianas are especially phenologically plastic, *H. helix* can change its structure and development in reaction to ecological pressures (Larocque, 1999; Wolkovich & Cleland, 2011), even mutating between cultivars (Strelau et al., 2018). This aligns with Davis et al. (2000)'s theory, which states that ecological disturbances, variability, and

fluctuating resource availability, can increase ecosystem invasibility (see also Hobbs & Huenneke, 1992).

H. helix can reproduce in two ways – sexually (seed) and asexually (vegetative). With sexual reproduction, its seeds can spread anywhere from November to June. The seeds are large and heavy, and thus not conducive to spread by wind (Larocque, 1999). Despite its seeds being mildly toxic, there are some birds which consume and disperse them, some of which reside in the Baltimore area (Strelau et al., 2018). *H. helix* seeds have very high germination rates (Metcalfe, 2005), but within forests it primarily spreads by its other reproductive mechanism, vegetative reproduction. If *H. helix* is in contact with the soil, it can continue to grow, and its adventitious roots can reproduce (Reichard, 2000). It also propagates extremely effectively, especially while in the juvenile stage (Strelau et al., 2018).

H. helix was introduced to North America as early as 1727 as an ornamental plant (Kling, 2022). It was also once believed to be effective at managing erosion, but this has been disproved based on its shallow root-depth (Strelau et al., 2018). It has become one of the most successful plant invaders in North America. This is due to its aggressive reproduction strategies, rapid growth rate and leaf production, its shade, pH, and temperature tolerance, and that it is an evergreen and can grow while other native plants are leafless and dormant (Reichard, 2000; Strelau et al., 2018; Thomas, 1980). Given its affinity for sun, tolerability for shade, phenological plasticity, and year-round rapid growth, it thrives especially well in mixed shade-sun forest environments. This makes urban forest patches, with ubiquitous fragmentation, ideal homes (Larocque,

1999; Reichard, 2000). Indeed, plant invasions in general have been shown to be more successful in environments with disturbance and fluctuating resource availability (nutrients, light, and water) (Davis et al., 2000), such as cities.

In forest settings, *H. helix*'s impacts on native vegetation are variable, but generally negative. It may strain native trees and shrubs by exposing them to herbivores and pathogens through bark removal or damage, deforming and breaking their stems, outcompeting them for light, water, and nutrients, and suppressing their root development (Larocque, 1999; Putz, 1991; Strelau et al., 2018). Ultimately, this may lead to decreased native plant growth rates and higher susceptibility to perturbations such as extreme climate (Strelau et al., 2018). There is some contending horticultural research which claims that *H. helix* does not harm tree hosts, though most ecologists do not agree (Larocque, 1999; Strelau et al., 2018). *H. helix* is also known to play a major role in preventing germination of all other vegetation by forming thick mats of groundcover, sometimes referred to as "ivy deserts" (Biggerstaff & Beck, 2007; Larocque, 1999; Reichard, 2000). However, it has been discovered that dormant seeds are able to germinate effectively when *H. helix* is removed (Biggerstaff & Beck, 2007). Little has been written on the effects of *H. helix* invasion on soil properties, but mat-like root growth in the shallow soil may impact soil physical, chemical, and biological properties. Meta-analyses and review papers on invasive plants indicate that they may alter soil properties such as temperature, hydraulic conductivity, nutrient concentrations and availability, and microbial communities (Ehrenfeld, 2003; Lone et al., 2019; Zhang et al., 2019).

Despite this long list of impacts on vegetation structure and diversity, there have been no studies analyzing the impacts of *H. helix* as an invasive plant on overall ecosystem function. There are also no studies analyzing the impacts of different characteristics or intensities of *H. helix* invasion, nor their effects in Baltimore. *H. helix* may alter urban forest patch ecology in Baltimore given its invasive nature and the advantageous position it has in these temperate, fragmented ecosystems. Understanding how N and C cycles are altered by invasive plants in other studies will help to guide expectations for *H. helix* impacts on nutrient cycling.

1.2.2 Nitrogen

When it comes to N and forest patch health and ecosystem service provisioning, we are primarily concerned with retention (inversely, leaching) and availability to plants. Plant available N drives growth (Enloe et al., 2015; Reich et al., 1997); high N availability favors aggressive invasive plants over most native plants (Davidson et al., 2011; Ehrenfeld, 2003, 2010; Liao et al., 2008; Lone et al., 2019; Weand, 2020). Plant available N also doubles as leachable N, coming in the inorganic forms of ammonia (NH_3), ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-). This is of great concern because urban forest patches should provide the ecosystem service of N retention. High levels of N in groundwater and surface water can contribute to eutrophication and toxic algal blooms in surface water (Boesch et al., 2001; United States Geological Survey, 2018), and groundwater with large amounts of N can pose health risks when used as drinking water (Gao et al., 2012; United States Geological Survey, 2018). Plant invasion may be driven by and contribute to N conditions in urban forest patches.

We may be able to predict how presence and characteristics of *H. helix* invasion hinder or support N retention in urban forest patches from existing meta-analyses on invasive plants. Some of these meta-analyses discern whether impacts on N cycling are caused by changes to litter or the rhizosphere. Invasive plants can impact N cycling dynamics by increasing plant biomass N stocks by 86-122% and releasing that N to the soil through litterfall with a 38% higher N concentration (Liao et al., 2008). Plant invasion can also increase microbial biomass N stocks by 26% N through litter and rhizosphere effects, as well as increase the rates of N mineralization and nitrification by 52-53% through altered litter traits (Liao et al., 2008). Other findings indicate that invasive plants primarily impact N cycling through rhizosphere effects (13.4-, 2.2-, and 3.2-times greater percent change in N mineralization rates, nitrification rates, and N enzyme activities via rhizosphere effects than litter effects) (Zhang et al., 2019). Also, N mineralization rates (195% change via rhizosphere effects) are impacted more strongly than nitrification rates (four percent change via rhizosphere effects) by invasion (Zhang et al., 2019). The same study suggests that the increase in N mineralization rates is more significant than changes to the mineral N pool. They suggest that soil NH_4^+ concentrations may increase (20.91% change via rhizosphere effects, not statistically significant), and that soil NO_3^- concentrations may decrease (-44.33% change via rhizosphere effects, not statistically significant), with invasion. This may indicate an increase in mineral N removal from the soil through stormwater runoff and leaching in the presence of invasion, which has been observed in other invasion studies (i.e., McEwan et al., 2012).

The impacts of invasive plants on N cycling and availability are highly variable. This is demonstrated across the above meta-analyses via conflicting findings and wide spreads (Liao et al., 2008; Zhang et al., 2019). Giving an additional perspective on variability, N mineralization rates were found to be positively correlated with plant invasion in 11 of 16 studies reviewed and mineral N was found to be positively correlated with plant invasion in nine of 17 studies analyzed (four studies indicated a decrease and four indicated no change) in another meta-analysis (Ehrenfeld, 2003). There are many cases where different species, or the same invasive species in different locations, have different impacts (Ehrenfeld, 2003, 2010; Liao et al., 2008; Zhang et al., 2019). Based on the variability demonstrated by these three meta-analyses, whether invasive plants impact N cycling, and whether the primary pathway of impacts is through rhizosphere effects or leaf litter effects, depends greatly on species and location.

Individual studies can guide expectations of the impacts of *H. helix* on N cycling as well, though they yield both contradictory and some inconclusive findings. First, multiple species should not be studied together and treated as one unit. The variability demonstrated in the meta-analyses is supported by the conflicting findings across individual studies and review papers, where some studies, or parts of them, discovered positive correlations between invasion and N cycling metrics (Ashton et al., 2005; Hickman et al., 2013; Jo et al., 2017; Lone et al., 2019; McEwan et al., 2012; Osunkoya et al., 2010; Ward et al., 2020; Weand, 2020), and other studies, or other parts of the same studies, discovered no correlation or a negative correlation between

invasion and N cycling metrics (Hull et al., 2020; Jo et al., 2016; Patil et al., 2020; Weand, 2020).

Second, most studies which looked at individual plants or the soil directly below them, often comparing native and invasive species which are directly beside each other, found insignificant results (Hull et al., 2020; Jo et al., 2016; Patil et al., 2020). Impacts by invasive plants seem to be made to entire plots, affecting the system around them and not only individuals (Ashton et al., 2005; Hawkes et al., 2005; Hickman et al., 2013; Jo et al., 2017; Ward et al., 2020; Weand, 2020). For example, Jo et al. (2016, 2017) conducted two studies in a temperate forest in Syracuse, NY. One study attempted to determine if N cycling was driven by litter decomposition of individual native and invasive plants and found insignificant results (Jo et al., 2016). The other study focused on the impacts of invasive monocultures on whole-plot N cycling rates and found a significant increase in N cycling through high-N litter and rapid uptake of N by invasive plants (Jo et al., 2017).

Third, the intensity of impacts may change with intensity of invasion, with monocultures making the most significant changes (Hickman et al., 2013; Jo et al., 2017; Ward et al., 2020). Ward et al. (2020) is a unique example of a study measuring soil metrics across gradients of liana invasion intensity and forest disturbance, which found a positive correlation between invasion intensity and N mineralization rates. Another interesting assertion from this study is that they believe pH is a main driver of N mineralization rates and invasibility. Hickman et al. (2013) compared decomposition rates of different mixtures of native and invasive leaves in plots on Long Island, NY

and found that mixed bags decomposed at the same rates as native litter while bags with only invasive litter decomposed faster, indicating the potential impact of monocultures.

Finally, we can conclude that there are cases where either or both litter content (Hickman et al., 2013; Jo et al., 2017; Osunkoya et al., 2010; Weand, 2020) and soil content and rhizosphere effects (Ashton et al., 2005; Jo et al., 2017; Ward et al., 2020) drive changes to N cycling. This is indicated by the variable conclusions made in both the meta-analyses and across individual studies. *H. helix* is an evergreen in Baltimore, so it is unlikely to alter litter quality significantly. However, with many of these studies indicating the importance of below-ground effects and ground cover, as well as more indirect impacts to the overall system, *H. helix* may impact N cycling (Jo et al., 2017; Lone et al., 2019; Ward et al., 2020; Zhang et al., 2019).

1.2.3 Carbon

We may be able to predict how presence and characteristics of *H. helix* invasion hinder or support C sequestration in urban forest patches from existing meta-analyses on invasive species. Some of these meta-analyses discern whether impacts on C cycling are caused by changes to litter or the rhizosphere. Invasive plants tend to impact C cycling dynamics by increasing plant biomass C stocks by five-132%, releasing 49% more C through litterfall, and increasing soil microbial C stocks by 34% (Liao et al., 2008). However, other findings indicate that invasive plants generally impact C dynamics by stimulating the microbial and fungal communities through not only litter, but rhizosphere effects as well. For example, microbial biomass changes are more

heavily influenced by litter effects (27.52% change) and C enzyme activities are more heavily influenced by rhizosphere effects (27.30% change) (Zhang et al., 2019). Additionally, increases in soil respiration and microbial activity may be driven primarily by rhizosphere effects (i.e., 35.9 times greater percent change in C enzyme activity via rhizosphere effects than litter effects; 1.2 times greater percent change in CO_2 efflux via rhizosphere effects than litter effects) (Zhang et al., 2019). Plant invasion, in addition to increasing C biomass stocks, can increase net primary productivity (NPP) (Ehrenfeld, 2003, 2010). Plant biomass was found to be positively correlated with invasion in 14 of 18 cases studied reviewed and NPP was found to be positively correlated with invasion in 10 of 12 studies reviewed (Ehrenfeld, 2003). However, only six of 12 studies reviewed found that litter mass increased with invasion (Ehrenfeld, 2003). This suggests that alterations to C sequestration potential are not strongly driven by litter effects, which is contested in one of the other meta-analyses (Liao et al., 2008), and may be supported by another (Zhang et al., 2019). As mentioned above, there are many cases where different species, or the same invasive species in different locations, have different impacts (Ehrenfeld, 2003, 2010; Liao et al., 2008; Zhang et al., 2019).

Individual studies can guide expectations of the impacts of *H. helix* on C cycling in addition to those mentioned in the above section which apply to all invasive plant studies (i.e., necessity of species-specific and location-specific studies, studying entire plots instead of individuals, and that impacts may change with intensity of invasion). Again, these studies yield both contradictory and some inconclusive findings. First, altered litter decomposition by invasive plants may (Ashton et al., 2005; Bush et al.,

2020; Hickman et al., 2013; Jo et al., 2017; Lone et al., 2019; Rodgers et al., 2008; Trammell et al., 2012; Ulyshen et al., 2020; Weand, 2020; Woodworth et al., 2020) or may not (Bush et al., 2020; Hickman et al., 2013; Jo et al., 2016; Ward et al., 2020) be a driver of C cycling alterations in invaded forest sites. This was discussed in the N background section and applies to C cycling as well. Most studies with significant findings attributed this to invasive litter quality, quantity, and timing (Ashton et al., 2005; Bush et al., 2020; Hickman et al., 2013; Jo et al., 2017; Rodgers et al., 2008; Trammell et al., 2012; Weand, 2020; Woodworth et al., 2020), which is unlikely to be a pathway by which *H. helix* alters nutrient cycling in this study because it is an evergreen in Baltimore. However, some studies and review papers found that other indirect and complex relationships between invasive plants and soil properties may contribute to decomposition rate alterations (Lone et al., 2019; Ulyshen et al., 2020).

Second, plant invasion can increase short-term C storage and alter long-term C storage in forest systems. For example, in a review paper by Peltzer et al. (2010), they concluded that the direct effect of forest invaders on C is short-term and small, acting through increased nutrient cycling and availability via high NPP. Meanwhile, long-term effects on C cycling and storage act through alterations to species composition and the cascading impacts of altered nutrient cycling, which can have unpredictable consequences (Peltzer et al., 2010). Invasive plants are associated with higher decomposition rates (Ashton et al., 2005; Ehrenfeld, 2003, 2010; Liao et al., 2008; Lone et al., 2019; Patil et al., 2020; Trammell et al., 2012; Weand, 2020; Zhang et al., 2019) and lower species diversity (Biggerstaff & Beck, 2007; Ehrenfeld, 2010; Liebhold et al., 2017; McEwan et al., 2012; Pyšek et al., 2020; Rai & Singh, 2020), especially lower

prevalence of old, large trees which are optimal for long-term C storage (Avins, 2013; Larocque, 1999; Liebhold et al., 2017). It is likely that *H. helix* will ultimately decrease long-term C storage in Baltimore urban forest patches by harming tree populations, as described above.

The potential impacts of plant invasion on C cycling are certainly present and relevant, but as discussed, every species in every location is likely to have a different effect. Some researchers even theorize that invasive plants may play an important role in sustaining C storage in novel ecosystems, such as urban forest patches (Tassin & Kull, 2015). Again, many studies ultimately call for more species-specific and location-specific studies (Ehrenfeld, 2003, 2010; Liao et al., 2008; Peltzer et al., 2010; Ulyshen et al., 2020; Zhang et al., 2019). The impacts of *H. helix* on C cycling and sequestration in urban forest patches in Baltimore are currently unknown. With many of these studies indicating the important roles that invasive plants play in C cycling via alterations to species diversity, rhizosphere effects, respiration and decomposition rates, and indirect impacts to the overall system, *H. helix* may impact C cycling.

1.3 Research Questions & Expected Findings

My study asks:

- How does invasion by *H. helix* impact ecological characteristics of Baltimore's forest patches?
- How does invasion by *H. helix* impact nitrogen (N) cycling and retention in Baltimore's forest patches?

- How does invasion by *H. helix* impact carbon (C) cycling and sequestration in Baltimore's forest patches?
- How are these impacts different across different canopy and ground cover characteristics of invasion?

To answer these questions, I compared canopy, litter, and soil properties, as well as rates of C and N cycling, between forest patch plots across different factors describing invasion by *H. helix*. Specifically, I explored impacts through three factors: 1) presence of invasion by *H. helix*, 2) intensity of canopy invasion by *H. helix*, and 3) presence of ground cover by *H. helix* during invasion.

I aim to contribute information to managers of forest patches in Baltimore about the exigency of the effects of this liana and to demonstrate the necessity of species-specific and location-specific studies with respect to biological invasions. My expected findings are outlined below (Figure 2).

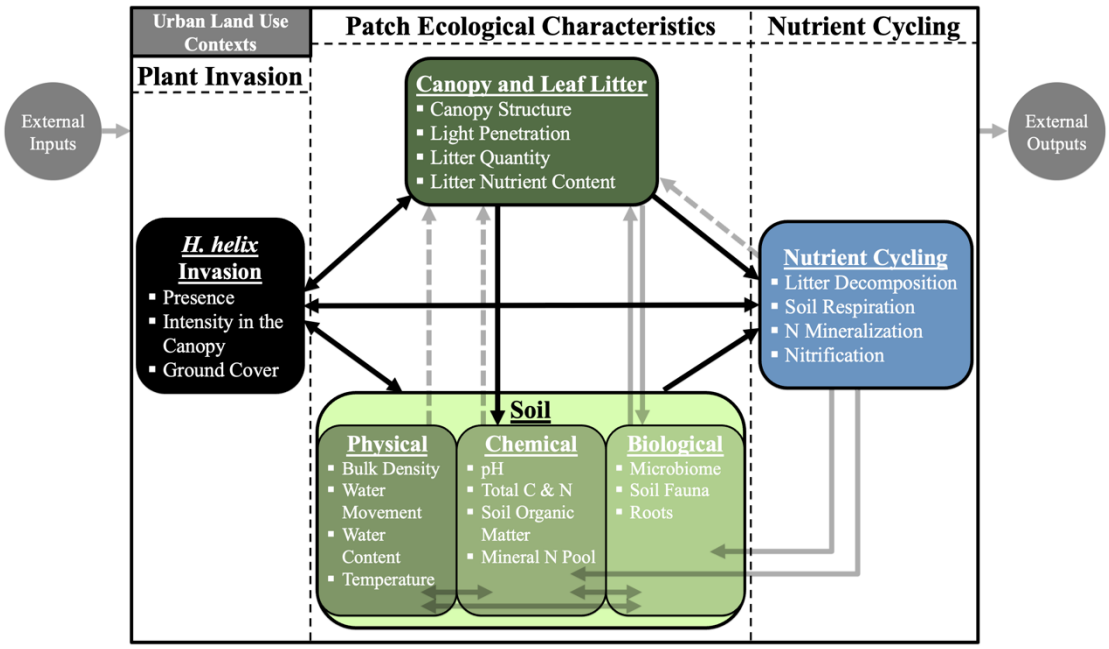


Figure 2. Conceptual model of the impacts of *Hedera helix* invasion on urban forest patches. Arrows represent direction of influence, with dashed arrows representing relatively long-term impacts. Black arrows are being studied in this project, while transparent arrows are not but remain relevant for context. Impacts are binned into two larger categories: ecological characteristics and nutrient cycling. Impacts on ecological characteristics are further binned into canopy and leaf litter, soil physical, soil chemical, and soil biological impacts. External inputs and outputs, as well as urban land use contexts, situate this conceptual model in the greater urban system (Figure 1).

With respect to the effects on trees and the canopy, I measured canopy openness and structure, as well as litter depth and chemical content. I expected canopy openness and canopy gap size, and thus light penetration, to have a positive relationship with invasion presence and canopy invasion intensity because *H. helix* restricts tree growth and may lead to death (Larocque, 1999; Putz, 1991; Strelau et al., 2018). Consequently, I expected there might be less total litter in plots with high-intensity canopy invasions. I expected that litter chemical content would not change significantly across plots because although invasive lianas tend to have higher foliar nutrients than native plants, *H. helix* is an evergreen in this region and does not contribute to litterfall (Lenaghan et al., 2013; Metcalfe, 2005; Strelau et al., 2018; Thomas, 1980). I did not expect presence

of *H. helix* ground cover to alter canopy and litter ecology, though I expected litter depth (the litter quantity metric I will use) to be greater in ground-invaded plots because of the volume of growth on the ground.

With respect to the impacts on soil physical components, I measured structural, hydrological, and temperature properties. I expected they would not change significantly with invasion presence and canopy intensity because other elements of the urban environment have strong controls on these, such as impervious cover and stormwater flows (Johnson, Johnson, et al., 2020). However, I expected that soil physical components would be altered by invasive ground cover through aggressive growth of fine roots and thick vegetation above the soil (Jo et al., 2017; Reichard, 2000; Strelau et al., 2018) and because soil disturbance benefits *H. helix* ground cover competition (Davis et al., 2000; Hobbs & Huenneke, 1992; Reichard, 2000). I expected a decrease in bulk density, an increase in gravimetric water content (though I thought this might not have been found given samples were taken in colder, dryer months), and an increase in unsaturated hydraulic conductivity. In the colder months when this study was conducted, I expected an increase in mean soil temperature, and a decrease in soil temperature range.

With respect to the impacts on soil chemical components, I measured total C (TC), total N (TN), soil organic matter (SOM), mineral N concentrations, and pH. I expected that TN and mineral N levels would have a slightly positive correlation with invasion presence and canopy invasion intensity because high levels of N are known to increase plant competition and drive invasion (Davidson et al., 2011) and invasion is

often associated with higher N mineralization rates (Ehrenfeld, 2003, 2010; Liao et al., 2008; Zhang et al., 2019), though increased leaching may balance this out (McEwan et al., 2012). I expected a more pronounced positive correlation with presence of invasive ground cover because of the increased rhizosphere interaction and potential for rapid turnover between *H. helix* and the microbial community (Jo et al., 2017; Zhang et al., 2019), though I suspected this also might be balanced by leaching (McEwan et al., 2012). I expected the opposite relationships with TC and SOM levels because higher N content and the presence of invasive plants both tend to increase soil respiration and litter decay (Ashton et al., 2005; Ehrenfeld, 2003, 2010; Liao et al., 2008; Trammell et al., 2021; Zhang et al., 2019). Soil respiration leads to immediate loss of C from the soil through the air, while N products from N mineralization and nitrification may remain in the soil. I did not expect soil pH to change significantly with invasion because of the general positive trend between forest disturbance and pH indicates that other elements of the urban environment have strong influences on pH (Ward et al., 2020; Yesilonis et al., 2022), though there is evidence to suggest both positive and negative relationships between pH and invasion presence (Ehrenfeld, 2003; Trammell et al., 2021; Ward et al., 2020).

With respect to nutrient cycling, I measured N mineralization, nitrification, respiration (which was also used as a measure of soil biological activity), and fine litter decomposition rates. I expected that soil N mineralization and nitrification rates would be positively correlated with invasion presence and canopy invasion intensity because of repeating trends seen in invasive lianas along with increases in microbial activity (Ashton et al., 2005; Ehrenfeld, 2003, 2010; Jo et al., 2017; Liao et al., 2008; Zhang et

al., 2019). I expected an even more pronounced positive correlation between N cycling and ground invasion presence as indicated by the higher effect proportion on N mineralization and nitrification assigned to the rhizosphere determined by Zhang et al. (2019). I expected that respiration rates would be positively correlated with invasion presence and canopy invasion intensity as indicated by some studies and meta-analyses (Ashton et al., 2005; Ehrenfeld, 2003, 2010; Liao et al., 2008; Zhang et al., 2019). I also expected an even more pronounced positive correlation between respiration rate and ground invasion as indicated by the higher effect proportion on C respiration and C enzyme activity assigned to the rhizosphere determined by Zhang et al. (2019). I expected to find the same trends in fine litter decomposition (Ehrenfeld, 2003, 2010; Liao et al., 2008; Trammell et al., 2021; Zhang et al., 2019), including herbaceous and woody litter.

Chapter 2. Materials & Methods

2.1 Plot Selection

2.1.1 Study Area

The study sites for my project are urban forest patches across Baltimore City, Maryland (Figure 3). My research was supported by previous studies in these sites by Baltimore Green Space and faculty at the University of Maryland, Baltimore County (UMBC). Urban forest patches exist within the urban land-use contexts of Baltimore and are self-sustaining systems with continuous canopy areas (not over impervious surfaces) with an edge width of at least 15 m and which contain regenerative forest vegetation (M. Baker, personal communication, 2023) (Figure 3). Baltimore has a wide variety of urban forest patches, 94% of which experience species invasion (Johnson, Trammell, et al., 2020). *H. helix* is one of the most prevalent invaders in this region (Johnson, Trammell, et al., 2020; K. Lautar, E. Fishel, M. Baker, and M. Pavao-Zuckerman, personal communication, 2021).

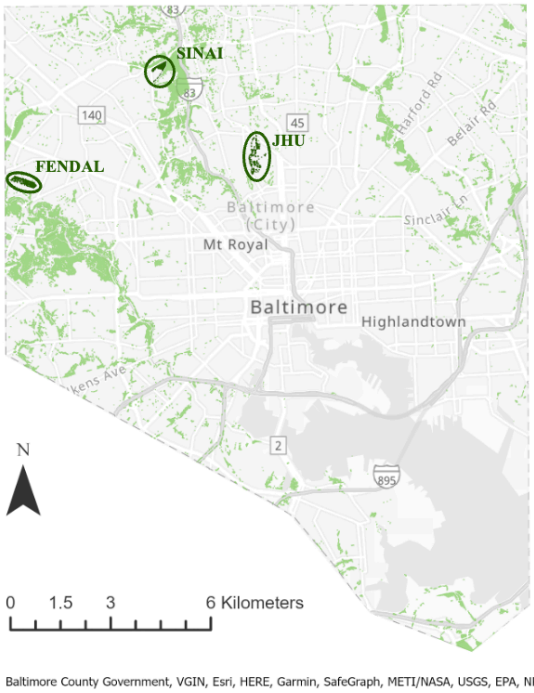


Figure 3. Map of Baltimore City, MD identifying all forest patch area in accordance with the forest patch definition of having a continuous canopy cover (not over impervious surfaces) with an edge width of at least 15 m (M. Baker, personal communication, 2023). Forest patches which have plots within them being studied in this project are labeled in dark green. SINAI (Sinai Hospital); JHU (Johns Hopkins University Homewood Campus); FENDAL (Between Fendall Road and the Forest Park Golf Course). This figure was made using data provided by Dr. Matthew Baker at the University of Maryland, Baltimore County (personal communication, 2021) in ArcGIS Pro (ESRI, 2022), and edited using PowerPoint (Microsoft Corporation, 2021b). Inspired by Map 2 from Avins (2013).

2.1.2 Plot Selection

I selected plots from a broad set of urban forest patches that are being studied by the aforementioned research collective using an existing dataset of ecological characteristics. The dataset has 869 plots across 47 urban forest patches in Baltimore and was provided by Dr. Matthew Baker at UMBC (Figure 3). This dataset includes coordinates, elevation, slope, landform, aspect, Schumacher index, and percent ground cover of every plant species. The Schumacher index (Figure 4**)**, is a valuation of the extent of a liana encroachment vertically on a given stem (usually of a tree), ranging

from zero to five. A stem with a Schumacher index score of zero has no liana on it, while a stem with a score of one has liana growth just on the bole, and so on until a score of five which would mean the liana is covering the entire canopy. An "A" class is when the liana comes from a neighboring tree (M. Baker, personal communication, 2021).

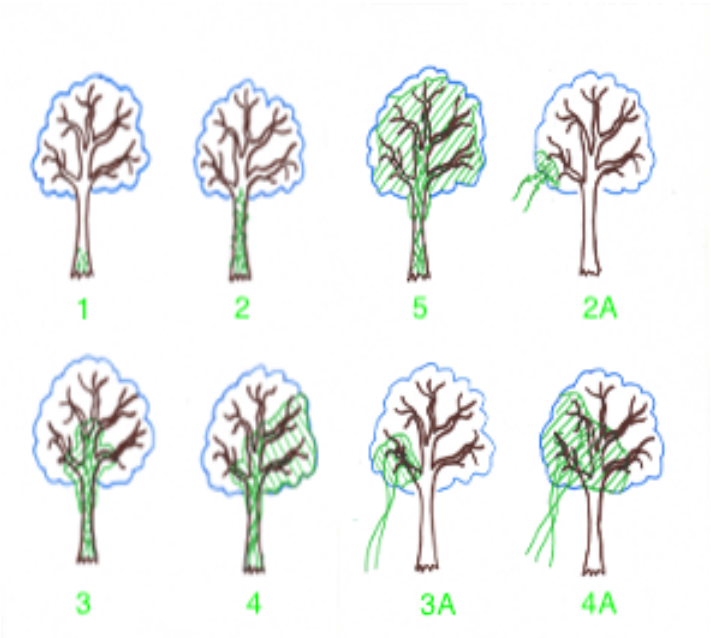


Figure 4. The Schumacher index, which describes liana invasion on individual trees, is illustrated. Invasion up the tree and into the canopy increases from scores one to five. A Schumacher index score of zero would indicate there is no invasion on that tree. Index scores with the letter "A" indicate that the liana climbed from another tree, while those without the letter "A" indicate that the liana climbed up the tree from the ground (M. Baker, personal communication, 2021). In this study, this index is being used to describe canopy invasion intensity by the invasive liana *Hedera helix*.

Table 1. Schumacher index scores used to bin plots for initial plot discovery for this project's canopy invasion intensity factor concerning the invasive liana *Hedera helix*. The Schumacher index describes liana invasion on individual trees and works on a scale from zero to five, with zero having no liana present and five having an intense invasion in the canopy (Figure 4). Schumacher indices were assigned to every tree per plot in urban forest patches in Baltimore City, MD. These values were averaged per plot. The scores were binned to describe plots as having no invasion (control), a low intensity invasion, medium intensity invasion, or high intensity invasion by *H. helix*. These bins were made using the "natural break" feature of ArcMap 2020 by Esri (Redlands, CA, USA) using data from plots of interest (with *H. helix* present) provided by Dr. Matthew Baker at the University of Maryland, Baltimore County (personal communication, 2021).

Schumacher Index	Canopy Invasion Designation
0.00	No Invasion (Control)
0.20-1.09	Low Intensity Invasion
1.10-2.83	Medium Intensity Invasion
2.84-5.00	High Intensity Invasion

I grouped plots into four categories based on invasion intensity using the Schumacher index (Table 1). Ranges for invaded groups were generated by using the "natural break" feature of ArcMap 2020 by Esri (Redlands, CA, USA) and separating these breaks from the no invasion group (throughout the rest of this paper I referred to this as the control group), with Schumacher index scores equaling 0, by a margin of 0.2. For plots in invaded groups to be considered, they were required to meet the criteria of at least 20% groundcover by *H. helix*, per the dataset of Baltimore urban forest patches provided by Dr. Matthew Baker (personal communication, 2021).

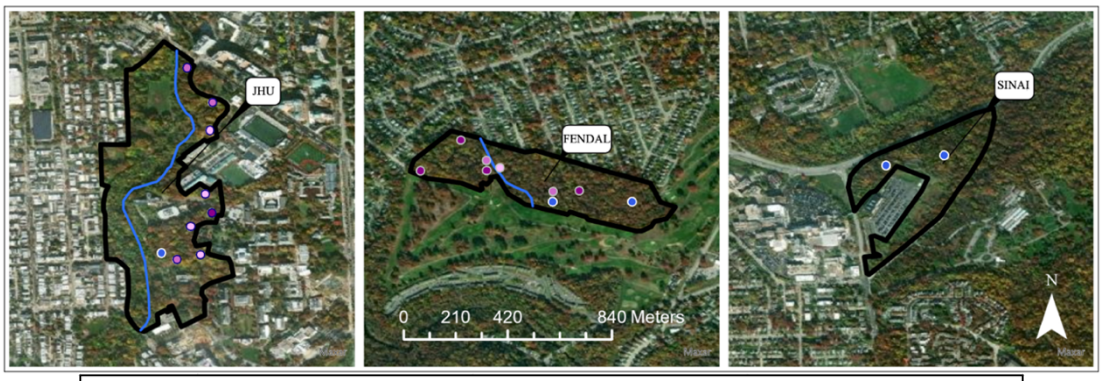
After I identified plots of interest using this dataset, I ground-truthed *H. helix* presence and canopy invasion intensity in the summer of 2022. I reduced the number of potential plots due to signs of management, influence by edge characteristics (removed if there was sun exposure on forest floor due to position on edge), position

in riparian zones (removed if plot was less than 15 m from any stream bank), and presence of large amounts of trash. I made final plot selections based on such observations in the field and location-based data collection convenience.

For data collection convenience, plots were narrowed down to be within three forest patches. These patches are labeled: JHU, SINAI, and FENDAL (Figures 3 & 5). All three patches are located on the Piedmont Plateau and have similar soil types (mostly silt loams and loams, primarily stony and having slopes ranging from zero to 15, with a few steeper exceptions) and hydrological characteristics (surrounding impervious cover, nearby urban streams, a mix of flat and sloped lands) based on observations made in the field and using ArcGIS Pro (ESRI, 2022), Google Earth Pro (Google, 2022a), and Web Soil Survey (Soil Survey Staff, 2022). They all experience similar pressures from the urban environment such as intense stormwater surges, trash, the urban heat island effect, and high nutrient loading based on geographic imagery and my observations in the field. The three most common trees in JHU are White Oak, Tulip Tree, and American Beech. The three most common trees in SINAI are Northern Red Oak, Northern White Oak, and American Beech. The three most common trees in FENDAL are White Oak, Red Maple, and Northern Red Oak (M. Baker, personal communication, 2021).

A total of 20 plots were chosen with five representatives from each level of canopy invasion intensity (Figures 3, 4, & 5; Table 1). The plots were further binned into factors for presence of invasion ($n_{control}$ = five, $n_{invasion}$ = 15) and ground cover ($n_{control}$ = five, $n_{no\ ground\ cover}$ = seven, $n_{ground\ cover}$ = eight). Control plots may have other

invasive species present. I did not control for presence of ground cover at the start of the project but added it after data collection as I noticed that canopy invasion intensity does not represent all characteristics of invasion (Figure 6). There were high invasion plots with no ground cover (Figure 6b) and low invasion plots with lots of ground cover (Figure 6c). Plots with ground cover always had complete coverage (Figure 6c), so presence was used to describe groups for this factor. A necessary clarification is that patches are not being used as a unit in this project; there is no connection between the patches and plot selection. Each plot is 3.05 m^2 with each corner in a cardinal direction.



Legend			
Object	**Presence**	**Canopy Invasion Intensity**	**Ground Cover Presence**
	Not Present (Control)	NA	NA
	Present	Low	Not Present
	Present	Low	Present
	Present	Medium	Not Present
	Present	Medium	Present
	Present	High	Not Present
	Present	High	Present
	Stream		
	Forest Patch Border		

Figure 5. Maps of three different urban forest patches in Baltimore City, MD (JHU, FENDAL, and SINAI) (Figure 3). 3.05 m^2 plots, with corners in cardinal directions, within patches are being studied in this project and are marked with dots, which are labelled by different fill and line colors according to characteristics of invasion by *Hedera helix*. Some plots appear closer to streams or borders than they truly are. Topography is not displayed but JHU has more and steeper slopes than FENDAL and SINAI, which are relatively flat. All invaded plots with ground cover present are in JHU and all invaded plots without ground cover present are in FENDAL. Urban pressure contexts (i.e., impervious surfaces) are shown with satellite imagery. This figure was made using data provided by Dr. Matthew Baker at the University of Maryland, Baltimore County (personal communication, 2021).

a.  b. 

c. 

Figure 6. Example images of three different types of urban forest patch plots in Baltimore City, MD. These demonstrate the contrast between plots with and without ground cover by *Hedera helix*. **Image a** (SINAI 7) is an example of a plot with no invasion (control). **Image b** (FENDAL 2) is an example of a plot with invasion but no ground cover by *H. helix* (this plot is also classified as having a high-intensity canopy invasion (Figure 4 & Table 1)). **Image c** (JHU 45) is an example of a plot with invasive ground cover by *H. helix* (this plot is also classified as having a low-intensity canopy invasion (Figure 4 & Table 1)). Locations of plots are shown in Figures 3 & 5. Images were taken during the ground-truthing phase of this project in the summer of 2022.

2.2 Data Collection & Analysis

I analyze descriptive plot ecological characteristics as well as specific N and C cycling measures across the three different factors: invasion presence, canopy invasion intensity, and ground invasion presence. Field sampling and data collection are intended to describe the impacts of *H. helix* on ecological forest characteristics including canopy and litter characteristics, soil physical, biological, and chemical

properties, and resulting effects on nutrient cycling (Figure 2). Collections and analyses follow standard protocols either from Robertson (1999) or manuals associated with data collection instruments.

2.2.1 Sample Collection

Sample collection began in September 2022 and ended in February 2023.

Ecological Characteristics – Canopy & Leaf Litter

To analyze canopy cover, hemispherical canopy photos were taken on one weekend during full leaf-out, September 1-3, 2022 (Figure 7). Photos were taken in the center of each plot 1.15 m off the ground with a Canon EOS 80D camera (Huntington, NY, USA) fixed with a SIGMA 4.5 mm F2.8 EX DC circular fisheye lens (Kawasaki-shi, Kanagawa, Japan). Photos were taken during dawn and dusk hours to avoid sun glare, and at multiple exposure levels until a clear contrast was apparent between canopy and sky. To analyze litter, litter samples were taken after all leaves had fallen for the season, December 16-17, 2022. Four samples were taken at random locations on each plot, each comprised of the litter that had naturally fallen on a 0.5 m^2 area. These samples are being used to determine TN and TC of the litter. Litter layer depth was recorded simultaneously at each random location as a measure of litter quantity. It is important to note that these depth measurements were taken after a rain event and the litter layer may have been compressed unevenly by the rain.

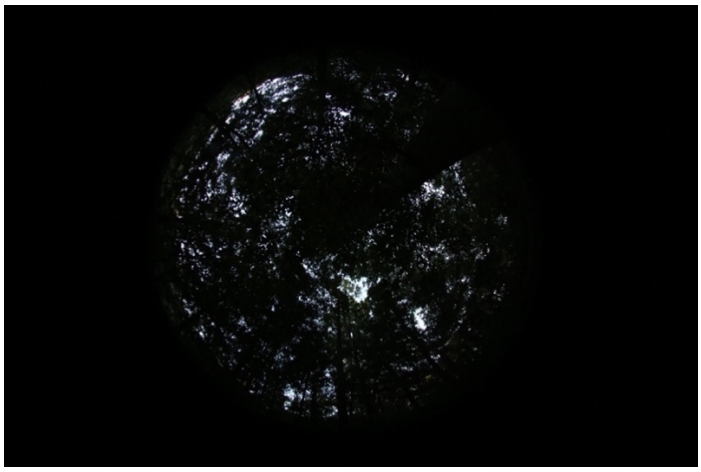


Figure 7. An example image of a hemispherical canopy photo taken at an urban forest patch plot in Baltimore City, MD for the purposes of canopy structure and light penetration analysis. This photo was taken at full leaf-out on September 2, 2022, at dawn to avoid sun glare. It is from a plot in the Johns Hopkins University Homewood Campus urban forest patch (plot JHU 27) which is a control plot for this project, it has no invasion by *Hedera helix* (Figures 3 & 5). This photo was taken in the center of the plot 1.15 m off the ground with a Canon EOS 80D camera (Huntington, NY, USA) fixed with a SIGMA 4.5 mm F2.8 EX DC circular fisheye lens (Kawasaki-shi, Kanagawa, Japan). It was later analyzed for percent canopy gap number, canopy openness, and effective leaf area index using ImageJ with the Hemispherical 2.0 plug-in (Beckschäfer, 2015) and Gap Light Analyzer v.2.0 (Frazer et al., 1999) using methods adapted from Moon et al. (2023) and Arietta (2019).

Ecological Characteristics – Soil Properties

Soil samples were used to measure soil ecological characteristics including bulk density, gravimetric water content, soil pH, TC, TN, SOM, and mineral N pool. All soil samples were collected using an AMS 404.05 soil corer (American Falls, ID, USA) which extracts soil cores measuring 5.08 cm in diameter and 12.70 cm in depth using a slide hammer mechanism. Soil samples were all collected over the same weekend (September 16-18, 2022) with no changes in weather and after several days with no rain. Four samples were taken per plot, 0.91 m away from each corner in the cardinal

directions. Samples were combined apart from the Eastern sample, which was reserved for bulk density analysis.

Other soil ecological characteristics were characterized using *in situ* methods. Soil temperature was recorded at 6.3 cm in the soil every 30 min from September 16-18, 2022, through October 30-31, 2023, using one DS1921G-F5 Thermochron iButton by Analog Devices (Wilmington, MA, USA) per plot. Unsaturated hydraulic conductivity was measured in two to three random locations per plot on September 16-18, 2022, after several days with no rain. Mini Disk Infiltrometers made by METER Group (Pullman, WA, USA) were used on flat surfaces of the soil after clearing away debris (Figure 8). Suction was set to two cm and volume measurements were taken every 30 s until between seven and 15 mL of water had transferred from the Mini Disk Infiltrometer to the soil.

Figure 8. A field volunteer, Benjamin Robinson, using a Mini Disk Infiltrometer made by METER Group (Pullman, WA, USA) on a random, flat point cleared of leaf litter at a plot in an urban forest patch located at Johns Hopkins University Homewood Campus (plot JHU 22) in Baltimore City, MD (Figures 3 & 5). This instrument is used to estimate unsaturated hydraulic conductivity by measuring the amount of water which transfers from the device into the soil through a porous stainless-steel disk over time, with a set suction. Suction was set to two cm and volume was recorded every 30 s until seven to 15 mL of water seeped into the soil.

Nutrient Cycling

Soil samples were used to measure the soil nutrient cycling metrics N mineralization rate and nitrification rate. The same soil samples used to measure soil ecological characteristics were used to determine the initial concentrations of NH_3-NH_4^+ and NO_2^--NO_3^-. A sample of the soil at each plot was also incubated for one month (September 16-18, 2022, until October 16-17, 2022) *in situ* by hammering a capped PVC pipe, with a diameter of 5.08 cm, 12.70 cm into the ground near the center of each plot (Figure 9). These samples were used to determine the concentrations of NH_3-NH_4^+ and NO_2^--NO_3^- after *in situ* incubation.

Figure 9. An example of an *in situ* soil incubation using a 5.08 cm diameter capped PVC pipe tapped 12.70 cm into the soil. This sample was taken at an urban forest patch plot located at Johns Hopkins University Homewood Campus (plot JHU 26) in Baltimore City, MD (Figures 3 & 5). This method was used alongside an unincubated soil sample to determine the rates of N mineralization and nitrification by measuring the change in NH_3-NH_4^+ and NO_2^--NO_3^- concentrations over the time of the incubation (from September 16-18, 2022, to October 16-17, 2022).

Other soil nutrient cycling metrics were measured using *in situ* methods. Respiration rate was measured using a PP Systems EGM-5 Portable CO_2 Gas Analyzer (Amesbury, MA, USA), which captures many data including the soil respiration rate

every second for one minute. One sample was taken per plot near the center of the plot by first calibrating the chamber in the air and then resting it into the soil surface and running the analyzer. The final soil respiration rate value was recorded in μmol CO_2/m^2 soil/s (PP Systems, 2018).

The fine litter decomposition analysis was conducted using buried tea bags, an adapted method from Keuskamp et al. (2013)'s Tea Bag Index project (TBI) (Tea Bag Index, n.d.). This method uses the weight change of two different types of tea in non-decomposable bags to extrapolate decay rates. Green tea is a representation of herbaceous fine litter (high labile fraction), and rooibos tea is a representation of woody fine litter (high recalcitrant fraction). 12 bags of each type of tea were buried 6.35 cm into the soil at each plot in a three-by-four array on October 16-17, 2022 (Figure 10). Every tea bag was weighed individually preceding burial. Four tea bags from each array were collected from each plot at three timesteps – one month (November 12, 2022), two months (December 16-17, 2022), and four months (February 18, 2022). From the change in dry weight of tea over time, decay rates can be extrapolated. Many tea bags were either torn or lost over the course of the experiment and were unusable, but 390 out of the 480 bags were successfully recovered.

Figure 10. An example image of the burial of two three-by-four arrays of non-decomposable bags being used to analyze the decay rate of herbaceous and woody fine litter in urban forest patch plots in Baltimore City, MD. This image was taken at a plot (FENDAL 76) in an urban forest patch between Fendall Road and the Forest Park Golf Course (Figures 3 & 5). Green tea was used to represent herbaceous fine litter (high labile fraction) (top array) and rooibos tea was used to represent woody fine litter (high recalcitrant fraction) (bottom array). Bags were buried 6.35 cm deep in the soil. Four of each tea bag type were collected at each plot at three timesteps – one month, two months, and four months. Decay rate was extrapolated. This method was inspired by the Tea Bag Index developed by Keuskamp et al. (2013) (Tea Bag Index, n.d.) and amended using methods from Robertson (1999).

2.2.2 Sample Processing & Data Organization

Ecological Characteristics – Canopy & Leaf Litter

Hemispherical canopy photos required digital processing (Figure 7). I analyzed these photos using methods adapted from Moon et al. (2023) and Arietta (2019). I first chose the best exposure captured in the field per plot. That is, the photo which best contrasts the canopy and the sky. I then used Lightroom 2023 by Adobe (San Jose, CA, USA) to clean images of any sun glare or other discrepancies. I then used ImageJ with the Hemispherical 2.0 plug-in to binarize the photos (Beckschäfer, 2015), measure the

canopy gap number, and convert the photos so they could be read by the next program. The next program, Gap Light Analyzer v.2.0 (GLA) (Frazer et al., 1999), was calibrated for each image based on plot data such as coordinates, growing season, and several radiation parameters. The radiation parameters were cloudiness index (K_t), spectral fraction (R_p/R_s), and beam fraction (H_b/H). 2019-2021 NSRDB data from Baltimore from the month surrounding collection (August 15th-September 15th) was downloaded in one hr time steps and trimmed to daytime hours (7 am-6 pm) (National Renewable Energy Laboratory, 2022). Global horizontal irradiance (H) and clearsky global horizontal irradiance (H_o) were used to calculate K_t. R_p/R_s and H_b/H were extrapolated from this value, using equations from the GLA V2 Users Manual (Frazer et al., 1999):

Cloudiness Index (K_t) $$K_t = \frac{H}{H_o} \quad \text{(Eq. 1)}$$

Spectral Fraction (R_p/R_s) $$\frac{R_p}{R_s} = 1 - e^{-0.449K_t^{-0.219}} \quad \text{(Eq. 2)}$$

Beam Fraction (H_b/H) $$\frac{H_b}{H} = 1 - e^{-3.044K_t^{2.436}} \quad \text{(Eq. 3)}$$

All the parameters I put into GLA can be found in Appendix I. From this analysis I extracted the values for percent canopy openness and effective leaf area index 4 ring (LAI_e), which is an estimate of the leaf area index over the zenith angles zero to 60° (Frazer et al., 1999).

Regarding litter depth, there were four values taken per plot, which were averaged. For litter TC and TN analyses, litter samples were allowed to air dry for a few months. Samples were then ground to five mm using a Wiley Mill Model No. 2 by Thomas Scientific (Swedesboro, NJ, USA). The four samples per plot were then

combined to make one sample per plot. An error made it so that plot FENDAL 28 was only made up of one sample and plot FENDAL 27 was only made up of three samples (Figures 3 & 5). Samples were further ground to two mm using a Type MHM5 Grinding Mill by Glen Mills (Clifton, NJ, USA) and three samples of 0.2 g per plot were placed in a part no. 502-186-100 tin cup capsules by LECO Corporation (St. Joseph, MI, USA) for analysis with a CN628 analyzer by LECO Corporation (St. Joseph, MI, USA) at the Joint Analytical Services Lab at the University of Maryland, College Park (UMD). Percent TC, TN, and C:N were calculated from the analyzer's results. Plot triplicates were averaged to one value per metric.

Ecological Characteristics – Soil Properties

Regarding *in situ* measurements, soil temperature was summarized in four variables – average daily mean temperature, average daily low temperature, average daily high temperature, and average daily range of temperature in °C. To get average daily values, I first removed data from incomplete days of collection. This meant removing the first and last day of collection from every plot, leaving 42 days per plot. I also had to remove several days of data from FENDAL 28 (Figures 3 & 5) because it was discovered unburied on October 16th. The data was checked, and it was clear that there were extreme values on the days which it was unburied. I cut off values starting from the day before those extremes appeared (September 21st) until October 17th, leaving 19 values for this plot. Once the four variables (average daily mean, low, high, and range) were calculated, standard deviations of FENDAL 28 were assessed and found to be within two standard deviations of the distribution from all plots.

For unsaturated hydraulic conductivity, K (cm/s) was calculated from raw Mini Disc Infiltrometer data using METER Group's (Pullman, WA, USA) associated Excel template (METER Group, 2021), factoring in soil type and suction settings. Due to volunteer availability and time constraints in the field, some plots had only two samples instead of three and some samples had below 10 mL drain into the soil, the standard requirement for the test. Standard deviations of all samples falling below this volume of drainage were assessed and I decided to omit all samples which had fewer than five mL enter the soil, remaining samples ranged from seven to 15 mL of water drained into the soil. All remaining samples were averaged to one K per plot.

Regarding soil samples, bulk density, TC and TN, and SOM samples were left in a refrigerator at 5.5 °C for a few months. Over this period, three samples had plant growth. For bulk density, the plants were removed and as much soil as possible was brushed off the roots back into the sample bag. For TC, TN, and SOM, plants were removed along with the soil in their rhizospheres to prevent any skewing of results by plants up-taking N from the surrounding soil. All the soil samples were then left out to air dry for several days. Next, the soil was sieved to two mm and dried at 105 °C to constant weight.

For soil TC and TN, sieved, dried soil was ground to 0.5 mm using an 8000M Mixer/Mill by Spex SamplePrep (Metuchen, NJ, USA), and three samples of 0.25 g per plot were placed in part no. 502-186-100 tin cup capsules by LECO Corporation (St. Joseph, MI, USA) for analysis with a CN628 analyzer by LECO Corporation (St. Joseph, MI, USA) at the Joint Analytical Services Lab at UMD. Percent TC, TN, and

C:N were calculated from the analyzer's results. Plot triplicates were averaged to one value per metric. For bulk density, sieved, dried samples were weighed and compared to the known volume to determine g/cm^3 of soil. For SOM, sieved, dried samples were weighed, burned at 450 °C for four hours, and reweighed. Percent loss was calculated.

Soil pH, gravimetric water content, and mineral N pool analyses had to be conducted with fresh soil samples. Samples were transported on ice and stored at 5.5 °C and analyzed within one week after being sieved to two mm. For pH, a slurry of 20 g of fresh, sieved soil and 20 mL of deionized (DI) water was prepared per sample. A PC60 Premium Multiparameter Pocket Tester Kit by APERA Instruments (Columbus, OH, USA) was soaked in a 3M KCl solution, calibrated, and used to measure pH after allowing the slurries to settle out. The meter was cleaned with DI water between samples. For gravimetric water content, 100 g of fresh, sieved soil was weighed in an aluminum boat. The soil was left to dry at 105 °C until reaching a constant weight, which was recorded. Water content was calculated in g water/g soil.

For mineral N pool (taken from the unincubated soil), NH_3-NH_4^+ and NO_2^--NO_3^- of five g of fresh, sieved soil was extracted using 20 mL of 2M KCl, a strong salt. The 2M KCl was freshly prepared with powdered KCl and DI water and was dispensed using a Varispenser Plus 0-50 mL by Eppendorf (Enfield, CT, USA) into a Falcon 50 mL High Clarity Conical Centrifuge Tube by Fisher Scientific (Hampton, NH, USA) with the soil sample inside. The slurry was left to mix with a HAG Rotator by Fine PCR (Gunpo-si, Gyeonggi-do, South Korea) set to 70 RPM for one hour at an angle of about 20°. After allowing the soil particles to settle, the supernatant liquid was isolated

using 70 mm Whatman No. 1 Qualitative Filter Papers by Cytiva (Marlborough, MA, USA) through a funnel into 20 mL Wheaton High Density Polyethylene Liquid Scintillation Vials by DWK Life Sciences (Millville, NJ, USA). Samples were placed immediately into a freezer and analyzed in the summer of 2023 by the Agroecology Lab at UMD for concentrations of NH_3-NH_4^+ and NO_2^--NO_3^- (mg/L) using a QuikChem 8600 by LACHAT Instruments (Loveland, CO, USA). Some samples were diluted by the Agroecology Lab because initial readings were too high for the standard curve (A. Schulenburg, personal communication, 2023). Sample results were adjusted appropriately. Concentration values were further converted to mg mineral N/kg soil using the extractant volume and soil moisture value taken from the unincubated sample. Mineral N pool was calculated by summing all concentrations per plot from the unincubated samples.

Nutrient Cycling

For the N mineralization and nitrification analyses, unincubated soil analyzed for mineral N content was regarded as time 0. Soil which was incubated *in situ* (Figure 9) was regarded as time 1 and was processed and stored using the same methods. After analysis by the Agroecology Lab at UMD, concentration values of time 1 samples in mg mineral N/kg soil were also calculated. However, soil moisture was not measured for the time 1 samples, so the same values were used for their adjustment. The samples were taken on days with similar climate, both several days after the most recent storm event. There may be a slight discrepancy because the incubated soils were isolated from surrounding soil and may have been drier or wetter as a result. N mineralization rate was calculated from the change in NH_3-NH_4^+ and NO_2^--NO_3^- over the incubation time

(d). Nitrification rate was calculated from the change in NO_2^--NO_3^- over the incubation time (d).

For fine litter decomposition using the tea bag experiment (Figure 10), after each collection date, tea bags were allowed to air dry for one to two days. The tea bags were then quality checked. Any minor tears were noted in a spreadsheet, but those samples were still processed, while tea bags with major tears were discarded. Intact tea bags were lightly cleaned of soil and small roots before being placed in an oven to dry at 70 °C until reaching a constant weight. Samples were then further cleaned of dry soil and cut open. The tea within was weighed (X_t) to be compared against initial weights (X_o) (minus the weight of the bag and tag). For herbaceous and woody litter decomposition, decay rates (k coefficient) were calculated over time in days (t) with a regression following protocols and an equation from Robertson (1999):

Decay Rate (k coefficient) $$\frac{X_t}{X_o} = e^{-kt} \quad \text{(Eq. 4)}$$

All k coefficient values of non-discarded bags were calculated and averaged to one value per tea type per plot. Any plot with a full time-step missing (at the one month, two months, or four months mark) were removed from the data (FENDAL 33 – herbaceous litter; FENDAL 76 – herbaceous and woody litter (Figure 3 & 5)).

Sample processing steps left one value per plot for every variable, except for the missing litter decomposition values. This allows for conservative use of all data tests without the need to interpolate. Multivariate tests later used do not allow for

missing values, though they were only used to evaluate the ecological characteristic variables, which does not include litter decomposition (see below).

2.2.3 Statistical Analysis

All data analyses were conducted, and all figures were made, using Google Sheets (Google, 2022b), Excel (Microsoft Corporation, 2021a), and the R programming language (R Core Team, 2023) through the RStudio interface (RStudio Team, 2020). Stack Overflow (Stack Overflow, n.d.), Stack Exchange (Stack Exchange, n.d.), GitHub (GitHub, n.d.), ResearchGate (ResearchGate, n.d.), GPT v3.5 (OpenAI, 2023), and advice from advisors and peers were used to fix and refine code.

p value

Before conducting my statistical tests, I set *p* value thresholds for significance. I am approaching this from the point of view that *p* values are not an exact science, rather, assigned thresholds for standardization of analysis. Researchers recently have started treating the 0.05 *p* value as less of a hard line on statistical significance (Castilho & Prado, 2021; Dahiru, 2008; Ganesh & Cave, 2018). Indeed, Fisher stated in *Statistical methods and scientific inference* that "no scientific worker has a fixed level of significance at which, from year to year, and in all circumstances [they reject] hypotheses; [they] rather [give their] mind to each particular case in the light of [their] evidence and [their] ideas" (1956) (found in Ganesh & Cave, 2018). Given that my sample size is low, which decreases the likelihood of my data properly representing the real population and outputting low *p* values (Castilho & Prado, 2021; Dahiru, 2008; Ganesh & Cave, 2018; Murtaugh, 2014), I will be using the following thresholds in

presenting the results of statistical tests below: a *p* value of below 0.01 is considered "convincingly significant", while a *p* value of 0.01-0.05 is considered "moderately significant" and a *p* value of 0.05-0.1 is considered "suggestive"; a *p* value of above 0.1 is considered insignificant (Murtaugh, 2014). I am considering all *p* values below 0.05 to be "significant." This choice was made recognizing I am trading off an increase in my Type-I error rate for the opportunity to make claims about results I feel are ecologically relevant.

Mean Separation Tests

Mean separation tests were run for every factor/response variable combination. I used the ANOVA test for parametric data and the Kruskal-Wallis test for nonparametric data. I assessed normality for each factor/response variable combination with the Shapiro-Wilk test from the R stats package (shapiro.test) (R Core Team, 2023). For the Shapiro-Wilk test, if a *p* value was less than 0.1, I considered the distribution not normal. To use the ANOVA test for a factor/response variable combination, the distribution of every factor's group had to be normal. The aov function from the R stats package (R Core Team, 2023) was used to run the ANOVA tests. Mean square, degrees of freedom, and *p* value were recorded. The lm function from the same package (R Core Team, 2023) was used to make a linear regression from the results for each test to extract the R^2 value as well. The kruskal.test function from the same package (R Core Team, 2023) was used to run the Kruskal-Wallis tests. The same statistics were extracted, though instead of mean square, the rank sum was reported. I then further analyzed any significant results to determine exactly which groups differ with post-hoc tests. For ANOVA tests I used Tukey's HSD tests (TukeyHSD from the R stats package

(R Core Team, 2023)) and for Kruskal-Wallis tests I used Dunn's tests with the Holm stepwise adjustment (dunnTest from the FSA package (Ogle et al., 2023)). Finally, to provide a visualization aid, I used R to generate boxplots for every factor/response variable combination using the ggplot2 (Wickham et al., 2023) and cowplot packages (Wilke, 2020), later labeling them and incorporating post-hoc results using PowerPoint (Microsoft Corporation, 2021b).

PERMANOVA

To determine if the overall ecology of plots varied across factors describing invasion, I ran a PERMANOVA test for each factor using strictly the ecological characteristic variables. I had guidance from Drs. Jennifer Mullinax and Travis Gallo at UMD, and Dr. Jessica Moon and Karen Baumann at Murray State University (personal communication, 2023). For multivariate analyses, it is important to remove variables which are highly correlated with (an)other variable(s) to prevent overfitting. Using a correlation matrix, correlation coefficients greater than (+/-) 0.7 were noted for removal of one of the variables, as indicated by the Pearson correlation method (Nettleton, 2014). I chose to remove soil TN and litter TN, LAI_e, average daily low temperature, and average daily high temperature for these tests.

Another prerequisite of the PERMANOVA test is that all the variables are on the same scale and non-negative. I used the scale function from the base R package (R Core Team, 2023) and added the absolute value of the most negative value to the entire matrix. Next, I calculated the Bray-Curtis distances between samples using the vegdist function from the vegan package with method set to "bray" (Oksanen et al., 2022). I

used set.seed to “36” to make this permutating function repeatable. I then ran a PERMANOVA for each factor using the adonis2 function from the vegan package with 10,000 permutations and method set to “bray” and recorded the *p* values (Oksanen et al., 2022). I then further analyzed any significant results to determine exactly which groups differ with a multilevel pairwise analysis from the package pairwiseAdonis (Martinez Arbizu, 2020), which incorporates the adonis2 function from the vegan package (Oksanen et al., 2022). With the same scaled and shifted data used for the PERMANOVAs, I additionally used NMDS scores to visualize significant findings from the PERMANOVAs and multilevel pairwise analyses. I used the metaMDS function with distance set to “bray” from the vegan package (Oksanen et al., 2022) and plotted the scores on a scatterplot with color coded factors using assistance from Zorz (2019).

Linear Regressions

To determine potential drivers of nutrient cycling, I ran regressions between nutrient cycling variables with significant ($p < 0.05$) and suggestive ($p < 0.1$) results from mean separation tests and ecological characteristics. I used the lm function from the R stats package (R Core Team, 2023) to determine regression equations, R^2 values, and *p* values. Significant and suggestive regressions were reviewed and qualitatively considered for their roles as drivers of each nutrient cycling variable using existing literature. Relevant findings were plotted as scatterplots with regression trendlines using ggplot2 (Wickham et al., 2023), and were later edited and labelled using PowerPoint (Microsoft Corporation, 2021b□).

Chapter 3. Results

To answer how invasion by *H. helix* impacts the ecology of Baltimore's forest patches I measured ecological characteristics and nutrient cycling across plots with different *H. helix* invasion structures, such as invasion presence, canopy invasion intensity, and ground cover presence. I used field measurements, environmental samples, and lab experiments to measure canopy and litter ecology, soil physical properties, soil chemical properties, and rates of steps in C and N cycles. Using mean separation tests, multivariate analyses, and linear regressions, I compared values across plots and groups.

3.1 Canopy & Litter Ecology

I observed a significant difference in litter depth for the ground cover presence factor, which separates plots based on the presence or absence of *H. helix* growth on the ground, including a control group with no invasion. Plots with *H. helix* ground cover have 1.8 times deeper litter layers than invaded plots without ground cover ($df = 2$, $p = 0.007$) (Table 2; Figure 11q; Appendix II.1). Variance increases notably across plots from control to no ground cover to ground cover plots ($CV_{control} = 0.183$, $CV_{no\ ground\ cover} = 0.204$, $CV_{ground\ cover} = 0.269$) (Figure 11q; Appendix III.1).

Metrics of canopy openness were influenced by invasion. I observed a suggestive difference in canopy gap number for the canopy invasion intensity factor, which separated plots based into control, low, medium, and high levels of canopy invasion by *H. helix*. Canopy gap number was suggestively lower in plots with high canopy invasion intensities than plots in other groups (means: control = 3684, low =

4631, medium = 3658, high = 3194) (df = 3, $p = 0.082$) (Table 3; Figure 12p; Appendix II.3). Meanwhile, percent canopy openness (df = 3, $p = 0.982$) and LAI_e (df = 3, $p = 0.905$) was not significantly different across gradients of canopy invasion intensity (Table 3; Figures 12n-o).

No significant differences were observed across metrics of canopy or litter ecology for the presence of invasion factor. However, like the ground cover factor, litter depth is more variable in the presence of invasion ($CV_{control} = 0.183$, $CV_{invasion} = 0.388$) (Figure 13q, Appendix III.3). Also notable, litter chemistry was not different across any of the invasion factors (Tables 2, 3, & 4; Figures 11r-t, 12r-t, & 13r-t), with C:N ranging from 33.976 to 59.658 across all plots (Appendix II.1).

3.2 Soil Physical Ecology

Several soil physical characteristics were significantly different across the ground cover factor. Soil in plots with ground cover have about a 1.06 times higher daily mean (df = 2, $p = 0.010$), 1.09 times higher daily low (df = 2, $p = 0.002$), and 0.65-0.73 times lower daily range (df = 2, $p = 0.039$) temperatures than control plots or invaded plots without ground cover (Table 2; Figures 11a,b,d; Appendix II.2). Since samples were taken during autumn, plots with ground cover by *H. helix* are associated with regulated, less extreme shallow soil temperatures. Another physical soil difference observed was a ~6.3 times lower unsaturated hydraulic conductivity in invaded plots without ground cover than control or plots with ground cover (means: control = $8.454e^{-5}$ cm/s, no ground cover = $1.330e^{-5}$ cm/s, ground cover = $8.359e^{-5}$ cm/s) (df = 2, $p = 0.031$) (Table 2; Figure 11h; Appendix II.2). Soil bulk density was not significantly different across

groups (df = 2, p = 0.224) (Table 2), averaging 0.841 g/cm^3 (Appendix II.1), but was notably more variable in ground invaded plots ($CV_{control}$ = 0.132, $CV_{no\ ground\ cover}$ = 0.121, $CV_{ground\ cover}$ = 0.311) (Figure 11f; Appendix III.1) and some plots with ground cover had particularly low bulk densities (i.e., 0.342 g/cm^3, 0.544 g/cm^3) (Figure 11f). Plots with particularly low bulk densities had similar gravimetric water contents to other plots, however (i.e., 0.252 g/g, 0.182 g/g, respectively; overall mean: 0.199 g/g).

I observed a suggestive difference in soil bulk density across canopy invasion intensity plots (df = 3, p = 0.080) (Table 3; Figure 12f) but there is no clear trend.[1]

I did not observe any significant differences in soil physical characteristics for the presence of invasion factor, though there were notable changes in variability across groups. Unsaturated hydraulic conductivity ($CV_{control}$ = 0.970, $CV_{invasion}$ = 1.400) (Figure 13h; Appendix III.3) and soil bulk density ($CV_{control}$ = 0.132, $CV_{invasion}$ = 0.239) (Figure 13f; Appendix III.3) are more variable in invaded plots.

3.3 Soil Chemical Ecology

I observed some differences in soil chemistry across groups for the ground cover factor. Soil TN was significantly 1.43-1.62 times higher (df = 2, p = 0.022) in ground cover plots than control plots or invaded plots without ground cover (Table 2; Figure 11j; Appendix II.2). Soil TC is suggestively 1.45-1.50 times higher (df = 2, p = 0.066) in ground cover plots than control plots or invaded plots without ground cover (Table 2;

[1] Mean separation tests for canopy invasion intensity yielded suggestive (p < 0.1) results for Soil Bulk Density (Figure 12f). However, due to a lack of statistical power (small n) and a high number of factor levels, the post-hoc tests were inconclusive in determining differences between pairs.

Figure 11i; Appendix II.2). Additionally, Soil TN is much less variable in ground cover plots ($CV_{control}$ = 0.436, $CV_{no\ ground\ cover}$ = 0.401, $CV_{ground\ cover}$ = 0.180) (Figure 11j; Appendix III.1). Interestingly, I did not observe any significant difference across groups for mineral N pool (Table 2).

I observed a suggestive increase of soil pH as canopy invasion intensity increases (means: control = 4.37, Low = 4.86, Medium = 5.67, High = 6.03) (df = 3, p = 0.069) (Table 3; Figure 12e; Appendix II.3).[2] Overall soil pH values ranged from acidic to neutral (min = 3.910, max = 7.720, mean = 5.322) (Appendix II.1).

Results regarding soil chemical ecology for the invasion presence factor demonstrated a suggestive difference and notable variability. Like canopy invasion intensity, I observed a suggestive 1.17 times increase in pH from control plots to all invaded plots (df = 1, p = 0. 090) (Table 4; Figure 13e; Appendix II.4). There is also increased variability in soil TC ($CV_{control}$ = 0.204, $CV_{invasion}$ = 0.405) (Figure 13i; Appendix III.2) and the mineral N pool ($CV_{control}$ = 0.336, $CV_{invasion}$ = 0.503) (Figure 13m; Appendix III.2) from control to invaded plots.

[2] Mean separation tests for canopy invasion intensity yielded suggestive ($p < 0.1$) results for pH (Figure 12e). However, due to a lack of statistical power (small n) and a high number of factor levels, the post-hoc tests were inconclusive in determining differences between pairs.

Table 2. Results from mean separation tests on the invasion factor Presence of Ground Cover by *H. helix* for ecological characteristic (no fill) and nutrient cycling (gray fill) response variables in urban forest patch plots in Baltimore City, MD. Parametric data was analyzed with ANOVA tests and non-parametric data was analyzed with Kruskal-Wallis tests. Degrees of freedom (df), R^2, and *p* value are reported for every result. Mean square is also reported for the ANOVA tests, and rank sum is reported for the Kruskal-Wallis tests. Significance of *p* values is noted as well, where significant (***** = $p < 0.05$) findings are bolded and suggestive findings (**.** = $p < 0.1$) are italicized. *p* values from post-hoc tests can be found in Appendix IV.1.

Response Variable	Mean Square (ANOVA)	Rank Sum (K-W)	df	R^2	*p* value	Significance
Daily Mean Soil Temperature	**2.009**	**NA**	**2**	**0.416**	**0.010**	*
Daily Low Soil Temperature	**3.508**	**NA**	**2**	**0.530**	**1.62E-03**	*
Daily High Soil Temperature	0.842	NA	2	0.166	0.214	
Daily Range Soil Temperature	**NA**	**6.488**	**2**	**0.292**	**0.039**	*
pH	NA	3.184	2	0.156	0.203	
Soil Bulk Density	NA	2.990	2	0.194	0.224	
Gravimetric Water Content	3.47E-04	NA	2	0.043	0.691	
Unsaturated Hydraulic Conductivity	**NA**	**6.967**	**2**	**0.223**	**0.031**	*
Soil TC	*NA*	*5.445*	*2*	*0.265*	*0.066*	.
Soil TN	**0.027**	**NA**	**2**	**0.361**	**0.022**	*
Soil C:N	NA	1.625	2	0.074	0.444	
Soil Organic Matter	11.180	NA	2	0.200	0.149	
Mineral N Pool	NA	3.457	2	0.170	0.178	
Percent Canopy Openness	1.587	NA	2	0.113	0.361	
Effective LAI	1.428	NA	2	0.182	0.181	
Canopy Gap Number	353351.393	NA	2	0.043	0.686	
Litter Depth	**NA**	**9.814**	**2**	**0.535**	**7.39E-03**	*
Litter TC	NA	0.665	2	0.055	0.717	
Litter TN	0.034	NA	2	0.137	0.287	
Litter C:N	NA	0.714	2	0.132	0.700	
Soil Respiration Rate	**NA**	**6.096**	**2**	**0.285**	**0.047**	*
Herbaceous Litter Decay Rate	*NA*	*5.439*	*2*	*0.321*	*0.066*	.
Woody Litter Decay Rate	6.81E-07	NA	2	0.149	0.275	
N Mineralization Rate	0.044	NA	2	9.17E-03	0.925	
Nitrification Rate	NA	2.579	2	0.183	0.275	

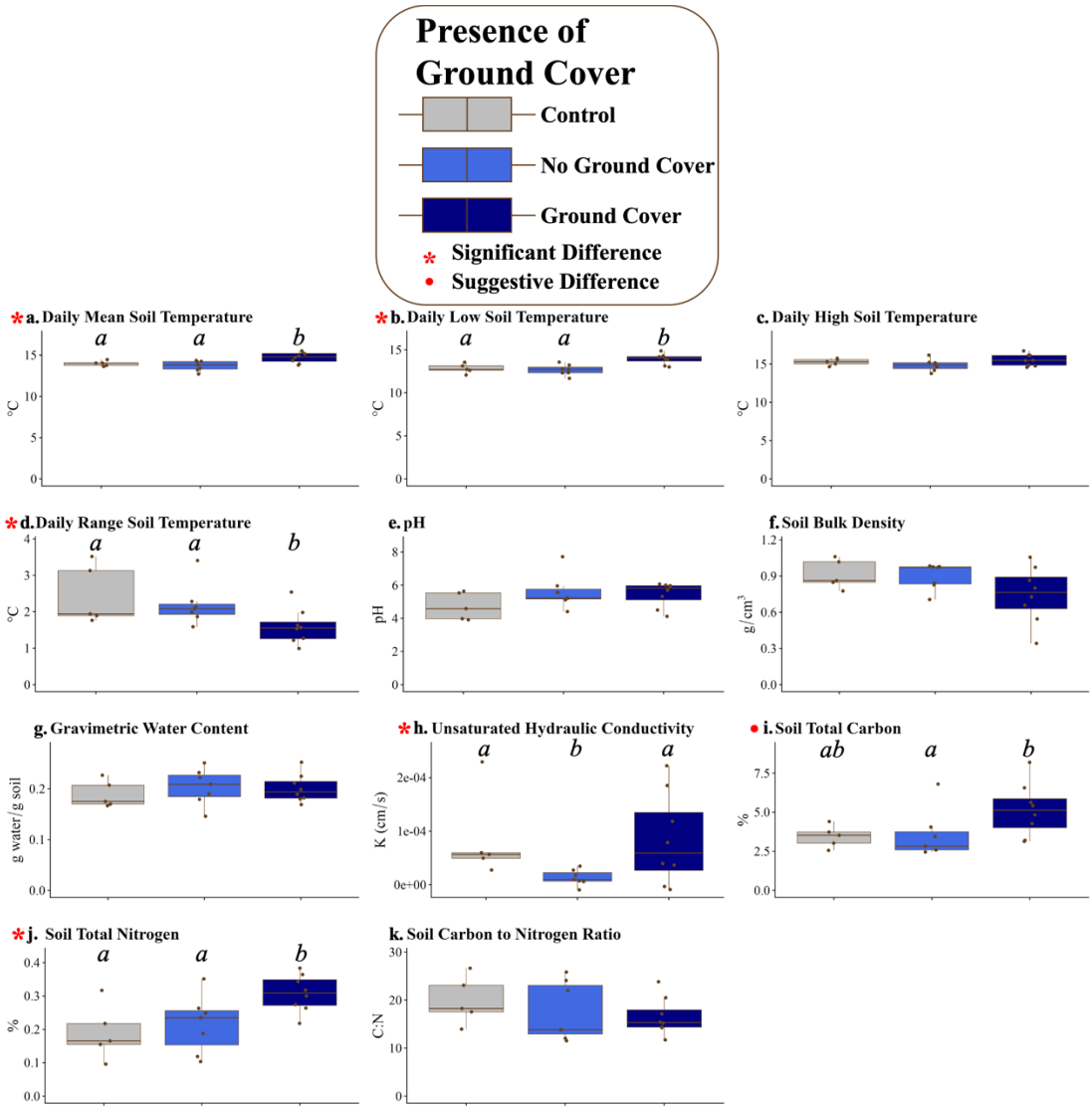


Figure 11. Comparisons of ecological characteristic response variables organized by groups of plots based on the factor presence of invasive *H. helix* ground cover in urban forest patch plots in Baltimore City, MD. Values and distributions are displayed as a grid of boxplots. Distributions are displayed with the medians (brown horizontal lines), interquartile ranges (25%-75%, bound for each box with brown lines), whiskers (values > 1.5 times the interquartile range on each side with brown vertical lines), and values for every represented plot (brown dots). Significant findings from ANOVA (for parametric distributions) and Kruskal-Wallis (for non-parametric distributions) tests are marked with red "*"s ($p < 0.05$), and suggestive findings are marked with red "."s ($p < 0.1$) (Table 2). Differences between groups determined from post-hoc tests associated with each mean separation test (Tukey's HSD for ANOVA tests; Dunn's Test with Holm stepwise adjustment for Kruskal-Wallis tests) are indicated with italicized letters above boxes for variables with significant findings.

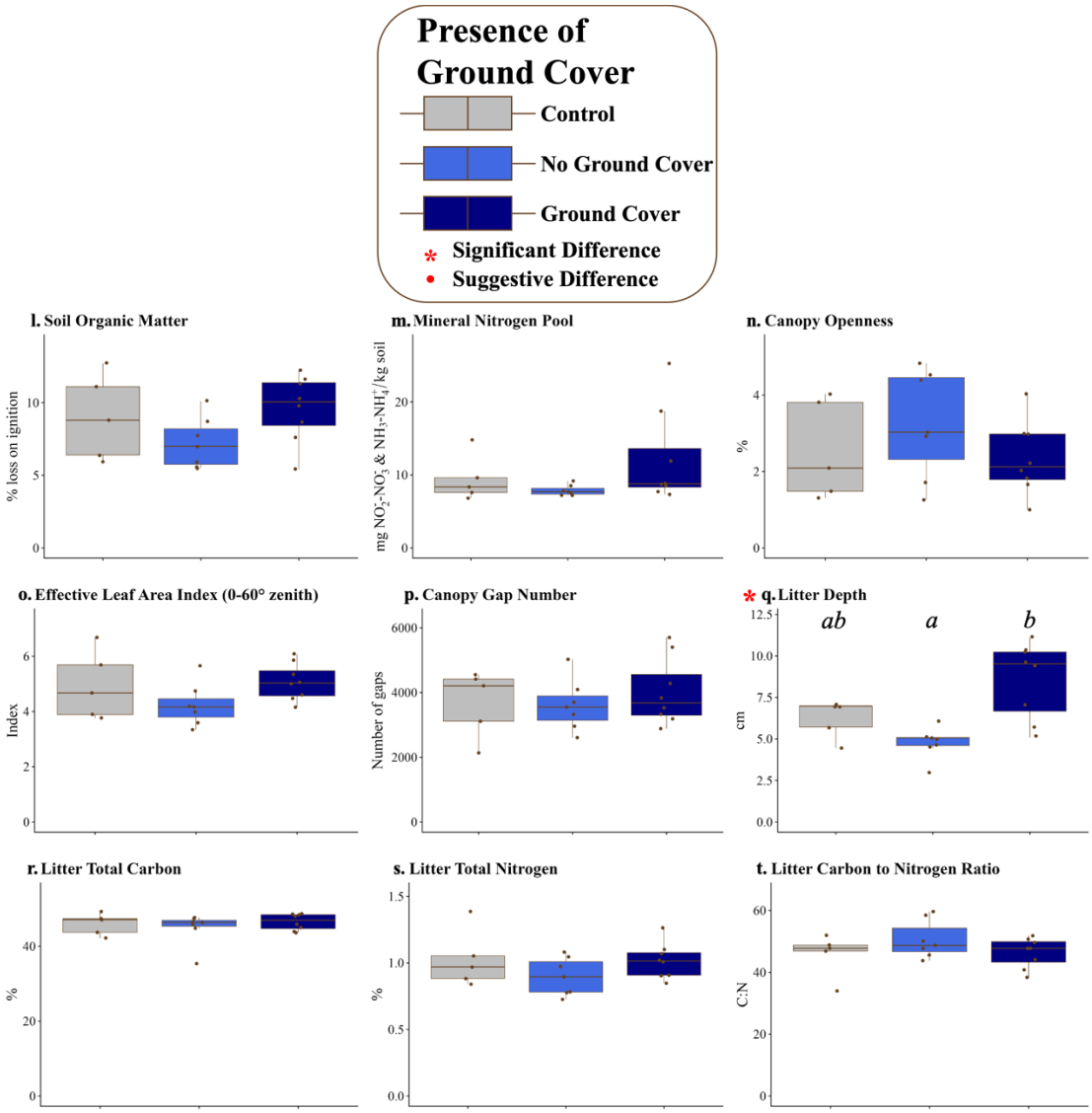


Figure 11 (Continued).

Table 3. Results from the mean separation tests for the intensity of canopy invasion factor for all the ecological characteristic (no fill) and nutrient cycling (gray fill) response variables. Parametric data was analyzed with ANOVA tests and non-parametric data was analyzed with Kruskal-Wallis tests. Degrees of freedom (df), R^2, and *p* value are reported for every result. Mean square is also reported for the ANOVA tests, and rank sum is reported for the Kruskal-Wallis tests. Significance of *p* values is noted as well, where significant (***** = $p < 0.05$) findings are bolded and suggestive findings (**.** = $p < 0.1$) are italicized. *p* values from post-hoc tests can be found in Appendix IV.2.

Response Variable	Mean Square (ANOVA)	Rank Sum (K-W)	df	R^2	*p* value	Significance
Daily Mean Soil Temperature	0.672	NA	3	0.209	0.278	
Daily Low Soil Temperature	1.184	NA	3	0.268	0.161	
Daily High Soil Temperature	0.476	NA	3	0.141	0.476	
Daily Range Soil Temperature	NA	3.366	3	0.161	0.339	
pH	*NA*	*7.077*	*3*	*0.381*	*0.069*	.
Soil Bulk Density	*0.070*	*NA*	*3*	*0.337*	*0.080*	.
Gravimetric Water Content	NA	1.846	3	0.069	0.605	
Unsaturated Hydraulic Conductivity	NA	3.583	3	0.231	0.310	
Soil TC	4.444	NA	3	0.268	0.162	
Soil TN	9.62E-03	NA	3	0.196	0.308	
Soil C:N	NA	3.960	3	0.166	0.266	
Soil Organic Matter	8.969	NA	3	0.241	0.208	
Mineral N Pool	NA	0.463	3	0.091	0.927	
Percent Canopy Openness	0.098	NA	3	0.010	0.982	
Effective LAI	0.175	NA	3	0.033	0.905	
Canopy Gap Number	*1818198.800*	*NA*	*3*	*0.335*	*0.082*	.
Litter Depth	NA	3.062	3	0.286	0.382	
Litter TC	NA	0.669	3	0.105	0.881	
Litter TN	0.025	NA	3	0.149	0.446	
Litter C:N	NA	2.406	3	0.169	0.493	
Soil Respiration Rate	NA	6.040	3	0.280	0.110	
Herbaceous Litter Decay Rate	NA	5.479	3	0.298	0.140	
Woody Litter Decay Rate	4.97E-07	NA	3	0.163	0.431	
N Mineralization Rate	0.315	NA	3	0.098	0.636	
Nitrification Rate	NA	3.594	3	0.202	0.309	

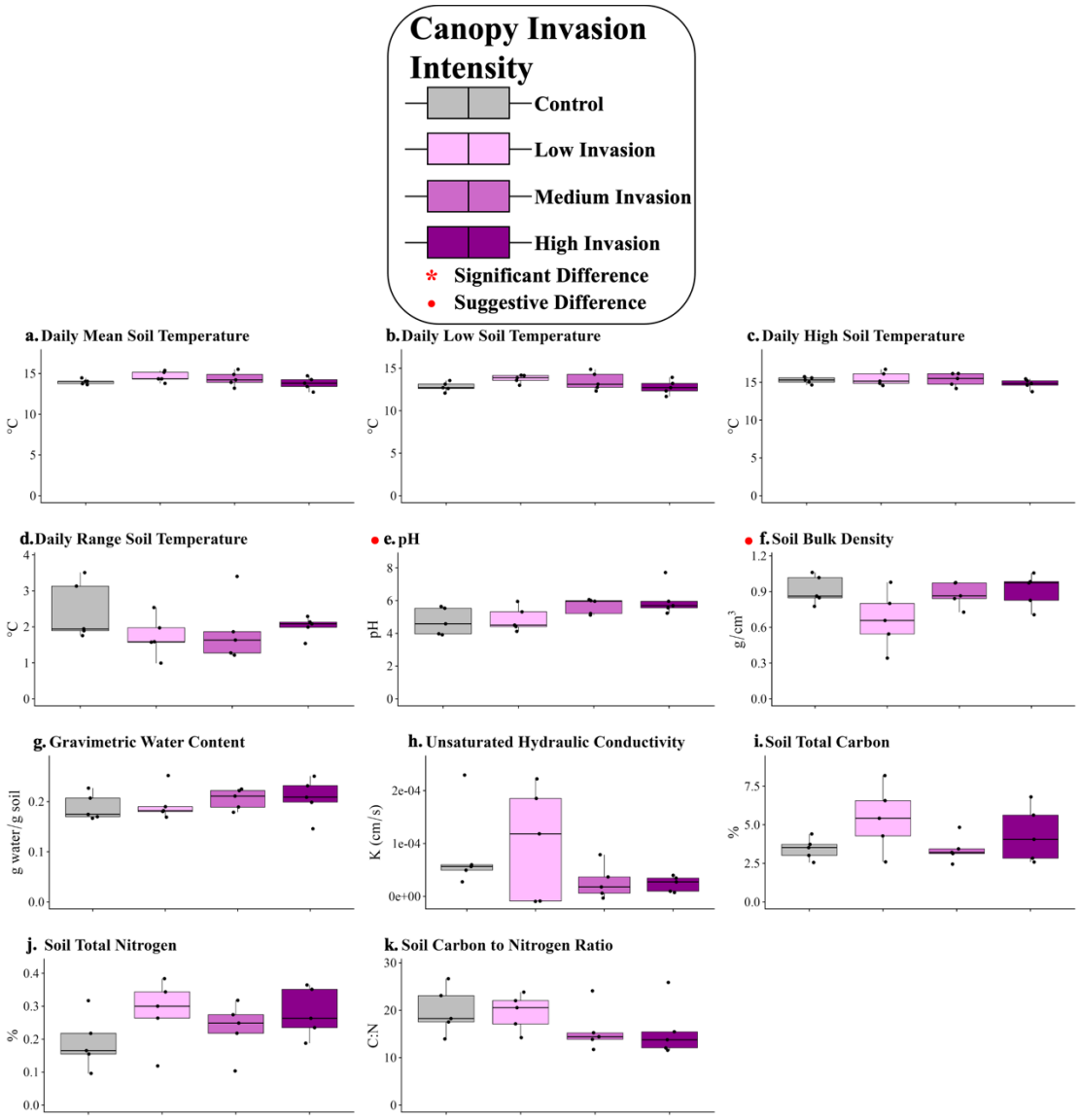


Figure 12. Comparisons of ecological characteristic response variables organized by groups of plots based on the factor *H. helix* canopy invasion intensity in urban forest patch plots in Baltimore City, MD. Values and distributions are displayed as a grid of boxplots. Distributions are displayed with the medians (black horizontal lines), interquartile ranges (25%-75%, bound for each box with black lines), whiskers (values > 1.5 times the interquartile range on each side with black vertical lines), and values for every represented plot (black dots). Suggestive findings from ANOVA (for parametric distributions) and Kruskal-Wallis (for non-parametric distributions) tests are marked with red "."s ($p < 0.1$) (Table 3). Differences between groups determined from post-hoc tests associated with each mean separation test (Tukey's HSD for ANOVA tests; Dunn's Test with Holm stepwise adjustment for Kruskal-Wallis tests) are indicated with italicized letters above boxes for variables with significant findings.

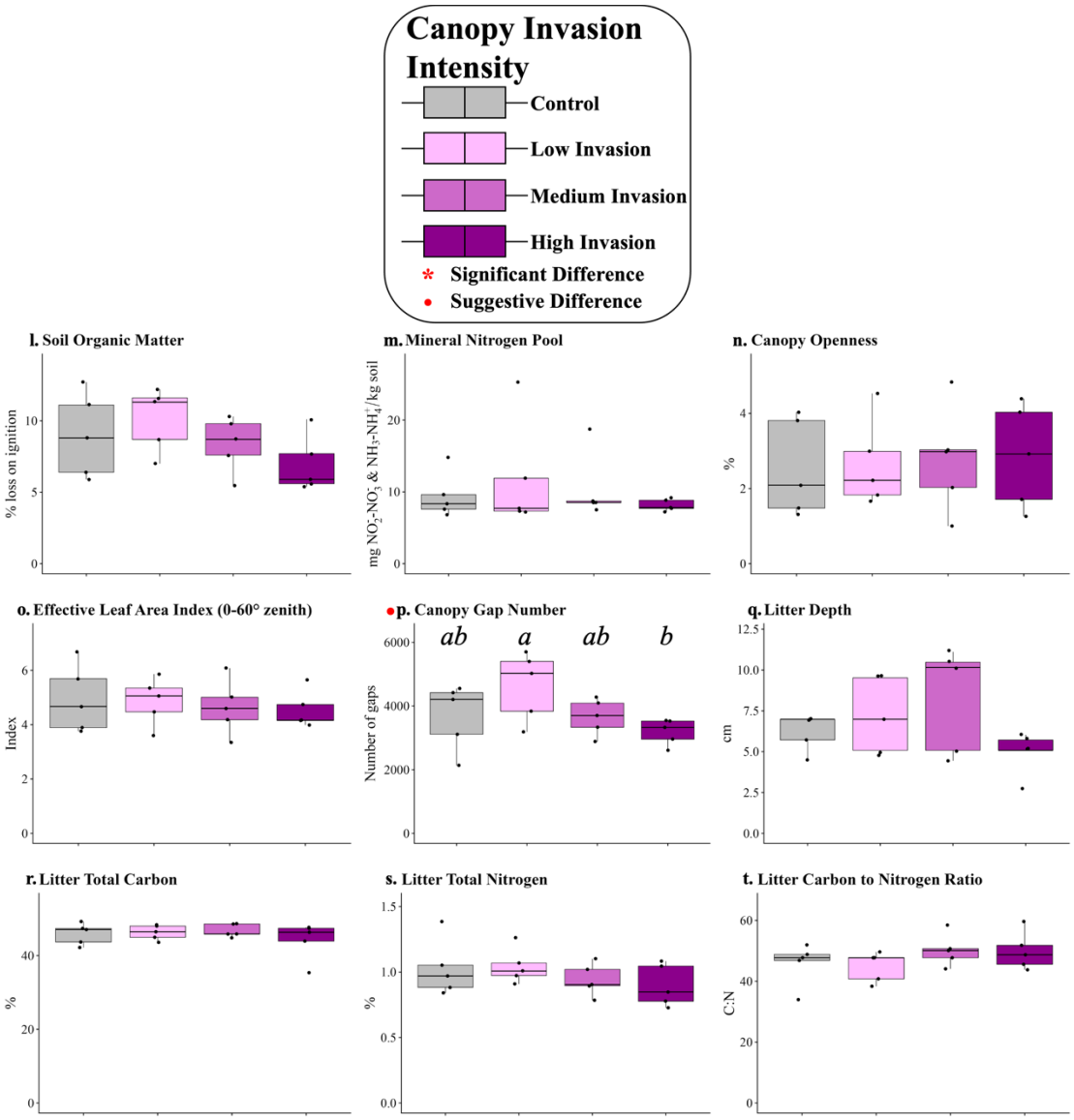


Figure 12 (Continued).

Table 4. Results from the mean separation tests for the presence of invasion factor for all the ecological characteristic (no fill) and nutrient cycling (gray fill) response variables. Parametric data was analyzed with ANOVA tests and non-parametric data was analyzed with Kruskal-Wallis tests. Degrees of freedom (df), R^2, and *p* value are reported for every result. Mean square is also reported for the ANOVA tests, and rank sum is reported for the Kruskal-Wallis tests. Significance of *p* values is noted as well, where significant (***** = $p < 0.05$) findings are bolded and suggestive findings (**.** = $p < 0.1$) are italicized.

Response Variable	Mean Square (ANOVA)	Rank Sum (K-W)	df	R^2	*p* value	Significance
Daily Mean Soil Temperature	0.251	NA	1	0.026	0.497	
Daily Low Soil Temperature	0.993	NA	1	0.075	0.242	
Daily High Soil Temperature	0.014	NA	1	1.40E-03	0.876	
Daily Range Soil Temperature	NA	1.602	1	0.140	0.206	
pH	*2.368*	*NA*	*1*	*0.151*	*0.090*	.
Soil Bulk Density	0.035	NA	1	0.056	0.316	
Gravimetric Water Content	6.53E-04	NA	1	0.040	0.397	
Unsaturated Hydraulic Conductivity	NA	2.608	1	0.042	0.106	
Soil TC	3.405	NA	1	0.068	0.265	
Soil TN	0.021	NA	1	0.143	0.101	
Soil C:N	NA	1.602	1	0.065	0.206	
Soil Organic Matter	0.888	NA	1	7.96E-03	0.708	
Mineral N Pool	NA	0.017	1	4.62E-03	0.896	
Percent Canopy Openness	0.176	NA	1	6.27E-03	0.740	
Effective LAI	0.243	NA	1	0.016	0.601	
Canopy Gap Number	76612.267	NA	1	4.70E-03	0.774	
Litter Depth	NA	0.000	1	0.012	1.000	
Litter TC	NA	0.017	1	7.16E-04	0.896	
Litter TN	0.016	NA	1	0.033	0.444	
Litter C:N	NA	0.048	1	0.034	0.827	
Soil Respiration Rate	**NA**	**5.350**	**1**	**0.200**	**0.021**	*
Herbaceous Litter Decay Rate	NA	0.411	1	0.015	0.522	
Woody Litter Decay Rate	6.47E-07	NA	1	0.071	0.271	
N Mineralization Rate	4.41E-04	NA	1	4.59E-05	0.977	
Nitrification Rate	NA	2.333	1	0.123	0.127	

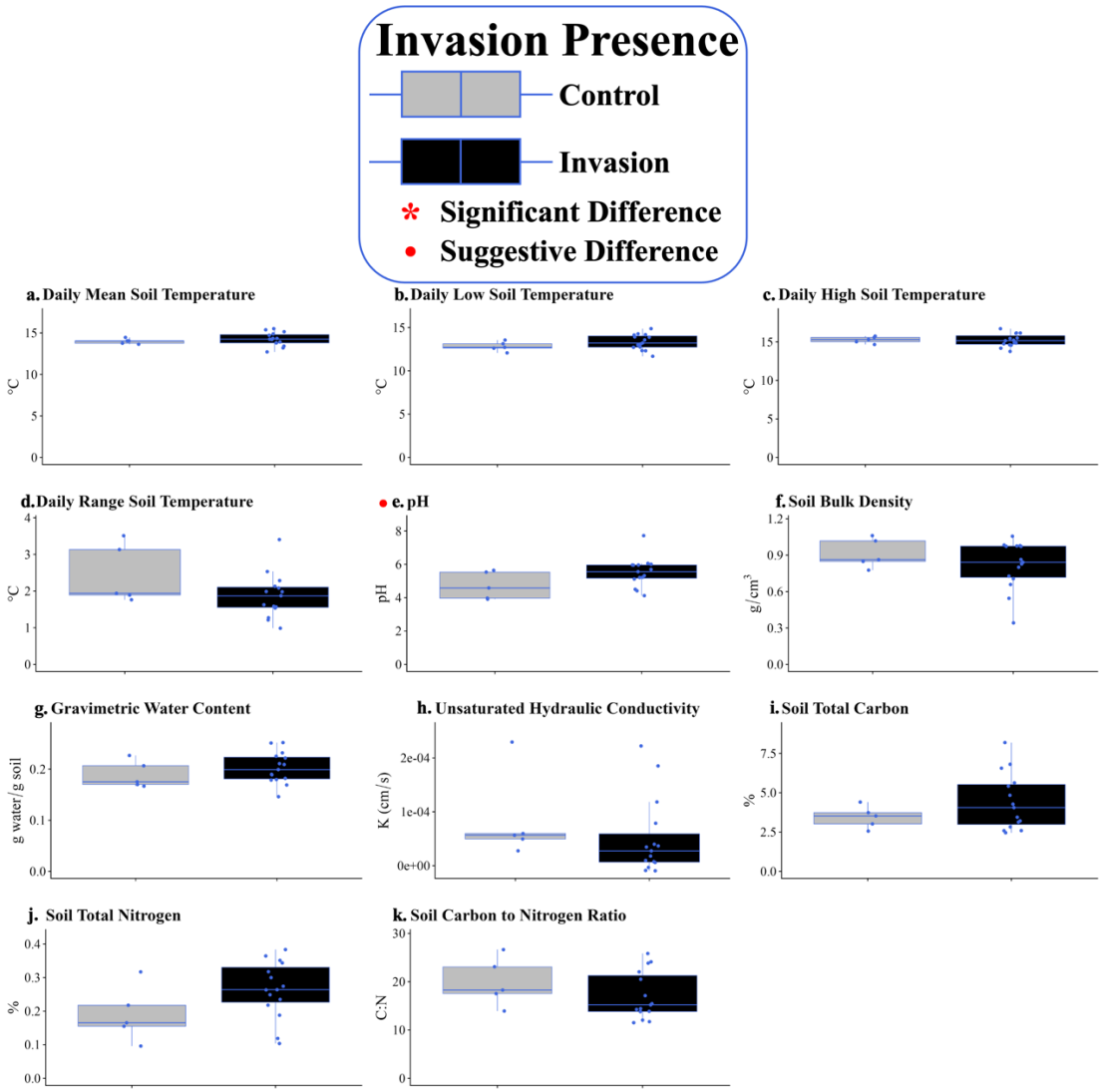


Figure 13. Comparisons of ecological characteristic response variables organized by groups of plots based on the factor *H. helix* invasion presence in urban forest patch plots in Baltimore City, MD. Values and distributions are displayed as a grid of boxplots. Distributions are displayed with the medians (light blue horizontal lines), interquartile ranges (25%-75%, bound for each box with light blue lines), whiskers (values > 1.5 times the interquartile range on each side with light blue vertical lines), and values for every represented plot (light blue dots). Suggestive findings from ANOVA (for parametric distributions) and Kruskal-Wallis (for non-parametric distributions) tests are marked with red "." s ($p < 0.1$) (Table 4).

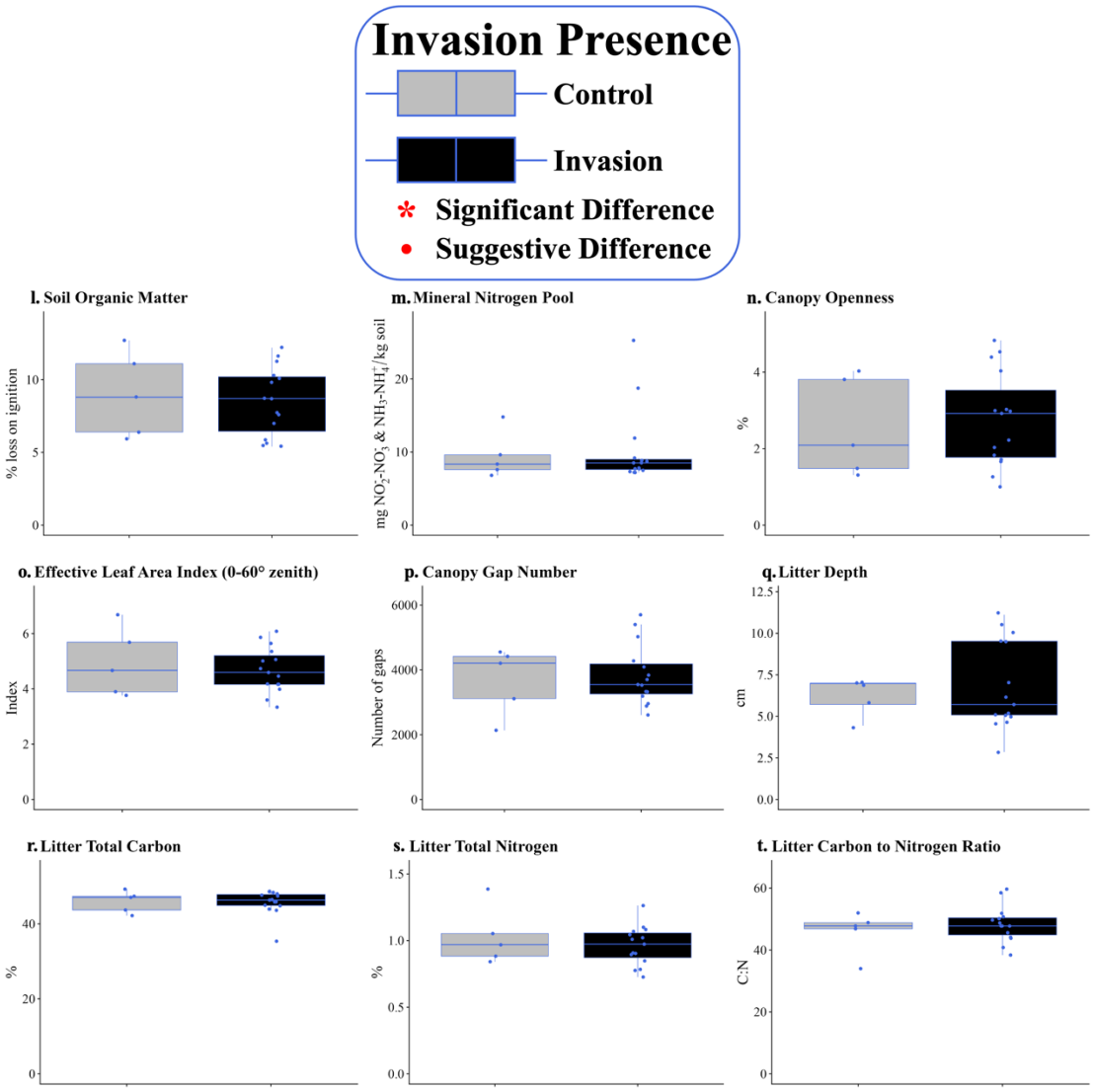


Figure 13 (Continued).

3.4 Overall Ecological Characteristics

There is evidence from this study that *H. helix* impacts the overall ecological characteristics (Figure 2) of urban forest patch plots in Baltimore, dictated by the characteristics of invasion. There is a significant difference in overall ecological characteristics across plots considering ground cover presence (df = 2, p = 0.011) (Table 5; Figure 14). Specifically, invaded plots with and without ground cover are significantly different (df = 1, adjusted p = 0.006) (Table 6, Figure 14). Plots across this factor differ in soil temperature (Table 2; Figures 11a,b,d), unsaturated hydraulic conductivity (Table 2; Figure 11h), soil TC (Table 2; Figure 11i), soil TN (Table 2; Figure 11j), and litter depth (Table 2; Figure 11q). The relationship between ground cover and overall ecological characteristics is visualized with the NMDS plot (Figure 14), where despite a wide scatter there is a clear gap in space on the NMDS1 axis between most plots with and without ground cover present, while control plots are dispersed in both areas. The three ecological response variables with the greatest influence on the NMDS1 axis are (in order) litter depth, unsaturated hydraulic conductivity, and soil bulk density (Appendix V). There are no significant differences in overall ecological characteristics across plots considering invasion presence (df = 1, p = 0.723) or canopy invasion intensity (df = 3, p = 0.185) (Table 5).

Table 5. Results from PERMANOVA tests using ecological response variables as inputs on three invasion factors in urban forest patch plots in Baltimore City, MD based on characteristics of *H. helix* invasion: invasion presence, canopy invasion intensity (as a gradient), and presence of ground cover. Sum of Squares (SS), degrees of freedom (df), R^2, F-statistic (F), and *p* value are reported. Results with significant *p* values (* = $p < 0.05$) are bolded.

Factor	SS	df	R^2	F	*p* value	Significance
Invasion Presence	0.010	1	0.037	0.687	0.723	
Canopy Invasion Intensity	0.053	3	0.193	1.272	0.185	
Presence of Ground Cover	**0.054**	**2**	**0.198**	**2.094**	**0.011**	*

Table 6. Results from PERMANOVA-based multilevel pairwise analyses using ecological response variables as inputs on the factor presence of invasive ground cover by *H. helix* in urban forest patch plots in Baltimore City, MD. Presence of ground cover has three groups: no invasion (control), invasion without ground cover, and invasion with ground cover. Sum of Squares (SS), degrees of freedom (df), R^2, F-statistic (F), and adjusted *p* values are reported. Results with significant adjusted *p* values (* = adjusted $p < 0.05$) are bolded.

Pairwise Comparison	SS	df	R^2	F	adjusted *p* value	Significance
Control vs. No Ground Cover	0.013	1	0.095	1.047	1.000	
Control vs. Ground Cover	0.020	1	0.121	1.520	0.423	
No Ground Cover vs. Ground Cover	**0.044**	**1**	**0.209**	**3.429**	**0.006**	*

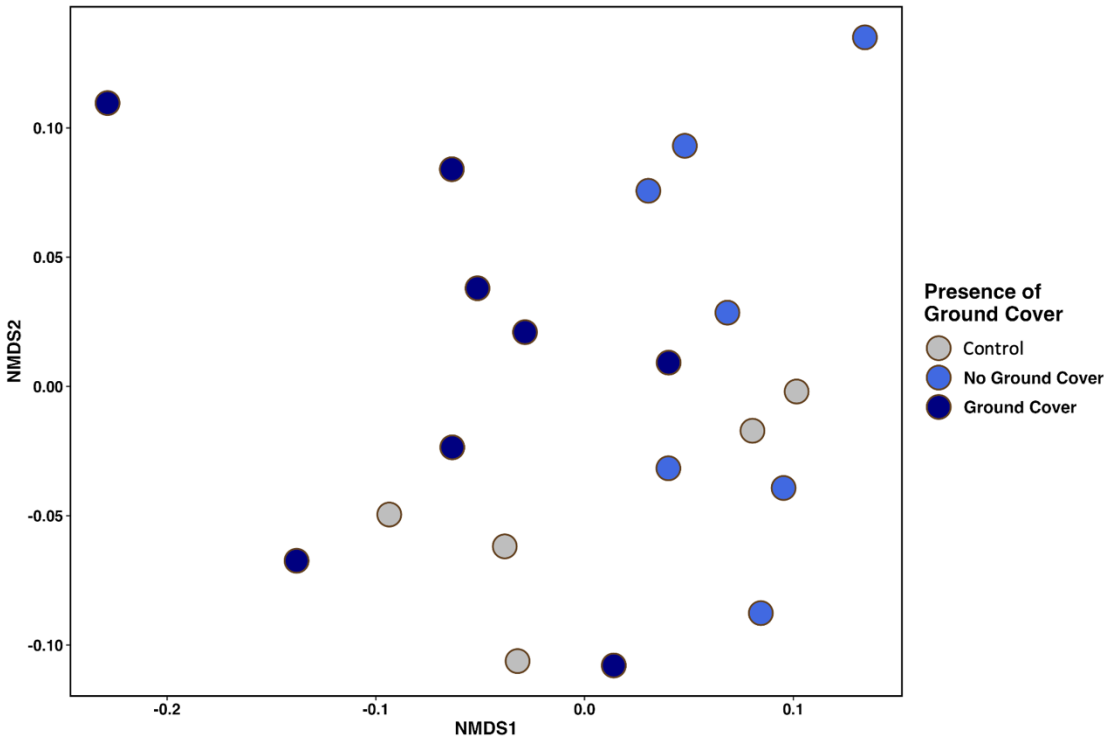


Figure 14. Results from an NMDS test displayed as a scatterplot. The test was run using ecological response variables on the *H. helix* invasion factor presence of ground cover in urban forest patch plots in Baltimore City, MD, which was found to have significant differences between the groups no ground cover and ground cover from a PERMANOVA test and associated multilevel pairwise analysis (Tables 5 & 6). Some response variables were removed using a correlation matrix to prevent overfitting. Removal was based on having a correlation coefficient of > (+/-) 0.7. Remaining variables that went in to the NMDS were: Daily Mean Soil Temperature, Daily Range Soil Temperature, pH, Soil Bulk Density, Gravimetric Water Content, Unsaturated Hydraulic Conductivity, Soil TC, Soil C:N, Litter TC, Litter C:N, Soil Organic Matter, Mineral N Pool, Percent Canopy Openness, Canopy Gap Number, and Litter Depth. A table of NMDS1 and NMDS2 dimensions influence by each response variable is in Appendix V.

3.5 Nutrient Cycling

Changes in soil temperature regulation, soil physical structure, soil water mobility, soil TC and TN, and litterfall quantity may be pathways to nutrient cycling changes, some of which are significantly different in plots with and without ground cover. I observed that soil respiration rate is 2.86 times greater in plots with ground cover than control

plots (means: control = 0.563 μmol $CO_2/m^2/s$; no ground cover = 1.087 μmol $CO_2/m^2/s$; ground cover = 1.612 μmol $CO_2/m^2/s$) (df = 2, p = 0.047) (Table 2; Figure 15a; Appendix II.2). Variance in respiration rate is particularly high in ground cover plots and particularly low in invaded plots without ground cover ($CV_{no\ invasion}$ = 0.595, $CV_{no\ ground\ cover}$ = 0.322, $CV_{ground\ cover}$ = 0.641) (Appendix III.1). I also observed a suggestive difference in herbaceous litter decay rate, where ground cover plots have 3.01 times faster rates than invaded plots without ground cover (df = 2, p = 0.066) (Table 2; Figure 15b; Appendix II.2). The variance in ground cover plots is also notably lower ($CV_{control}$ = 0.746, $CV_{no\ ground\ cover}$ = 1.236, $CV_{ground\ cover}$ = 0.303) (Appendix III.1). Interestingly, I did not observe any significant differences pertaining to N mineralization rate or nitrification rate (Table 2).

No significant or suggestive results were observed for nutrient cycling metrics across groups for the canopy invasion intensity factor (Table 3; Figure 16).

I observed that soil respiration rate is 2.42 times higher in all invaded plots than control plots (means: control = 0.563 μmol $CO_2/m^2/s$, invasion = 1.367 μmol $CO_2/m^2/s$) (df = 1, p = 0.021) (Table 4; Figure 17a; Appendix II.4). These findings indicate a variable but certain increase in C cycling, specifically soil C loss, and microbial activity in all invaded plots, particularly in plots with ground cover. Invasion also appears to make nitrification rate more variable. This cannot be supported with a CV because the mean of the control group is too close to zero (Appendix III.3), but there is clearly a wide spread of nitrification rates and many outliers in invaded plots (Figure 17e).

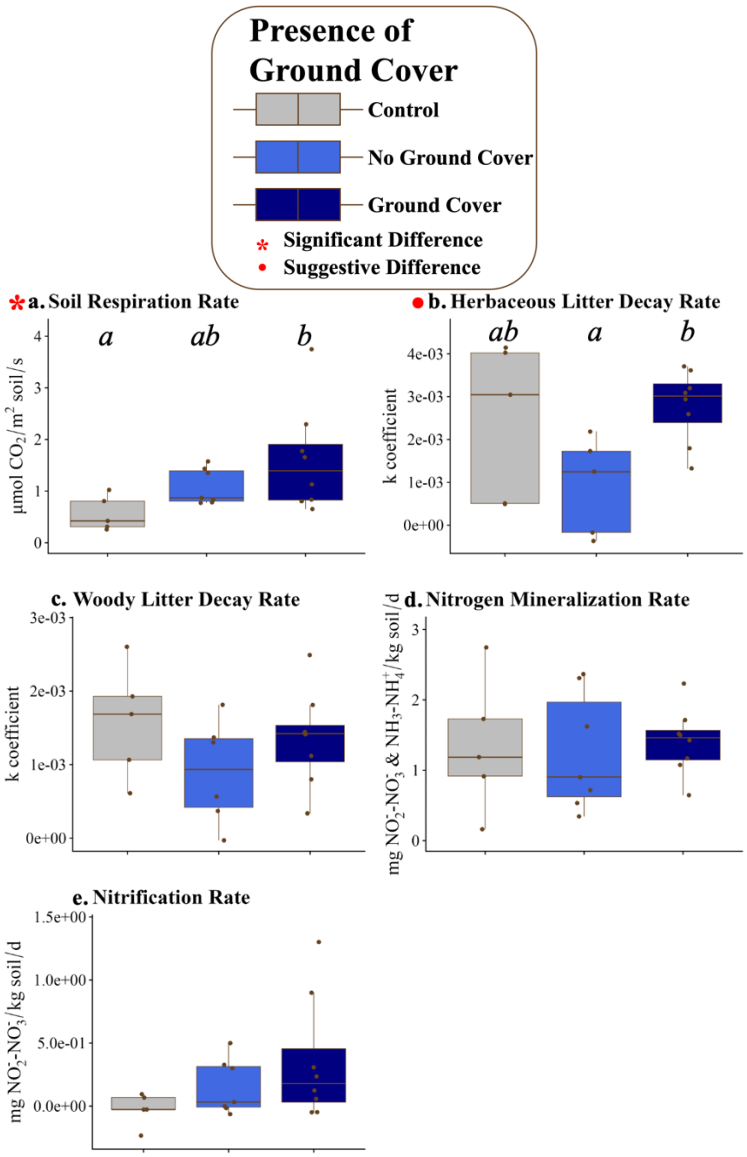


Figure 15. Comparisons of nutrient cycling response variables organized by groups of plots based on the factor presence of invasive H. helix ground cover in urban forest patch plots in Baltimore City, MD. Values and distributions are displayed as a grid of boxplots. Distributions are displayed with the medians (brown horizontal lines), interquartile ranges (25%-75%, bound for each box with brown lines), whiskers (values > 1.5 times the interquartile range on each side with brown vertical lines), and values for every represented plot (brown dots). Significant findings from ANOVA (for parametric distributions) and Kruskal-Wallis (for non-parametric distributions) tests are marked with red "*"s ($p < 0.05$), and suggestive findings are marked with red "."s ($p < 0.1$) (Table 2). Differences between groups determined from post-hoc tests associated with each mean separation test (Tukey's HSD for ANOVA tests; Dunn's Test with Holm stepwise adjustment for Kruskal-Wallis tests) are indicated with italicized letters above boxes for variables with significant findings.

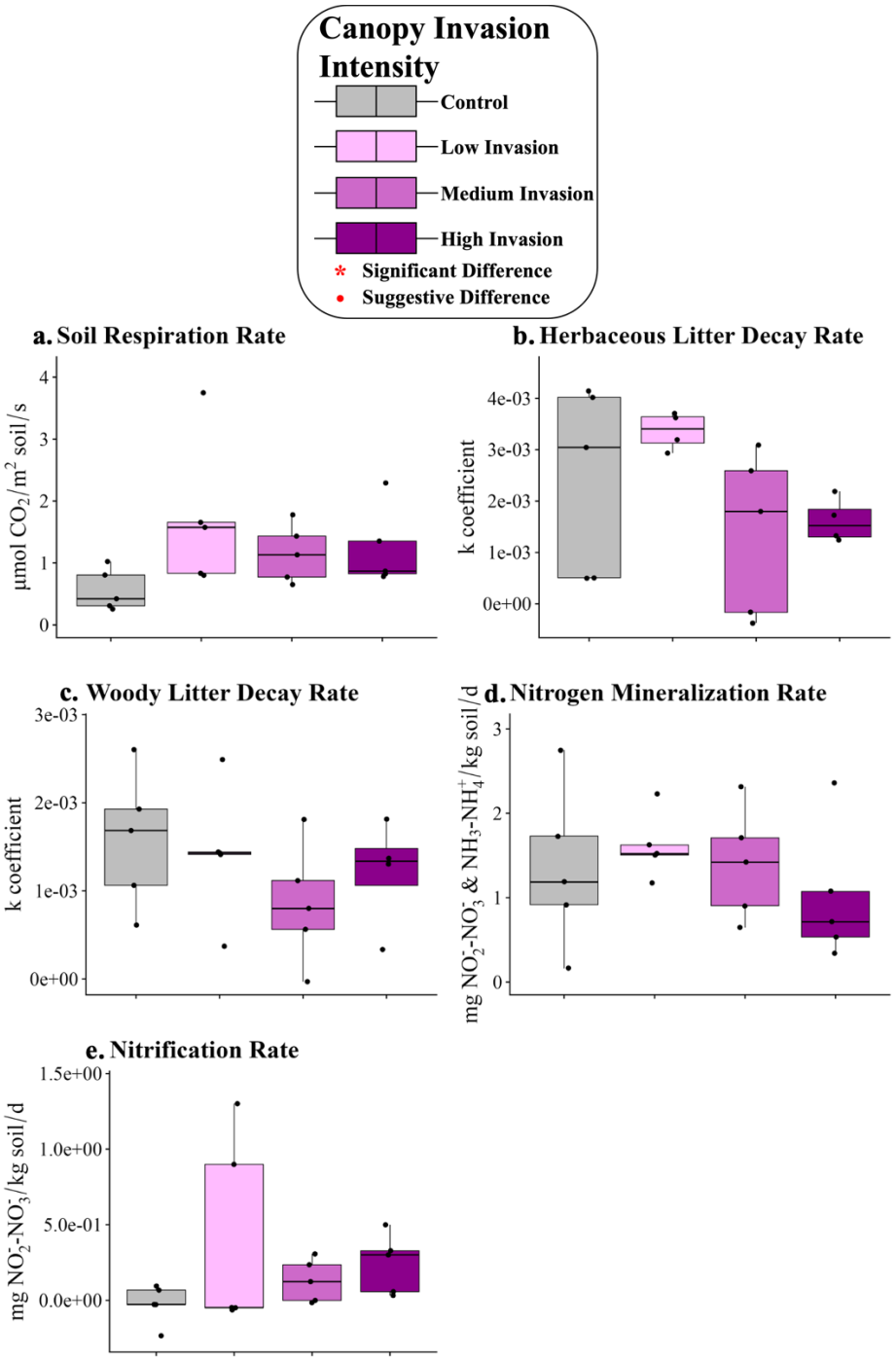


Figure 16. Comparisons of nutrient cycling response variables organized by groups of plots based on the factor *H. helix* canopy invasion intensity in urban forest patch plots in Baltimore City, MD. Values and distributions are displayed as a grid of boxplots. Distributions are displayed with the medians (black horizontal lines), interquartile ranges (25%-75%, bound for each box with black lines), whiskers (values > 1.5 times the interquartile range on each side with black vertical lines), and values for every represented plot (black dots).

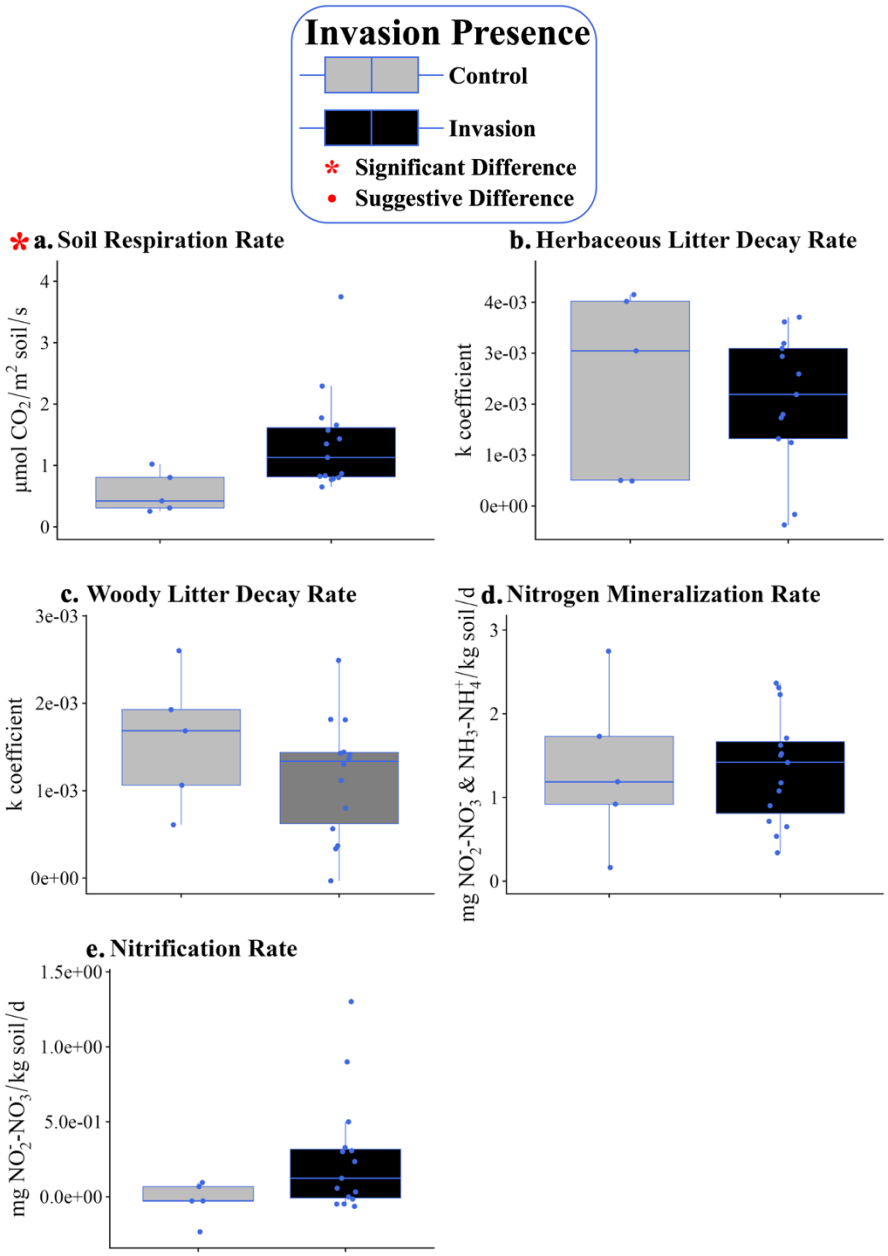


Figure 17. Comparisons of nutrient cycling response variables organized by groups of plots based on the factor *H. helix* invasion presence in urban forest patch plots in Baltimore City, MD. Values and distributions are displayed as a grid of boxplots. Distributions are displayed with the medians (light blue horizontal lines), interquartile ranges (25%-75%, bound for each box with light blue lines), whiskers (values > 1.5 times the interquartile range on each side with light blue vertical lines), and values for every represented plot (light blue dots). Significant findings from ANOVA (for parametric distributions) and Kruskal-Wallis (for non-parametric distributions) tests are marked with red "*"s ($p < 0.05$) (Table 4).

I used regressions between ecological characteristics and nutrient cycling variables which had significant and suggestive differences across plots to explore pathways by which *H. helix* may cause such differences. Soil respiration rate is negatively related to daily soil temperature range (slope = -0.561, $R^2 = 0.231$, $p = 0.032$) (Figure 18a) and soil bulk density (slope = -2.095, $R^2 = 0.227$, $p = 0.034$) (Figure 18b). Soil respiration is positively related to gravimetric water content (slope = -11.108, $R^2 = 0.166$, $p = 0.075$) (Figure 18c), soil TC (slope = 0.303, $R^2 = 0.377$, $p = 0.004$) (Figure 18d), soil TN (slope = 4.603, $R^2 = 0.257$, $p = 0.023$) (Figure 18e), and mineral N pool (slope = 0.082, $R^2 = 0.228$, $p = 0.033$) (Figure 18f). Mean, low, and high daily temperature is not related to soil respiration. All significant relationships with soil respiration rate pertained to soil physical and chemical properties, and not canopy properties. The strongest relationships pertained to soil chemical properties, which were soil TC, soil TN, and mineral N pool, in descending order. Daily soil temperature range had a slightly stronger relationship with soil respiration than mineral N pool, and the other soil physical relationships were less strong (bulk density and gravimetric water content). Strength ranged greatly, with soil TC ($R^2 = 0.377$) explaining respiration rate twice as much as gravimetric water content ($R^2 = 0.166$) (Figures 18d,c).

Herbaceous litter decay rate is negatively related to daily soil temperature range (slope = -0.001, $R^2 = 0.295$, $p = 0.020$) (Figure 19b), soil bulk density (slope = -0.003, $R^2 = 0.172$, $p = 0.087$) (Figure 19c), percent canopy openness (slope = -0.001, $R^2 = 0.428$, $p = 0.003$) (Figure 19f), and litter C:N (slope > -0.001, $R^2 = 0.374$, $p = 0.007$) (Figure 19j). Herbaceous litter decay rate is positively related to daily low soil

temperature (slope = 0.001, R^2 = 0.195, p = 0.067) (Figure 19a), unsaturated hydraulic conductivity (slope = 9.327, R^2 = 0.235, p = 0.041) (Figure 19d), mineral N pool (slope < 0.001, R^2 = 0.212, p = 0.054) (Figure 19e), litter depth (slope < 0.001, R^2 = 0.258, p = 0.031) (Figure 19g), litter TC (slope < 0.001, R^2 = 0.237, p = 0.026) (Figure 19h), and litter TN (slope = 0.006, R^2 = 0.471, p = 0.002) (Figure 19i). Significant relationships with herbaceous litter decay rate pertained to several canopy and litter properties, some soil physical properties, and one soil chemical property. The strongest relationships pertained to canopy and litter properties, including litter TN, percent canopy openness, and litter C:N, in descending order. Litter depth and litter TC were less strongly influential. Daily soil temperature range had a slightly stronger relationship with soil respiration than litter depth and litter TC. All other soil physical and chemical relationships were less strong, including unsaturated hydraulic conductivity, mineral N pool, daily low soil temperature, and bulk density. Strength ranged greatly, with litter TN (R^2 = 0.471) explaining respiration rate 2.7 times as much as soil bulk density (R^2 = 0.172) (Figures 19i,c).

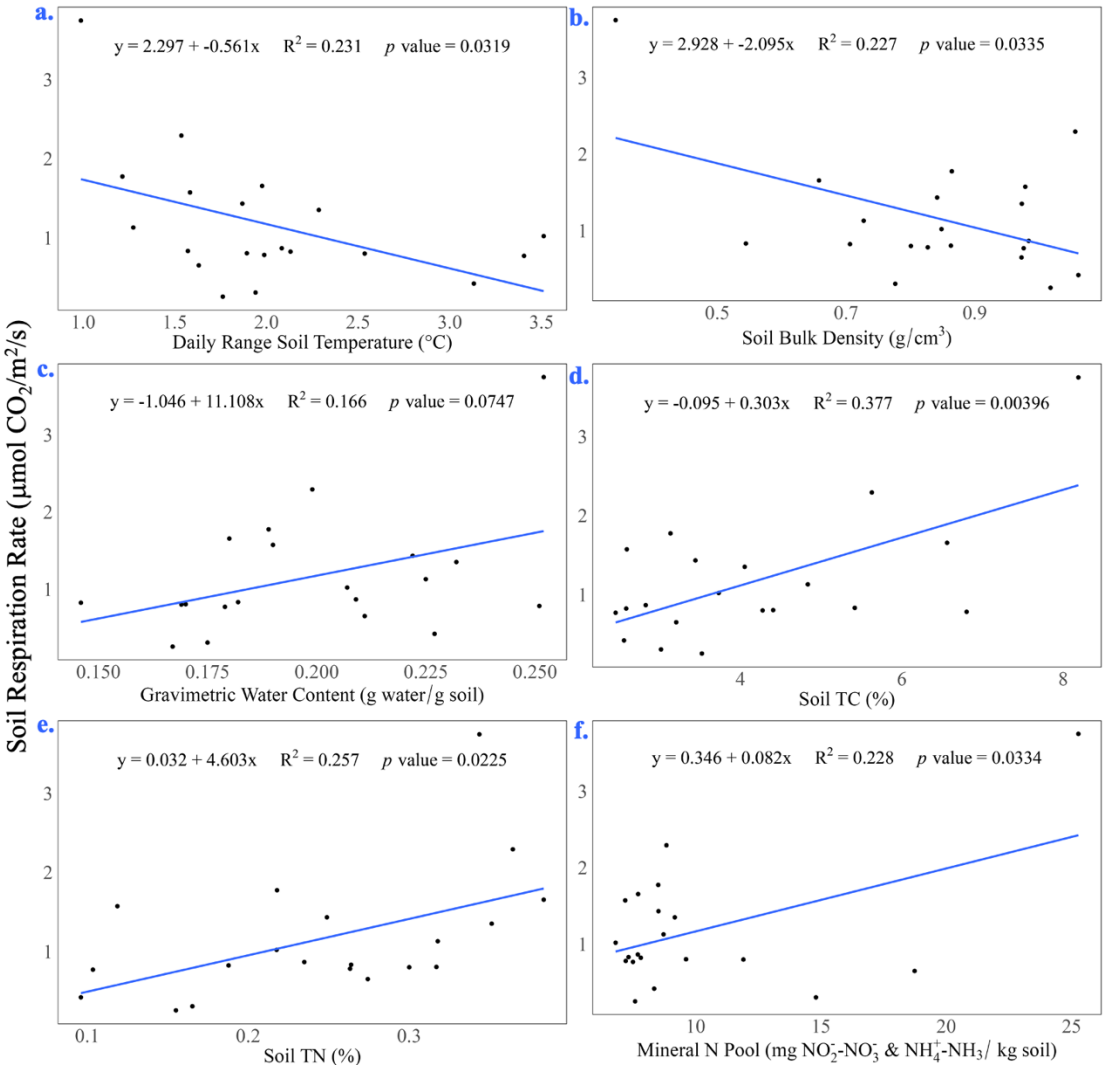


Figure 18. Significant and relevant regressions between ecological characteristics as drivers and soil respiration rate as a nutrient cycling response variable for forest patch plots in Baltimore City, MD.

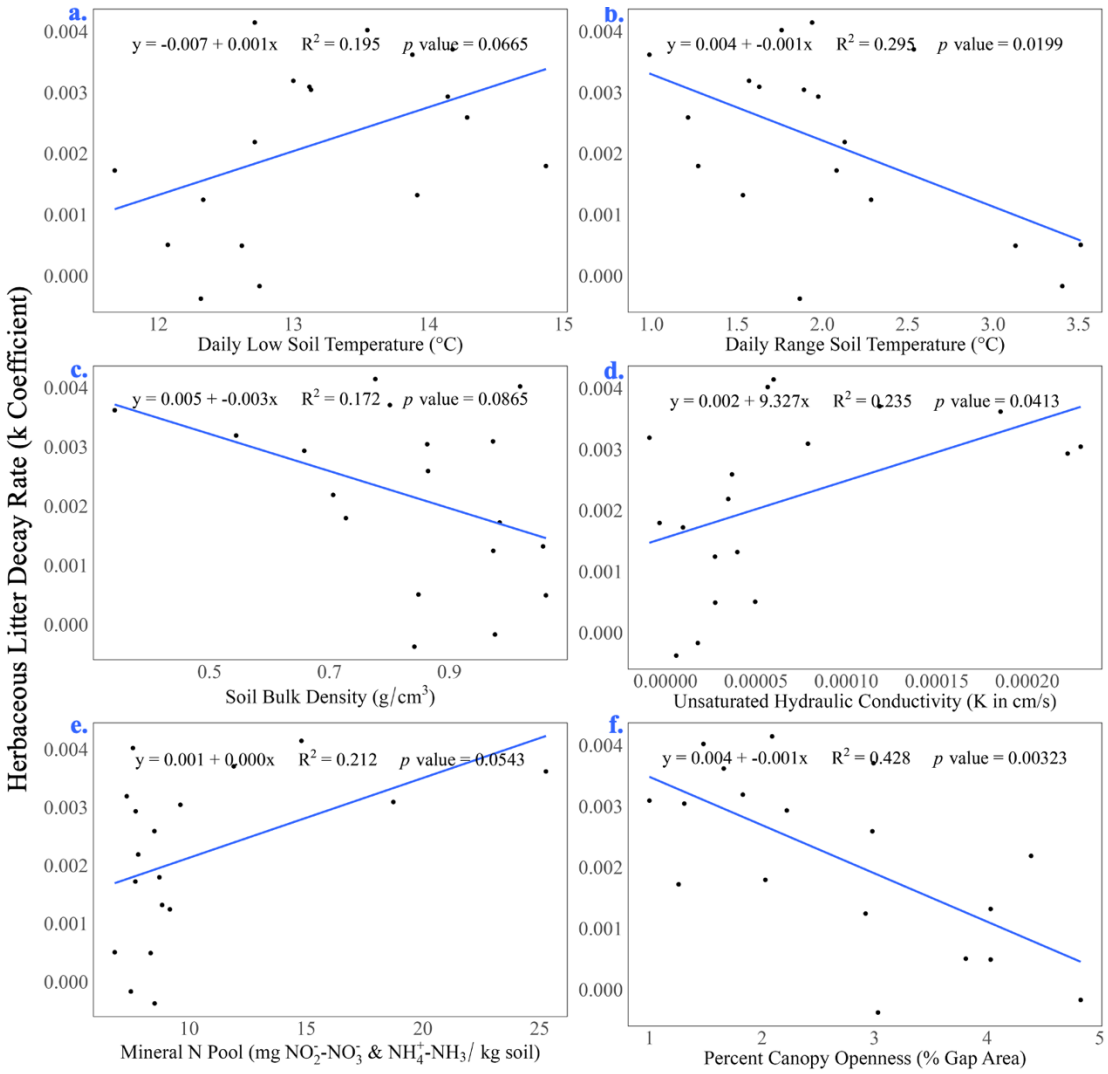


Figure 19. Significant and relevant regressions between ecological characteristics as drivers and herbaceous litter decay rate as a nutrient cycling response variable for forest patch plots in Baltimore City, MD.

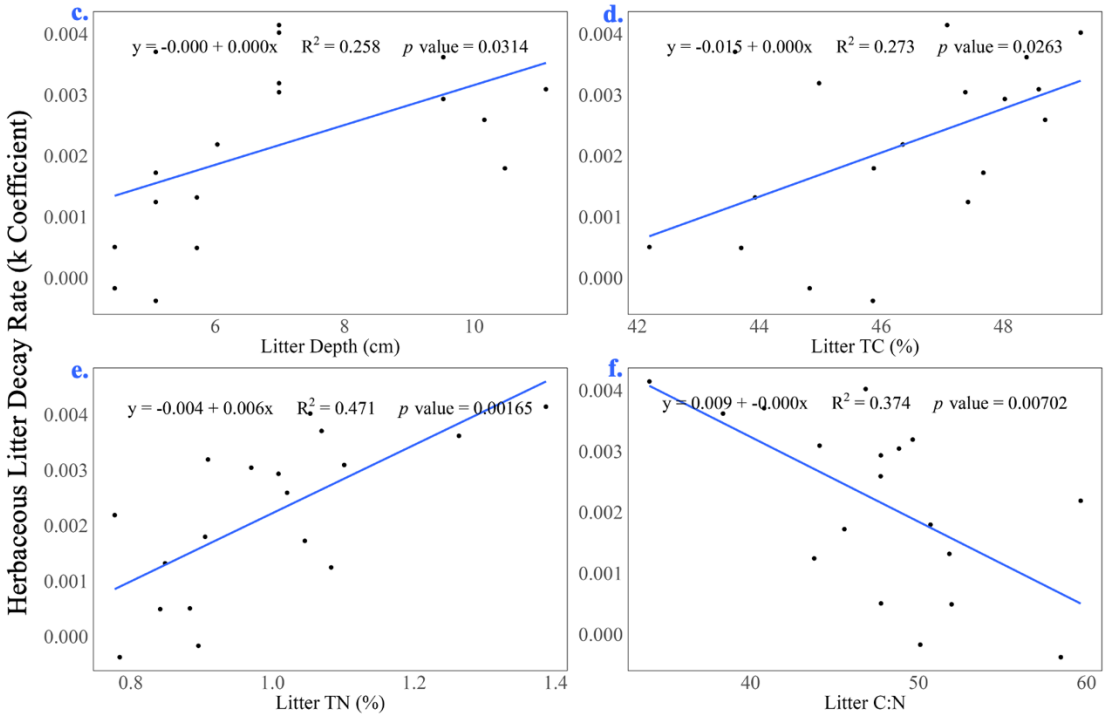


Figure 19 (Continued).

Chapter 4. Discussion

4.1 Research Questions & Findings Summary

This study set out to determine if and how different structures and intensities of *H. helix* invasion impact ecological characteristics, C cycling, and N cycling in Baltimore's forest patches. My results support the hypothesis that the structure of *H. helix* invasion dictates the impact it may have on the ecological characteristics and nutrient cycling of Baltimore's urban forest patches. High intensity canopy invasions may be associated with increased canopy gap sizes. Ground cover by *H. helix* is significantly associated with altered soil properties and increased C cycling rates. Invasion presence may be associated with increased variability of certain ecological characteristics and nutrient cycling variables. The results of my analyses do not support the hypothesis that *H. helix* invasion increases N cycling rates.

4.2 Canopy & Litter Ecology

4.2.1 Canopy Structure

My results suggestively confirmed that canopy invasions alter canopy structure (Table 3; Figures 12n,o,p). High levels of *H. helix* canopy invasion may have decreased the number of gaps in the canopy (Table 3; Figure 12p), while the percent canopy openness was not significantly impacted by degree of invasion (Table 3; Figure 12n). This suggests that high levels of invasion are associated with fewer, but larger gaps in the canopy (Figure 20). Further, this relationship indicates there has been some tree or branch loss in plots with intense canopy growth. As an example, in Figure 20b, it appears as though a tree died due to *H. helix* invasion. It has not fallen but produces no

canopy. Both downed trees and dead trees were observed in the field, especially in the FENDAL forest patch (Figures 3, 5, 6a, 6b, 20b).

Tree and branch loss and subsequently larger gaps provide more direct sun to the forest floor than several smaller gaps (Gorchov et al., 2011; Thomas, 1980; Whitmore, 1989). This disturbance may create a more aggressive setting for undergrowth, favoring *H. helix* and other invasive plants, such as Oriental bittersweet, Japanese honeysuckle, and Porcelain berry (Johnson, Trammell, et al., 2020; Robertson et al., 1994). Based on the theory of fluctuating resource availability and its influence on invasibility, pulses of light favor plant invasion by giving invasive plants a competitive growth advantage (Davis et al., 2000; Hobbs & Huenneke, 1992). Dead, still-standing trees also provide ideal growth settings for *H. helix* because it can climb into the canopy and receive large amounts of light without the growth of the dead tree's leaves (Thomas, 1980). My findings are not as stark as Thomas (1980)'s, who discovered a positive relationship between *H. helix*, tree loss, light penetration, and further invasion. The timescale of invasion in my plots is unknown and cannot be compared to that of Thomas (1980), which was unknown as well. Given the extent to which *H. helix* has invaded trees in some of plots, one might expect findings closer those of Thomas (1980). This disparity could be the result of invasion timescale, better resistance of trees in my plots to invasion pressure, past management I am unaware of, or other ecological differences between our study sites.

There is strain by *H. helix* on trees taking place over a long, though unknown, period, regardless of the disparity between my study's and Thomas (1980)'s findings.

Weight stress imposed by intense canopy invasion make trees more susceptible to pressures such as storms and herbivory (Larocque, 1999; Putz, 1991; Strelau et al., 2018; Thomas, 1980). *H. helix* is not an ectoparasitic plant, so it does not take nutrients directly from trees, but it can suppress tree root development (Strelau et al., 2018), compete for water and nutrients in the soil (Larocque, 1999), and compete for light (Larocque, 1999; Putz, 1991; Strelau et al., 2018; Thomas, 1980). These stresses eventually lead to broken branches, dead trees, and fallen trees (Larocque, 1999; Reichard, 2000; Thomas, 1980). Again, the timescale from onset of invasion to treefall is not entirely known, and trees often die while ivy continues to climb them long before they fall (Thomas, 1980) (Figure 20b). This may result in "ivy deserts" on the forest floor or other forms of invasive monocultures in the future (Reichard, 2000). At that stage, invasion would be more likely to significantly change metrics measured in my study even more aggressively than ground cover without tree loss (see below). Trees facilitate many ecosystem services provided by a forest patch. Tree loss, especially of big, old trees, means losing important sinks for carbon and conduits for water, urban heat island effect mitigation, and culturally valuable aspects of ecosystems (Avins, 2013; Johnson, Johnson, et al., 2020). If tree loss is indeed occurring in plots with high-intensity canopy invasions, the cascading effects on urban forest patch ecology could eventually become severe.

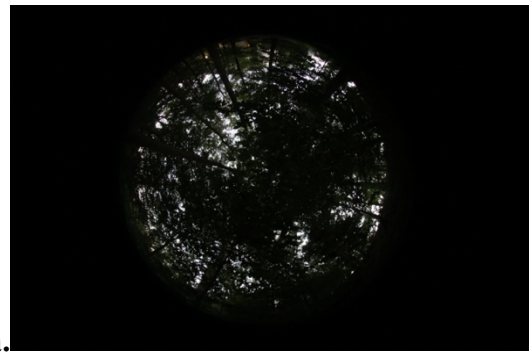
a.  **b.** 

Figure 20. Example images of two different hemispherical canopy photos taken at urban forest patch plots in Baltimore City, MD for the purposes of canopy structure and light penetration analysis. These photos were taken during full leaf-out on September 2 & 3, 2022. **Image a** (JHU 45) is an example of a plot with a low intensity canopy invasion by *Hedera helix* (Figures 3 & 5; Table 1). It has a canopy gap number of 5,402 and a percent canopy openness of 2.99. **Image b** (FENDAL 27) is an example of a plot with a high intensity canopy invasion by *H. helix* (Figures 3 & 5; Table 1). It has a canopy gap number of 2,607 and a percent canopy openness of 4.39.

4.2.2 Litter Quantity & Quality

My results did not support my hypothesis that canopy invasions alter litter quantity but did align with my assumption that ground cover invasions contribute to litter depth. Furthermore, results did support my hypothesis that invasion does not alter litter chemistry. Tree loss or stress at canopy invaded plots was not substantial enough to alter litterfall quantity (Table 3; Figure 12q). Many other invasive species have been found to alter litterfall quantity and quality (Ehrenfeld, 2003; Hickman et al., 2013; Jo et al., 2016, 2017; Liao et al., 2008; Patil et al., 2020; Pereira & Ferreira, 2021; Rodgers et al., 2008; Torres et al., 2021; Weand, 2020; Woodworth et al., 2020; Zhang et al., 2019). Some other invasive species have also been found to alter litter timing (Trammell et al., 2012; Weand, 2020; Woodworth et al., 2020), which has consequences for C and N cycling, even when litter chemistry is not altered (Weand, 2020). However, there are also cases where plant invasions do not alter litter timing or

quantity (i.e., Ashton et al., 2005). Despite *H. helix* having high foliar nutrients, it makes sense that litter quality was not different across plots because it is an evergreen in Baltimore and its leaves do not contribute substantially to the litter pool (Lenaghan et al., 2013; Metcalfe, 2005; Strelau et al., 2018; Thomas, 1980). This is evident in the litter C:N results, which range from 33.976 to 59.658 (Figures 12t, 13t, 14t; Appendix II.1) while *H. helix* litter typically has a C:N of 10 (Lenaghan et al., 2013). If my study had measured litter timing, I may have seen evidence of *H. helix* stress on trees altering this aspect of canopy and litter. However, the studies which found differences in litter timing were due to senescence of the invasive plants themselves, not other native plants in the same plots (Trammell et al., 2012; Weand, 2020; Woodworth et al., 2020). Additionally, the significant positive trend observed between ground cover and leaf litter depth (Table 2; Figure 11q) is likely the result of ground cover volume adding to the space between the top of the leaf litter layer to the soil. Different results may have been observed if direct measures of litter fall were used.

I did find that litter depth may be more variable in invaded plots (Figure 13q; Appendix III.3). If invasion reduces the predictability of litter quantity, an important step in nutrient cycling, it may alter nutrient pulses, soil shading dynamics, and other resource availability. These changes could ultimately result in further ecological disturbances and invasions (Davis et al., 2000; Hobbs & Huenneke, 1992). This variability could also be a factor driving *H. helix* invasion, and not the other way around. Ultimately, my results indicate that *H. helix* likely does not alter litter quantity or quality in Baltimore urban forest patches.

4.3 Soil Physical Ecology

4.3.1 Soil Temperature

My results confirmed my hypothesis that ground cover is associated with altered soil physical properties, but canopy invasions do not necessarily alter them. Ground cover invasions in plots had a strong, mediating influence on soil temperature. Temperature measurements were taken in autumn, so higher mean and low temperatures in invaded plots with ground cover suggest that *H. helix* ground cover effectively controls fluctuations (Table 2; Figures 11a,b,d), acting as a sort of mulch. This is a novel finding for *H. helix* impacts as an invasive which align with other findings in the literature. For example, Strelau et al. (2018) noted that *H. helix* is sometimes used to control temperature and increase humidity in homes as green walls. Regarding other invasive species, a review paper by Lone et al. (2019) found that invasive plants can alter soil physical properties, including temperature. Additionally, Jo et al. (2017) found that increased leaf production by invasive lianas and shrubs decreased soil temperature in the spring. Strickland et al. (2011) found that invasive grasses' alterations to soil temperature drive increasing respiration rates.

This impact of *H. helix* may have negative and positive results for urban forest patch health. Regulated soil temperatures allow for more microbial activity in the winter by keeping the soil warmer and in the summer by keeping the soil from drying (Qu et al., 2023; Strickland et al., 2011). If samples had been taken in the summer, I may have found that soil moisture was higher in invaded plots with ground cover. Microbial activities responsible for respiration, decomposition, N mineralization, and

nitrification rates increase with soil temperature within the mesophilic temperature range, which is 20-45 °C (Paul, 2015; Quemada & Cabrera, 1997). These rates also increase with soil moisture below certain water potentials (Paul, 2015), around -0.024 MPa for N mineralization and close to saturation for respiration (Quemada & Cabrera, 1997). A high soil respiration rate in invaded plots with ground cover (means: Control = 0.563, No Ground Cover = 1.087, Ground Cover = 1.612) (Appendix II.2), and a significant negative correlation between daily range in soil temperature and soil respiration rate (see below) (Figure 18a), confirm this relationship between soil temperature and soil biology, and consequently C cycling, in my plots.

4.3.2 Soil Structure & Water Movement

Invasive ground cover was also related to changes in soil structure and water movement. I found that unsaturated hydraulic conductivity was higher in ground cover plots and control plots than invaded plots without ground cover (Table 2; Figure 11h). This may be a driver of invasion growth characteristics, as low unsaturated hydraulic conductivity indicates a greater potential for soil saturation, and *H. helix* does not fare well in waterlogged soils (Metcalfe, 2005; Reichard, 2000; Thomas, 1980). Therefore, ground cover growth may not be well supported in plots with low unsaturated hydraulic conductivity (see below). The differences in unsaturated hydraulic conductivity and other soil physical properties between these groups may be due to either differences in abiotic features (i.e., slopes), legacies in the soil (i.e., past agricultural use or construction), or both. Higher unsaturated hydraulic conductivity in ground cover plots may also be caused or exacerbated by *H. helix*'s mat-like root growth in the shallow

soil (Strelau et al., 2018). This system might create more channels for water movement (Lone et al., 2019).

Dense, shallow root growth may also be the reason behind the higher variability of soil bulk density in ground cover plots than other plots (Figure 11f, Appendix III.1). Soil bulk density and unsaturated hydraulic conductivity were also more variable in all invaded plots than control plots (Figures 13f,h; Appendix III.3). These soil physical relationships are not explored in most studies on invasive plants but have been recognized as common effects by some meta-analyses, specifically altered soil temperature, hydraulic conductivity, and habitat (Ehrenfeld, 2003; Lone et al., 2019). It is possible that all invasions drive or are driven by these increased variabilities in soil physical properties. Lone et al. (2019) viewed invasion as the driver in this relationship, leading to a positive feedback loop inducing further invasion. This aligns with the theory that ecological disturbance favors further invasion (Davis et al., 2000; Hobbs & Huenneke, 1992). Additional consequences include altered resource availability and habitat for soil microbes, and the potential for increased leaching of nutrients (Ehrenfeld, 2003; Lone et al., 2019).

From a stormwater management perspective, ideal green spaces in urban environments such as Baltimore provide high enough hydraulic conductivity to mitigate storm flows. Rehabilitated urban soils in Milan, Italy had an average unsaturated hydraulic conductivity of $4.456e^{-4}$ cm/s (Galli et al., 2021) (this study also used Mini Disk Infiltrometers made by METER Group (Pullman, WA, USA)), which is substantially higher than the conductivities observed in my study (means: control =

$8.454e^{-5}$ cm/s, no ground cover = $1.330e^{-5}$ cm/s, ground cover = $8.359e^{-5}$ cm/s) (Figure 11h; Appendix II.2). Rehabilitated urban soils in Virginia, USA had an average bulk density of 1.49 g/cm^3 (Chen et al., 2014), which is substantially higher than the bulk densities observed in my study (overall mean: 0.841 g/cm^3) (Appendix II.1). These comparisons are interesting because soil bulk density and unsaturated hydraulic conductivity have a negative relationship, so having a relatively low bulk density and conductivity is uncommon; the variability across plots may play a role in this disparity. Ultimately, the comparisons indicate that Baltimore forest patch soils have low compaction, typically a good indicator for water absorption and retention, though they still may not be in the ideal range for stormwater infiltration. It appears *H. helix* ground cover is not exacerbating the problem of low conductivity.

4.4 Soil Chemical Ecology

4.4.1 Carbon & Nitrogen

My results confirmed that invasive ground cover has a significant impact on nutrient concentrations in the soil, though not in all the directions hypothesized, and without any significant impacts via invasion presence or canopy invasions. There are greater soil TC and TN concentrations in invaded plots with ground cover (Table 2; Figures 11i,j), but no difference in SOM or mineral N pool (Table 2). Higher concentrations of C and N in soil, and soil microbes, have been observed in many cases of plant invasion, either noted as a driver or result of invasion (Davidson et al., 2011; Ehrenfeld, 2003; Liao et al., 2008; Lone et al., 2019; Weand, 2020). There have also been cases of invasion with no change in soil TN, either due to increased N cycling rates balancing

out high N inputs (Ashton et al., 2005; Jo et al., 2017) or there simply being no effect (Hull et al., 2020). Similarly, some studies have suggested that high decomposition and respiration rates in cases of invasion lead to decreased TC and SOM (Peltzer et al., 2010; Pouyat et al., 2009; Trammell et al., 2012). In the case of *H. helix* ground invasions, high TC and TN may be due directly to the large quantity of roots in the soil (Jo et al., 2017; Reichard, 2000; Strelau et al., 2018), which brings more C and N directly into the soil environment. If there is truly a positive relationship between ground cover and leaf litter quantity (Table 2; Figure 11q), though it is likely that this was driven by ground cover volume (see above), then that may also be a driver of increased nutrient concentrations. High concentrations of nutrients in the soil increase microbial activity, especially of decomposers (Paul, 2015; Pereira & Ferreira, 2021; Torres et al., 2021). A high soil respiration in invaded plots with ground cover (Figure 15a; Appendix II.2), and a significant positive regression between TC and soil respiration rate (Figure 18d), and between TN and soil respiration rate (Figure 18e) (see below), confirm this relationship between nutrient concentrations, soil biology, and C cycling in my plots.

I had hypothesized that an increase in soil respiration and litter decay at invaded plots (Ashton et al., 2005; Patil et al., 2020; Peltzer et al., 2010; Trammell et al., 2012; Weand, 2020), especially those with ground cover, would result in a decrease in soil SOM and TC (Peltzer et al., 2010; Pouyat et al., 2009; Trammell et al., 2012). While ground cover plots indeed had higher rates of soil respiration and litter decay (Table 2; Figures 15a,b) (see below), rates must not have been significant enough to ultimately decrease these concentrations. There was no significant change in SOM (Table 2;

Figure 11l), and an increase in TC (Table 2; Figure 11i). Soil TN in plots with ground cover was higher as expected, though I had also hypothesized that the mineral N pool would be greater in invaded plots. Findings by other studies varied but most found that invasion increases the mineral N pool (Ehrenfeld, 2003; Liao et al., 2008). Some studies found that invasion decreases the mineral N pool through increased exports (i.e., Jo et al., 2017). Other studies considered NH_3-NH_4^+ and NO_2^--NO_3^- separately, most determining that invasion may increase NH_3-NH_4^+ concentrations and decrease NO_2^--NO_3^- concentrations (Ashton et al., 2005; Zhang et al., 2019). No studies on *H. helix* discussed changes in soil mineral N pool concentrations. My results indicate that *H. helix* does not shift mineral N pool concentrations in a specific direction in urban forest patches in Baltimore in the fall, which is not entirely unexpected due to the variability across other studies' findings. However, the mineral N pool was more variable across all invaded plots than control plots (Figure 13m; Appendix III.3). Soil TC was more variable as well (Figure 13i; Appendix III.3). Based on the theory of fluctuating resource availability and its influence on invasibility, variability of nutrient availability favors plant invasion by giving invasive plants a competitive growth advantage (Davis et al., 2000; Hobbs & Huenneke, 1992), it may be a result or driver of *H. helix* invasion. This likely also impacts the soil microbial community, specifically the rhizosphere decomposer community (Lone et al., 2019; van der Putten et al., 2007), leading to cascading impacts on nutrient cycling.

It is unclear from this study whether *H. helix* invasion is the driver of these soil nutrient relationships or a result of complex urban nutrient dynamics (Johnson, Johnson, et al., 2020; Trammell et al., 2021; Yesilonis et al., 2022), but it is likely to

exacerbate them. Within the context of urban pressures, an increase in soil nutrients may be helpful at mitigating excess nutrients in waterways if it is stored well in the soil (Paul, 2015). However, suggestions of increased nutrient processing rates (see below) may lead to greater exports, at least of C (Tables 2,4; Figures 15a,b & 17a). Increased nutrient leaching is a common finding across many studies of urban spaces (i.e., Boesch et al., 2001; Hobbie et al., 2017; Wollheim et al., 2005) and plant invasion (i.e., Jo et al., 2017; McEwan et al., 2012).

4.4.2 pH

While ground cover makes a more obvious and directional impact on soil chemistry, invasion presence and canopy invasion still seem to have some impacts on soil chemistry. My results suggest that pH is higher in all invaded plots (Table 4; Figure 13e) and may increase stepwise with canopy invasion intensity based on visual inspection of the boxplots (Table 3; Figure 12e). Ehrenfeld (2003)'s meta-analysis found that there are an equal number of cases where invasion increases and decreases pH. The increased pH discovered in my study may be a driver of invasion and not a result of it according to Ward et al. (2020), based on pH having a strong positive relationship with overall forest disturbance and evidence from other studies suggesting that soil pH and plant invasion have a positive relationship. Yesilonis et al. (2022) found a soil pH of 4.5 in Baltimore forests in 2018, noting that soils were continuing to become more basic over time (they found that soil pH was 4.1 in 2001). My results yield an average soil pH of 4.726 in control plots and 5.521 in invaded plots (Appendix II.4). The implications of more basic soils in the Baltimore region are complex but great. Increased pH has been shown to trend positively with both plant invasions

(Trammell et al., 2021) and N cycling (Szlavecz et al., 2006), but pH plays a role in all soil chemical processes by influencing solubility and ionization of chemical compounds (Paul, 2015). This ultimately impacts microbial activity in complex ways by controlling the availability of nutrients and activity of enzymes (Paul, 2015).

4.5 Overall Ecological Characteristics

Looking at the big picture, out of all the factors and groups, overall ecological characteristics only differed between invaded plots with and without ground cover (Tables 5 & 6; Figure 14). Ground cover altered soil temperature, unsaturated hydraulic conductivity, soil TC and TN, and litter depth (Table 2; Figures 11a,b,d,h,i,j,q). These ecological characteristics were not different across canopy invasion or invasion presence plots (Tables 3 & 4; Figures 12 & 13). This supports my hypotheses that characteristics of invasion are important controllers of the ecology of urban forest patch plots, and that ground cover by *H. helix* alters soil properties more than canopy invasions. This is a novel finding about *H. helix* invasions that was anticipated by past research for invasive plants in general. Ward et al. (2020) is one of the few studies which evaluated impacts of different characteristics of invasion, finding that invasive liana impacts correlate positively with intensity. Most meta-analyses and review papers, and several individual studies, on plant invasions suggest that invasion impacts vary by species and location (Ashton et al., 2005; Ehrenfeld, 2003, 2010; Jo et al., 2016; Liao et al., 2008; Patil et al., 2020; Tassin & Kull, 2015; Ward et al., 2020; Zhang et al., 2019). I can conclude this this extends to the individual cultivars and growth characteristics within species, and to scales even smaller than regional.

Despite plots being the sampling unit of this study (not urban forest patches), all the ground cover invaded plots are within JHU while all the no ground cover invaded plots are within FENDAL. FENDAL is flatter than JHU (Figures 3 & 5), and I noticed that its soil becomes waterlogged after rain events while doing fieldwork. This is supported by a 6.3 times lower unsaturated hydraulic conductivity at invaded plots in FENDAL compared to invaded plots at JHU (Table 2; Figure 11h; Appendix II.2). *H. helix* does not fare well in waterlogged soils (Metcalfe, 2005; Reichard, 2000; Thomas, 1980), and is phenologically plastic (Larocque, 1999; Strelau et al., 2018; Wolkovich & Cleland, 2011), so it likely adapted its growth to this patch's conditions, reaching adulthood earlier or mutating between cultivars to minimize soil interaction and focus on climbing trees. Drier slopes in JHU are more suitable for *H. helix* ground cover (Metcalfe, 2005). Even across similar ecosystems in one city, the characteristics and impacts of one invasive plant species vary. If this study controlled for individual urban forest patches, I may have seen further evidence of location-based impacts of *H. helix*. It is worth noting that these different urban forest patches with their complex dynamics (i.e., fragmentation structure, land use, soil legacies, and specific pollutants), aside from driving differences in *H. helix* growth, may also be confounders of some ecological characteristic and nutrient cycling metrics. For example, FENDAL is situated besides a golf course and JHU is on a university campus. FENDAL may receive more pollution from fertilizers applied to the course while JHU may receive more pollution from cars driving through the campus.

Invasions with ground cover may significantly impact the overall ecological characteristics of plots based on the metrics I measured due to their direct interaction

with the soil and undergrowth. Ground cover by *H. helix*, often as a juvenile, in deciduous forests can decrease herb, shrub, and small tree count and diversity by smothering plants and preventing germination (Biggerstaff & Beck, 2007; Larocque, 1999; Metcalfe, 2005; Reichard, 2000; Strelau et al., 2018; Thomas, 1980), resulting in what are sometimes referred to as "ivy deserts" (Reichard, 2000). Invasive lianas, such as *H. helix*, in general have greater fine root production than native plants (Jo et al., 2017). From my observations in the field, *H. helix* indeed creates "ivy deserts" on urban forest patch floors in Baltimore when it covers the ground (Figure 6c). This suppresses native undergrowth and may have cascading consequences for ecological characteristics. Fine root production by this thick ground cover can also stimulate microbial activity and nutrient cycling (Zhang et al., 2019), altering TC and TN contents of the soil (Table 2; Figures 11i,j). Fine roots also interact with soil structure (Lone et al., 2019; Strelau et al., 2018), potentially contributing to the differences and variability I observed in unsaturated hydraulic conductivity and bulk density (Figures 11f,h; Appendix III.1). Significant changes in soil temperature I observed are likely due to the mulching effect of *H. helix* ground cover's thick vegetation (Jo et al., 2017; Strelau et al., 2018). These overarching findings confirm the influence of growth characteristics on impacts of invasion by a single species and suggest that location-specific conditions drive these different characteristics, as well as suggest pathways by which these characteristics affect ecology.

4.6 Nutrient Cycling

My results confirmed an increase in C cycling rates with *H. helix* invasion, particularly when there is ground cover, but did not confirm an increase in N cycling rates. Some

differences in ecological characteristics in invaded plots may explain pathways to significant and suggestive alterations of nutrient cycles.

4.6.1 Soil Respiration Rate

Soil respiration rate was significantly higher across all invaded plots than control plots (Table 4; Figure 17a), especially in plots with ground cover present (Table 2; Figure 15a). Comparing my results to other studies, Groffman et al. (2006) observed an approximate soil respiration rate of 700 g $C/m^2/yr$ in Baltimore urban forests. Garvey et al. (2022) observed a soil respiration rate of about 3.4 μmol $CO_2/m^2/s$ in Boston urban forests during the same season my measurements were taken. My results, which only measured soil respiration in September, yielded average respiration rates of 0.563 μmol $CO_2/m^2/s$ (213.091 g $C/m^2/yr$) for control plots, 1.367 μmol $CO_2/m^2/s$ (517.664 g $C/m^2/yr$) for all invaded plots, and 1.612 μmol $CO_2/m^2/s$ (610.399 g $C/m^2/yr$) for invaded plots with ground cover (Figures 15a & 17a; Appendices II.2,4). These rates are substantially lower than the other studies. This may be due to my samples being a one-time, minute-long measurement, not necessarily during times of peak respiration rates, while the other studies took samples over longer periods. Despite that disparity, there is a clear positive trend between invasion presence, ground cover, and soil respiration rate. Findings from meta-analyses also show a typically positive, but highly variable, relationship between invasion and respiration rate. Ehrenfeld (2003) found four studies which discovered a positive relationship, two with a negative relationship, and two with a negligible relationship between invasion and soil respiration rate. Lone et al. (2019) had similar findings. Zhang et al. (2019) concluded that invasion incurs a

21.92% positive change in soil respiration rate via rhizosphere effects. They also found that invasion incurs a 27.30% positive change in enzyme activities (Zhang et al., 2019), an indicator of soil microbial activity (Lone et al., 2019). Peltzer et al. (2010) similarly concluded that invasive plants tend to increase all C cycling rates.

In my study, the reasons behind this positive relationship between soil respiration and invasion may be explained by ecological characteristics. As discussed above, soil temperature plays a role in microbial activity, with higher temperatures within the mesophilic range increasing respiration rate (Paul, 2015; Quemada & Cabrera, 1997). While this is likely to be a direct pathway by which plots with ground cover increase soil respiration rate, my results indicated that a reduced daily temperature range had a greater control on respiration than increased temperature itself (Figure 18a). There may have been a stronger relationship between high soil temperatures and respiration rate if respiration rate had been measured over a longer period or during the summer, a more active time of year. The negative relationship between daily soil temperature range and soil respiration demonstrates a higher microbial activity and carbon loss under conditions with mitigated temperature fluxes (Figure 18a). A relationship between temperature swings and microbial activity or respiration is not discussed in the literature.

Soil respiration also has a negative relationship with soil bulk density (Figure 18b) and a positive relationship with gravimetric water content (Figure 18c). Soil bulk density controls soil porosity, water availability and capacity, nutrient availability, rooting restrictions, and microbial activity (Paul, 2015). Optimal soil bulk density for

microbial activity and respiration depends on many other factors, especially moisture content in the soil because respirating aerobic microbes require a balance of air and moisture (Paul, 2015). In unsaturated soils, as my samples were when collected, higher moisture content and lower soil bulk density allow for access to moisture without facilitating anaerobic processes, increasing respiration rate (Paul, 2015). Soil bulk density varied greatly across plots and did not differ significantly between plots with and without ground cover, though some plots with ground cover had particularly low bulk densities (i.e., 0.342 g/cm^3, 0.544 g/cm^3) (Figure 11f) while having comparable gravimetric water contents to other plots (i.e., 0.252 g/g, 0.182 g/g, respectively) (Figure 11g). With regards to soil chemistry, soil respiration rates regressed significantly and positively with soil TC, soil TN, and the mineral N pool (Figures 18d,e,f). High concentrations of nutrients in the soil increases microbial activity and therefore soil respiration, especially when there are high concentrations of available nutrients such as mineral N (Paul, 2015; Pereira & Ferreira, 2021; Torres et al., 2021).

It appears that increases in soil respiration rates in this experiment were driven by control of soil temperature, decreased soil bulk density, increased soil moisture, and increased nutrient availability. These changes to soil temperature and nutrient availability were observed to be made by *H. helix* in plots with ground cover. Another factor that potentially impacts soil respiration rate, but lies outside the findings of the regressions, is soil pH. Soil pH may explain variability in soil respiration rate, and acidic soils tend to have lower respiration rates than more neutral soils (Sitaula et al., 1995). Soil pH was around or below neutral for all plots (min = 3.910, max = 7.720, average = 5.322) (Appendix II.1), and was suggestively higher in invaded plots (df =

1, p = 0.090) (Table 4; Figure 13e). Soil respiration rate was significantly higher in invaded plots (df = 1, p = 0.021) (Table 4; Figure 17a). While respiration rate differences may be driven by other ecological differences in plots with ground cover, and the regression between pH and respiration rate was insignificant, pH may play some role in higher respiration rates based on the literature. Ultimately, increased soil respiration rates indicate both a more active microbial community and a reduction in potential of invaded Baltimore forest patch soils to sequester C and mitigate climate change.

4.6.2 Herbaceous Litter Decay Rate

Herbaceous litter decay rate was suggestively higher in invaded plots with ground cover present (Table 2; Figure 15b). There are many cases in other studies where litter decomposition rates increased with invasion (Ashton et al., 2005; Bush et al., 2020; Hickman et al., 2013; Jo et al., 2017; Rodgers et al., 2008; Trammell et al., 2012; Ulyshen et al., 2020; Weand, 2020; Woodworth et al., 2020). There are also some studies which did not find a connection between invasion and litter decomposition (Bush et al., 2020; Hickman et al., 2013; Jo et al., 2016; Ward et al., 2020). Of the studies which determined a relationship between invasion and decomposition, almost all impacts were attributed directly to leaf litter quality, quantity, and senescence timing of invasive plants themselves (Ashton et al., 2005; Bush et al., 2020; Hickman et al., 2013; Jo et al., 2017; Rodgers et al., 2008; Trammell et al., 2012; Weand, 2020; Woodworth et al., 2020). This is an unlikely pathway in the case of *H. helix* invasion in Baltimore due to it being an evergreen in this region (Lenaghan et al., 2013; Metcalfe, 2005; Strelau et al., 2018; Thomas, 1980). Ulyshen et al. (2020) found that

decay rates were extremely dependent on species and location, and that of the invasive plants which increased decay rates, their litter traits were not a clear driver of the relationship. They asserted that complex relationships with other aspects of the ecosystem, including decomposer communities and soil properties, were likely to play a major role in decay rates (Ulyshen et al., 2020).

Findings from meta-analyses and review papers also show a typically positive, but highly variable, relationship between invasion and litter decomposition rates. Ehrenfeld (2003) noted that the influence of invasive plants on decomposition varied greatly across studies but found that 10 of 14 studies determined a positive relationship between invasion and litter decomposition rates. These cases were associated with invasive litter quantity and quality. Liao et al. (2008) found an 117% increase in litter decomposition rates in the face of plant invasion, also attributing it to invasive litter quantity and quality. Lone et al. (2019) made similar claims about the impact of invasive plants on litter decomposition but discussed other possible pathways beyond invasive litter traits. Specifically, they claimed that invasive plants may indirectly impact litter decomposition through other alterations to an ecosystem. They elaborate that high soil pH, which has been observed to correlate with invasion (Lone et al., 2019; Trammell et al., 2021; Ward et al., 2020), increases litter decomposition rates (Lone et al., 2019). They also explain that invasive plants can impact the soil microbial community and enzyme activity, as well as the soil fauna and invertebrate communities, which all play a role in facilitating decomposition (Lone et al., 2019).

Regarding my study, the reasons behind the positive relationship between ground cover invasion and litter decomposition may be explained by some of these ecological characteristic alterations, as well as others not mentioned in the literature. Like respiration rates, litter decay was influenced by soil temperature, regressing positively with daily low soil temperature and negatively with daily temperature range (Figures 19a,b). Tea bags for this experiment were buried 6.35 cm into the soil, so the temperature conditions facilitated decomposer activity. As discussed above, soil temperature plays a role in microbial and decomposer activity, with higher temperatures within the mesophilic range increasing respiration and decomposition rates (Paul, 2015; Quemada & Cabrera, 1997). The relationship between mean daily low temperature and litter decay is significant, while the relationship between mean daily low temperature and respiration rate is not. This is likely due to the length of time the litter bag samples were buried. Tea bag burial overlapped with soil temperature probe samples for over a month. Litter decay rates were also influenced by soil physical components, like respiration rates. The pathways of this influence are likely similar to that of respiration, in that soil bulk density (Figure 19c) and water accessibility facilitate microbial activity responsible for decomposition. In this case, unsaturated hydraulic conductivity trended positively with decay rates and not gravimetric water content (Figure 19d). This is a measure of how quickly water moves through the soil and is also an important factor in creating conditions optimal or suboptimal for microbial and decomposer activity (Paul, 2015).

Like soil respiration, litter decay rates were driven by nutrient concentrations and availability. They trended positively with mineral N pool, as this available N feeds

microbes and increases their activity (Paul, 2015; Pereira & Ferreira, 2021; Torres et al., 2021). Total soil nutrient content did not play a role in litter decay, but litter quantity and nutrient concentrations did. High litter TC and TN concentrations trended positively with decay rates (Figures 19h,i). N concentrations in litter were a greater limiting factor for decomposition rates (Litter TC: $R^2 = 0.273$; Litter TN: $R^2 = 0.471$). This was confirmed by the negative relationship between litter C:N and decay rate (Figure 19j). Litter depth trended positively with decay rates (Figure 19g). Percent canopy openness trended negatively with decay rate (Figure 19f). Because I was confused by this relationship, I ran linear regressions between canopy openness, litter quantity, soil temperature, and soil moisture. I found that canopy openness likely influences herbaceous litter decay rate through altering litter quantity (negative relationship between canopy openness and litter depth; $p = 0.0457$; $R^2 = 0.203$) and controlling soil temperature fluxes (positive relationship between canopy openness and daily soil temperature range; $p = 0.025$; $R^2 = 0.249$).

All literature concerning rates of litter decomposition and invasion emphasize the crucial role that high litter TN, low C:N, and high litter quantity play in increasing rates (Ashton et al., 2005; Bush et al., 2020; Ehrenfeld, 2003; Hickman et al., 2013; Jo et al., 2017; Liao et al., 2008; Paul, 2015; Rodgers et al., 2008; Trammell et al., 2012; Weand, 2020; Woodworth et al., 2020). However, *H. helix* invasion did not drive litter quality (Tables 2, 3, & 4), and likely did not drive litter quantity (see above). These contributors likely acted independently from presence or structure of invasion by *H. helix* and may have coincided with some invaded plots with ground cover. An increased litter decay rate quickens turnover of leaf nutrients into the soil and into other forms

more easily available to plants and microbes (Ashton et al., 2005; Jo et al., 2016, 2017; Patil et al., 2020). Given that higher concentrations of soil TN and TC were observed in the plots with invasive ground cover (Table 2; Figures 11i,j), these are likely consequences. This may result in increased plant growth, which is advantageous to most invasive plants (Davidson et al., 2011; Enloe et al., 2015; Reich et al., 1997), including *H. helix* (Larocque, 1999; Putz, 1991; Strelau et al., 2018). It may also result in increased nutrient exports (Enloe et al., 2015; Pavao-Zuckerman & Coleman, 2005; Wollheim et al., 2005).

Synthesizing these C cycling findings, in plots where *H. helix* covered the ground, it was associated with increased soil C cycling rates (respiration and herbaceous litter decay). This ground cover was associated with increased soil TC and TN concentrations. Increased soil nutrient contents allow for increased microbial activity, including decomposition and respiration. Additionally, ground cover appears to act as a mulch, maintaining optimal soil conditions for the microbial community, contributing further to increased activity. Other soil physical conditions may play a role in increased C cycling rates. Low soil bulk density and high water availability, which were associated with ground cover invasions, also provide preferable conditions for microbial respiration. Litter quality influences decay rates significantly, but this did not vary significantly across plots. Ultimately, ground cover by *H. helix* is associated with increased soil respiration rates and may be associated with increased herbaceous fine litter decay rates. Together, these decrease the potential for C sequestration as organic C is released to the microbial community at an increased rate and also used for and released through respiration at an increased rate.

4.6.3 Nitrogen Cycling

Unexpectedly, there were no significant differences across plots for mineral N pool, nitrification rate, or N mineralization rate (Tables 2, 3, & 4). However, my results suggest that invasion presence increases the variability of mineral N and nitrification rates (Figures 13m & 17e; Appendix III.3), and thus the variability of urban forest patch ecology under invasion. Based on the theory of fluctuating resource availability and its influence on invasibility, variability of nutrient cycling and availability favors plant invasion by giving invasive plants a competitive growth advantage (Davis et al., 2000; Hobbs & Huenneke, 1992). N cycling variability may be a result or driver of *H. helix* invasion. If *H. helix* is the driver, this may be due to the complex alterations invasive plants make on soil chemistry and the microbial community, which depend greatly on other site factors (Lone et al., 2019). Otherwise, the novel and complex nutrient dynamics and pulsing induced by urban environments may drive this variability (Johnson, Trammell, et al., 2020; Pouyat et al., 2009; Trammell et al., 2021; Yesilonis et al., 2022) and encourage *H. helix* invasion. Variability is also likely to further affect the soil microbial community, specifically the rhizosphere decomposer community (Lone et al., 2019; van der Putten et al., 2007), leading to cascading impacts on other aspects of nutrient cycling.

Invasive plants' impacts on N mineralization and nitrification are mixed in the literature. Some studies found N mineralization rates to be higher under invasion (Hawkes et al., 2005; Jo et al., 2017; Ward et al., 2020), some found it to be lower (Hull et al., 2020) or the difference to be negligent (Weand, 2020). Some found nitrification rates to be higher under invasion (Hawkes et al., 2005; Jo et al., 2017; Ward et al.,

2020), none found it to be lower, but one found the difference to be negligent (Weand, 2020). One individual study noted the astonishing variability in N cycling rates across species and location (Ward et al., 2020), while several meta-analyses made similar remarks (Ehrenfeld, 2003; Liao et al., 2008; Zhang et al., 2019). Despite these notes of variability, meta-analyses and review papers concluded that most invasive plants increase nitrification and mineralization rates (Ehrenfeld, 2003; Liao et al., 2008; Lone et al., 2019; Zhang et al., 2019). Given the wide range of impacts of different species in different locations, though, it is not surprising that my hypothesis of *H. helix* increasing N mineralization and nitrification rates was not supported by my results.

Thus, no claims about the effect of *H. helix* on N cycling can be made from this study based on the conducted analyses as there were no significant findings. However, visual inspection of the boxplots indicates that nitrification may increase with the presence of invasion and ground cover (Figures 15e & 17e), while N mineralization rate may not change much (Figures 15d & 17e). This may suggest that a disproportionally high level of NH_4^+ is already in the soil, which may be a feature of some urban environments (Enloe et al., 2015; Reche et al., 2022), so the nitrification process is occurring while the other N mineralization processes do not change significantly over time. Invasion can lead to dramatic and complex changes in microbial abundance and diversity, dependent on species and location (Hawkes et al., 2005; Lone et al., 2019; Torres et al., 2021; van der Putten et al., 2007). These complex alterations may explain the variability found across plots and the different responses of N mineralization and nitrification to invasion.

Synthesizing these N cycling findings, increased soil nutrient contents, along with other features described above, can allow for increased microbial activity, including N mineralization and nitrification. However, this is only the case when N is available to the microbial community as mineral N. The mineral N pool was not significantly different across plots. This may indicate that the higher soil TN in invaded plots with ground cover is organic N. This could mean invaded plots with ground cover have higher N retention, a beneficial ecosystem service for urban environments. However, this may not be a uniform result of invasion as there was high variability in mineral N pool concentrations and nitrification rates in invaded plots with ground cover. Ultimately, *H. helix* ground cover is associated with increased TN and increased variability in mineral N pool concentrations and nitrification rates. There are no clear or significant relationships between *H. helix* and N cycling rates, though my findings indicate the need for further evaluation given the increased variability and a hint that ground cover may be associated with increased nitrification rates. If nitrification rates are indeed higher when *H. helix* ground cover is present, N leaching would be higher in these plots as well.

4.7 Recommendations for Management

With regards to observed impacts of *H. helix* from this study, whether they are an issue for the ecology of Baltimore's urban forest patches and their provisioning of their ecosystem services boils down to cascading effects. That is to say, the cascading effects between *H. helix* canopy invasion and tree health and canopy cover, and the cascading effects between *H. helix* ground cover and soil physical, chemical, and biological properties. Some of the most valuable ecosystem services of concern are cycling and

retention of water and nutrients, urban heat island effect mitigation, and accessibility of green spaces. It may be prudent to further investigate these cascading effects on ecosystem services before pursuing management actions. For example, with regards to *H. helix* ground cover, this would involve further monitoring of microbial activity and nutrient cycling in invaded plots to determine if ground cover is worth managing from this perspective. Soil structure and water availability and its influence on support, or lack of support, for native plants, invasive plants, and the microbial community, similarly requires further monitoring efforts. Though increased soil respiration and soil nutrient content is certain in invaded plots with ground cover, whether it is an issue depends on its ultimate influence on plant growth, nutrient leaching, and goals for urban forest patch C sequestration. Plots with high nutrient content should be surveyed over time to determine what plants are best supported, and if invasive species have an advantage. Pathways for nutrient exports must be monitored as well, such as stormwater flow paths leading to water bodies and those nearby water bodies themselves.

Given that specific characteristics of invasion seem to have a greater influence on ecological characteristics in an urban forest patch plot than invasion itself, I also recommend that managers and researchers should make note of more complex details of invasion when outlining forest patch pressures to start building a more robust understanding of *H. helix* impacts. This should include identifying the age and cultivars of *H. helix* and tracking if there are certain cultivars which prefer to grow as ground cover, up trees, or in certain landforms.

If these monitoring efforts are beyond the resources available to managers, it is often recommended to refer to the natural state of forests when determining management goals for them. This school of thought begs for the removal of *H. helix* due to it being non-native. Though it is ecologically valuable to consider if *H. helix* is acting the same way as native plants are or once were, or filling a necessary niche a native plant is now unable to fill under new urban and climatic conditions (Sax et al., 2022; Wallingford et al., 2020). There are native lianas in Baltimore, such as Virginia creeper. However, this liana is less harmful to trees and is deciduous, not growing year-round. Thinking specifically about ground cover, according to *History of Maryland* by Matthew Andrews, the historically natural undergrowth in forests preceding urbanization was relatively sparse (MDNR, n.d.). Thus, it appears that *H. helix* is not filling a niche that was historically filled in these forests and may therefore be considered unfavorable, warranting removal and management.

Protection of trees from being damaged by *H. helix* should be a priority. Protecting trees from dying and falling will prevent further invasion and retain the large quantities of nutrients stored in them over a long period of time. Trees which are intensely invaded should be monitored for severe stress and damaged. In cases with stringent resource availability for managers, simply cutting stems of *H. helix* around the base of invaded trees may help to preserve their wellbeing (Putz, 1991; Strelau et al., 2018), though there is some contending horticultural research which advises against this on the basis that *H. helix* is not destructive to host trees (Larocque, 1999; Strelau et al., 2018). Planting native tree saplings and protecting them from invasion by either continued *H. helix* removal or chemical control around them is also a necessary step in

initiating a healthy midstory, which provides a more diverse habitat and will eventually replace older trees. The three most common native trees in the FENDAL plots (in descending order) are White Oak, Red Maple, and Northern Red Oak. The three most common native trees in the JHU plots (in descending order) are White Oak, Tulip Tree, and American Beech.

The most impactful form of *H. helix* invasion based on this study is with ground cover present. Therefore, efforts may be best assigned to clearing *H. helix* on the ground and replanting with aggressive native species that can compete with future ground cover by *H. helix* or other invasive plants. *H. helix* tends to cover the ground more as a juvenile than as an adult (Larocque, 1999; Strelau et al., 2018), so this step may be even more crucial for controlling invasion down the road. Ground cover control should be conducted in the summer when growth rates in native plants are high, and native plant replacements must effectively uptake nutrients and compete with ivy. Native ground cover plant (vines and shrubs) in my plots include Green Briar, Lowbush Blueberry, and Mapleleaf Viburnum (M. Baker, personal communication, 2021). If manual removal is being used, removing as much of the roots as possible is necessary to prevent propagation and regrowth (Strelau et al., 2018). An important consideration is that *H. helix* ground cover is not associated with decreased unsaturated hydraulic conductivity. If stormwater retention is a key management goal, removal of *H. helix* ground cover may not aid in this. After any management projects, managed plots should be comparatively analyzed with plots still facing invasion to determine effectiveness of the method.

Considering the overall picture, it is my belief that *H. helix* negatively impacts the health and ecosystem services of Baltimore forest patches. It competes with and may harm native plants, potentially lowering biodiversity and decreasing ecosystem resilience to perturbations. It may encourage the success of other invasive plants as well. It grows in naturally unfilled niches, seemingly altering the ecology of forest floors, soils, and canopies. *H. helix* is extremely pervasive and impossible to fully remove from the region. Thus, it must be managed in the most exigent situations as resources permit. However, we must also gain an understanding of how it may play a beneficial role in forest patch health and the provisioning of ecosystem services, as it is here to stay.

4.8 Future Studies

In future studies exploring impacts of other invasive species or *H. helix* in other environments, I would make, or suggest others to make, several amendments. The scope and resources available for this project resulted in a sample size that was likely too small given the variability observed in invaded sites. Because I found differences between canopy and ground invasions by *H. helix*, future studies should measure changes in metrics over different seasons to capture phenological differences. Moreover, repeated *in situ* analyses of mineral N content and movement in the soil alongside soil samples for TN should be conducted in all seasons as these cycles are greatly influenced by climate and seasonal variability. These analyses should also be paired with samples of stormwater and nearby waterbody mineral N contents, as well as measurements of change in soil mineral N content after rain events, to determine if invasion impacts nutrient exports.

Another gap in this study is that not all invasion characteristics were controlled for uniformly. For example, canopy invasion plots were separated into five groups based on invasion intensity and were spread across multiple forest patches. Ground cover plots on the other hand were not further characterized (i.e., by patchiness or intensity, by existence of other ground cover plants), had groups with different sample quantities, and each group fell under just one forest patch (except for the control group). Given that more significant results were found for the presence or absence of ground cover, a follow-up study might control for different features and combinations of these invasions. For example, studies could explore variability in ground cover, sites with combinations of ground and canopy invasion, or site selection that accounts for different *H. helix* cultivars or that account for variation in *H. helix* age.

This study was conducted across three different forest patches under the assumption that they were all the same and that only plots differ with invasion presence, canopy invasion intensity, or presence of ground cover. It may be prudent to conduct a study with all factors represented within one forest patch. Complex pressures are likely to make forest patches differ. A repeat study across several forest patches where each is considered separately may be more robust. It is difficult, however, to find patches with enough plot diversity to provide a large enough sample size for each factor.

Additional metrics may better capture invasion impacts on nutrient cycling through leaf litter and canopy effects. For example, capturing litterfall with baskets and measuring leaf quantity by weight and volume instead of measuring the depth after natural litterfall, as ground cover volume may have skewed results. In place of a

standard substrate (tea bags), litter collected from each plot could be used for decomposition analysis. This makes it more difficult to compare across plots given that litter contents will be different. However, given that both litter and microbial communities at each plot are unique and influence one another, this analysis would be more representational of actual decomposition rates per plot. With either analysis, samples should be taken in other seasons of the year as well. There should also be better litter bag sample retention by either using cages to prevent animals from disturbing the samples or tougher bags.

Finally, I recommend that studies should also be paired with plots following management practices. This study and similar ones can increase knowledge on the traits and impacts of plant invasion, informing managers of their exigence and necessity for control. However, there is a possibility that although *H. helix* and other invasive plants negatively affect ecosystem health, their removal may present unforeseen cascading negative effects. Additionally, different management methods may yield different results ecologically.

4.9 Conclusion

My study demonstrates that characteristics of *H. helix* invasion are essential to understanding its potential impacts on Baltimore forest patch ecology. Characteristics were greatly controlled by location-specific environmental factors which drove *H. helix* to assume different phenological traits. My observations indicated that soil properties such as hydrology play a major role in this. Other complex factors may contribute to their diverse success in different locations.

I found that *H. helix* ground cover is associated with dampened soil temperature fluxes, greater water movement, and higher soil TC and TN concentrations. Ground cover was also associated with altered C cycling rates, such as increased soil respiration and fine litter decomposition. Little can be claimed about alterations to N cycling from my study. Ground cover by *H. helix* may be associated with more variable mineral N pool concentrations and nitrification rates.

Canopy invasions were associated with tree large canopy gaps. This appeared to be caused by *H. helix* straining and killing trees. There may be severe cascading impacts of tree loss in the future, though my results demonstrated that the impact is negligible at this stage.

Invasion presence was associated with increased soil pH. This alters the lability of nutrients and may impact microbial communities and nutrient cycling in complex ways. Invasion was associated with marked increases in the variability of many factors. This may encourage further invasion and make it more difficult to understand and track the impacts of *H. helix* on urban forest patches in Baltimore, complicating management goals.

My study lays groundwork and goals for future research and management of urban forests with regards to *H. helix* and other invasive plants. My findings reveal a strong differential in the impacts of *H. helix* in different locations. They indicate the necessity for further exploration of species-specific, location-specific research on invasive plants. This extends to specific cultivars of invasive plants and location on a scale even smaller than regional because there were great differences in the

characteristics and impacts of invasion even across forest patches within Baltimore. My study also sets a difficult path for management with a lot of uncertainty. Removal of *H. helix* ground cover with replacement by competitive native plants may be the first step in amending impacts on soil properties and nutrient cycling. Protection of trees from canopy invasions may also be crucial to ensuring the long-term health of these forest patches. Invasions and the results of invasion management must be monitored closely to determine the best courses of action. Whether or not *H. helix* is a problem depends on how it affects the ecosystem services provided by these forest patches, such as biodiversity, stormwater management, nutrient cycling and retention, and greenspace accessibility for residents.

Appendices

Appendix I. Gap Light Analyzer Parameters

A table of the parameters which were input into the GLA program (Frazer et al., 1999) to analyze the hemispherical canopy photos taken for percent canopy openness and LAI_e. All unspecified parameters were left unchanged, using standards provided by the program. The "Color Plane" and "Threshold" did not impact image processing because the photos had been binarized prior to being uploaded to GLA.

Initial Cursor Point	North; Geographic North
Projection Distortion	Lambert's Equal Area
Orientation	Horizontal
Location (Coordinates and Elevation)	Site Dependent
Growing Season	April 15th – October 30th
Solar Constant	$1367 \frac{\frac{M}{m^2}}{d}$
Average Global Horizontal Irradiance (H) from August 15th-September 15th 2019-2021 from 7 am-6 pm, measured in one hr time steps (National Renewable Energy Laboratory, 2022)	$401.957 \frac{W}{m^2}$
Average Clearsky Global Horizontal Irradiance (H) from August 15th-September 15th 2019-2021 from 7 am-6 pm, measured in one hr time steps (National Renewable Energy Laboratory, 2022)	$539.916 \frac{W}{m^2}$
Cloudiness Index (K_t)	0.744
Spectral Fraction $\left(\frac{R_p}{R_s}\right)$	0.413
Beam Fraction $\left(\frac{H_b}{H}\right)$	0.773
Color Plane	Blue
Threshold	128

Appendix II. Data Summaries

II.1 All Plots

A table of each variable measured, summarized across all plots. The unit, number of samples (n), mean, range, standard deviation (SD), and variance (VAR) is shared for each variable.

Variable	Unit	n	Mean	Range	SD	VAR
Daily Mean Soil Temperature	°C	20	14.176	2.799	0.713	0.509
Daily Low Soil Temperature	°C	20	13.203	3.190	0.835	0.696
Daily High Soil Temperature	°C	20	15.218	2.952	0.731	0.534
Daily Range Soil Temperature	°C	20	2.015	2.524	0.684	0.468
pH	pH	20	5.322	3.810	0.909	0.826
Soil Bulk Density	g/cm^3	20	0.841	0.719	0.182	0.033
Gravimetric Water Content	g water/g soil	20	0.199	0.106	0.029	8.568E-04
Unsaturated Hydraulic Conductivity	cm/s	20	5.923E-05	2.391E-04	7.326E-05	5.366E-09
Soil TC	%	20	4.162	5.734	1.619	2.622
Soil TN	%	20	0.246	0.288	0.088	7.738E-03
Soil C:N	C:N	20	17.759	15.122	4.950	24.504
Soil Organic Matter	%	20	8.615	7.300	2.423	5.873
Mineral N Pool	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil	20	9.967	18.457	4.630	21.441
Percent Canopy Openness	%	20	2.707	3.830	1.216	1.478
Effective LAI	Index	20	4.747	3.340	0.908	0.825
Canopy Gap Number	#	20	3791.800	3567.000	926.050	857568.695
Litter Depth	cm/s	20	6.652	8.255	2.334	5.449
Litter TC	%	20	45.783	13.892	3.135	9.825
Litter TN	%	20	0.977	0.660	0.162	0.026
Litter C:N	C:N	20	47.724	25.682	5.947	35.364
Soil Respiration Rate	µmol CO_2 /m^2 soil/s	20	1.166	3.492	0.798	0.637
Herbaceous Litter Decay Rate	k coefficient	18	2.172E-03	4.518E-03	1.427E-03	2.037E-06
Woody Litter Decay Rate	k coefficient	19	1.269E-03	2.633E-03	7.127E-04	5.079E-07
N Mineralization Rate	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil/d	20	1.341	2.589	0.711	0.506
Nitrification Rate	mg NO_2^--NO_3^- /kg soil/d	20	0.189	1.535	0.361	0.131

A table of each variable measured, summarized across groups under the presence of ground cover factor. The unit, number of samples (n), mean, range, standard deviation (SD), and variance (VAR) is shared for each variable.

Variable	Unit	Control					No Invasive Ground Cover				
		n	Mean	Range	SD	VAR	n	Mean	Range	SD	VAR
Daily Mean Soil Temperature	°C	5	13.982	0.821	0.318	0.101	7	13.705	1.631	0.621	0.385
Daily Low Soil Temperature	°C	5	12.817	1.476	0.556	0.309	7	12.654	1.893	0.624	0.390
Daily High Soil Temperature	°C	5	15.264	1.095	0.438	0.192	7	14.846	2.393	0.775	0.600
Daily Range Soil Temperature	°C	5	2.448	1.750	0.812	0.659	7	2.192	1.821	0.579	0.335
pH	pH	5	4.726	1.730	0.828	0.685	7	5.601	3.310	1.046	1.094
Soil Bulk Density	g/cm^3	5	0.913	0.285	0.121	0.015	7	0.898	0.278	0.109	0.012
Gravimetric Water Content	g water/g soil	5	0.189	0.060	0.026	7.022E-04	7	0.204	0.105	0.035	1.254E-03
Unsaturated Hydraulic Conductivity	cm/s	5	8.454E-05	2.021E-04	8.201E-05	6.726E-09	7	1.330E-05	4.425E-05	1.473E-05	2.170E-10
Soil TC	%	5	3.447	1.848	0.704	0.495	7	3.537	4.349	1.550	2.402
Soil TN	%	5	0.190	0.221	0.083	6.886E-03	7	0.215	0.248	0.087	7.484E-03
Soil C:N	C:N	5	19.892	12.730	4.994	24.937	7	17.605	14.305	6.136	37.655
Soil Organic Matter	%	5	8.980	6.800	2.937	8.627	7	7.214	4.600	1.736	3.015
Mineral N Pool	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil	5	9.436	7.991	3.174	10.075	7	7.876	1.977	0.727	0.529
Percent Canopy Openness	%	5	2.544	2.720	1.292	1.668	7	3.239	3.570	1.410	1.987
Effective LAI	Index	5	4.938	2.920	1.241	1.539	7	4.237	2.310	0.767	0.588
Canopy Gap Number	#	5	3684.600	2416.000	1035.683	1072639.300	7	3608.429	2418.000	791.546	626544.619
Litter Depth	cm/s	5	6.223	2.540	1.136	1.290	7	4.763	3.175	0.970	0.941
Litter TC	%	5	45.924	7.068	2.891	8.356	7	44.854	12.297	4.287	18.380
Litter TN	%	5	1.027	0.545	0.217	0.047	7	0.898	0.356	0.141	0.020
Litter C:N	C:N	5	45.881	17.995	6.929	48.017	7	50.584	15.866	6.157	37.912
Soil Respiration Rate	µmol CO_2 /m^2 soil/s	5	0.563	0.765	0.335	0.112	7	1.087	0.803	0.350	0.123
Herbaceous Litter Decay Rate	k coefficient	5	2.443E-03	3.651E-03	1.823E-03	3.324E-06	5	9.244E-04	2.562E-03	1.142E-03	1.305E-06
Woody Litter Decay Rate	k coefficient	5	1.578E-03	1.991E-03	7.719E-04	5.958E-07	5	8.983E-04	1.846E-03	7.046E-04	4.964E-07
N Mineralization Rate	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil/d	5	1.349	2.589	0.966	0.933	7	1.256	2.020	0.842	0.708
Nitrification Rate	mg NO_2^--NO_3^- /kg soil/d	5	-0.025	0.328	0.129	0.017	7	0.155	0.563	0.218	0.048

Variable	Unit	Invasive Ground Cover				
		n	Mean	Range	SD	VAR
Daily Mean Soil Temperature	°C	8	14.710	1.725	0.647	0.418
Daily Low Soil Temperature	°C	8	13.924	1.869	0.614	0.377
Daily High Soil Temperature	°C	8	15.515	2.143	0.765	0.585
Daily Range Soil Temperature	°C	8	1.591	1.548	0.486	0.236
pH	pH	8	5.450	1.940	0.749	0.562
Soil Bulk Density	g/cm^3	8	0.746	0.714	0.232	0.054
Gravimetric Water Content	g water/g soil	8	0.201	0.083	0.027	7.501E-04
Unsaturated Hydraulic Conductivity	cm/s	8	8.359E-05	2.312E-04	8.538E-05	7.290E-09
Soil TC	%	8	5.155	5.054	1.700	2.890
Soil TN	%	8	0.308	0.166	0.055	3.075E-03
Soil C:N	C:N	8	16.562	12.129	3.883	15.075
Soil Organic Matter	%	8	9.613	6.800	2.288	5.233
Mineral N Pool	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil	8	12.129	17.941	6.486	42.066
Percent Canopy Openness	%	8	2.343	3.030	0.950	0.902
Effective LAI	Index	8	5.074	1.920	0.669	0.448
Canopy Gap Number	#	8	4019.250	2818.000	1037.668	1076753.929
Litter Depth	cm/s	8	8.573	6.033	2.308	5.328
Litter TC	%	8	46.507	5.082	2.160	4.665
Litter TN	%	8	1.016	0.415	0.133	0.018
Litter C:N	C:N	8	46.374	13.477	4.834	23.368
Soil Respiration Rate	µmol CO_2 /m^2 soil/s	8	1.612	3.097	1.033	1.068
Herbaceous Litter Decay Rate	k coefficient	8	2.783E-03	2.386E-03	8.438E-04	7.121E-07
Woody Litter Decay Rate	k coefficient	8	1.355E-03	2.154E-03	6.454E-04	4.165E-07
N Mineralization Rate	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil/d	8	1.410	1.589	0.470	0.221
Nitrification Rate	mg NO_2^--NO_3^- /kg soil/d	8	0.353	1.350	0.489	0.239

A table of each variable measured, summarized across groups under the *H. helix* canopy invasion intensity factor in urban forest patch plots in Baltimore City, MD. The unit, number of samples (n), mean, range, standard deviation (SD), and variance (VAR) is shared for each variable.

Variable	Unit	Control					Low Intensity Canopy Invasion				
		n	Mean	Range	SD	VAR	n	Mean	Range	SD	VAR
Daily Mean Soil Temperature	℃	5	13.982	0.821	0.318	0.101	5	14.599	1.589	0.651	0.424
Daily Low Soil Temperature	℃	5	12.817	1.476	0.556	0.309	5	13.755	1.179	0.487	0.237
Daily High Soil Temperature	℃	5	15.264	1.095	0.438	0.192	5	15.486	2.143	0.899	0.809
Daily Range Soil Temperature	℃	5	2.448	1.750	0.812	0.659	5	1.731	1.548	0.572	0.327
pH	pH	5	4.726	1.730	0.828	0.685	5	4.860	1.830	0.755	0.570
Soil Bulk Density	g/cm^3	5	0.913	0.285	0.121	0.015	5	0.665	0.637	0.243	0.059
Gravimetric Water Content	g water/g soil	5	0.189	0.060	0.026	7.022E-04	5	0.195	0.083	0.033	1.086E-03
Unsaturated Hydraulic Conductivity	cm/s	5	8.454E-05	2.021E-04	8.201E-05	6.726E-09	5	1.015E-04	2.319E-04	1.077E-04	1.161E-08
Soil TC	%	5	3.447	1.848	0.704	0.495	5	5.407	5.594	2.137	4.565
Soil TN	%	5	0.190	0.221	0.083	6.886E-03	5	0.282	0.265	0.102	0.010
Soil C:N	C:N	5	19.892	12.730	4.994	24.937	5	19.549	9.581	3.859	14.889
Soil Organic Matter	%	5	8.980	6.800	2.937	8.627	5	10.160	5.200	2.217	4.913
Mineral N Pool	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil	5	9.436	7.991	3.174	10.075	5	11.883	18.073	7.735	59.828
Percent Canopy Openness	%	5	2.544	2.720	1.292	1.668	5	2.646	2.870	1.171	1.372
Effective LAI	Index	5	4.938	2.920	1.241	1.539	5	4.868	2.260	0.869	0.755
Canopy Gap Number	#	5	3684.600	2416.000	1035.683	1072639.300	5	4630.800	2514.000	1073.476	1152350.700
Litter Depth	cm/s	5	6.223	2.540	1.136	1.290	5	7.176	4.763	2.307	5.323
Litter TC	%	5	45.924	7.068	2.891	8.356	5	46.293	4.778	2.022	4.087
Litter TN	%	5	1.027	0.545	0.217	0.047	5	1.045	0.354	0.135	0.018
Litter C:N	C:N	5	45.881	17.995	6.929	48.017	5	44.865	11.296	4.958	24.584
Soil Respiration Rate	µmol CO_2 /m^2 soil/s	5	0.563	0.765	0.335	0.112	5	1.723	2.947	1.201	1.442
Herbaceous Litter Decay Rate	k coefficient	5	2.443E-03	3.651E-03	1.823E-03	3.324E-06	4	3.363E-03	7.729E-04	3.638E-04	1.324E-07
Woody Litter Decay Rate	k coefficient	5	1.578E-03	1.991E-03	7.719E-04	5.958E-07	5	1.429E-03	2.120E-03	7.496E-04	5.619E-07
N Mineralization Rate	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil/d	5	1.349	2.589	0.966	0.933	5	1.611	1.062	0.388	0.150
Nitrification Rate	mg NO_2^--NO_3^- /kg soil/d	5	-0.025	0.328	0.129	0.017	5	0.408	1.365	0.648	0.419

Variable	Unit	Medium Intensity Canopy Invasion					High Intensity Canopy Invasion				
		n	Mean	Range	SD	VAR	n	Mean	Range	SD	VAR
Daily Mean Soil Temperature	°C	5	14.345	2.316	0.891	0.794	5	13.779	2.002	0.770	0.593
Daily Low Soil Temperature	°C	5	13.468	2.553	1.072	1.149	5	12.771	2.238	0.851	0.724
Daily High Soil Temperature	°C	5	15.346	1.971	0.869	0.754	5	14.776	1.690	0.651	0.424
Daily Range Soil Temperature	°C	5	1.878	2.190	0.894	0.799	5	2.005	0.750	0.283	0.080
pH	pH	5	5.670	0.940	0.463	0.215	5	6.032	2.490	0.979	0.959
Soil Bulk Density	g/cm^3	5	0.876	0.249	0.103	0.011	5	0.909	0.350	0.141	0.020
Gravimetric Water Content	g water/g soil	5	0.205	0.046	0.020	4.142E-04	5	0.207	0.105	0.040	1.587E-03
Unsaturated Hydraulic Conductivity	cm/s	5	2.718E-05	8.205E-05	3.247E-05	1.055E-09	5	2.373E-05	3.239E-05	1.462E-05	2.136E-10
Soil TC	%	5	3.414	2.382	0.876	0.767	5	4.379	4.218	1.815	3.293
Soil TN	%	5	0.232	0.214	0.081	6.536E-03	5	0.280	0.177	0.076	5.757E-03
Soil C:N	C:N	5	15.860	12.407	4.792	22.959	5	15.735	14.305	5.856	34.292
Soil Organic Matter	%	5	8.380	4.800	1.918	3.677	5	6.940	4.700	1.988	3.953
Mineral N Pool	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil	5	10.401	11.235	4.686	21.956	5	8.149	1.958	0.824	0.678
Percent Canopy Openness	%	5	2.774	3.830	1.417	2.009	5	2.862	3.130	1.378	1.899
Effective LAI	Index	5	4.642	2.740	1.014	1.028	5	4.540	1.660	0.683	0.466
Canopy Gap Number	#	5	3658.000	1396.000	566.416	320827.500	5	3193.800	942.000	404.950	163984.700
Litter Depth	cm/s	5	8.255	6.668	3.214	10.333	5	4.953	3.175	1.242	1.542
Litter TC	%	5	46.765	3.859	1.757	3.087	5	44.149	12.297	5.124	26.250
Litter TN	%	5	0.941	0.317	0.122	0.015	5	0.896	0.356	0.160	0.026
Litter C:N	C:N	5	50.230	14.365	5.288	27.966	5	49.920	15.866	6.250	39.064
Soil Respiration Rate	µmol CO_2 /m^2 soil/s	5	1.153	1.124	0.465	0.216	5	1.225	1.510	0.640	0.410
Herbaceous Litter Decay Rate	k coefficient	5	1.389E-03	3.467E-03	1.585E-03	2.512E-06	4	1.621E-03	9.437E-04	4.340E-04	1.883E-07
Woody Litter Decay Rate	k coefficient	5	8.519E-04	1.842E-03	6.812E-04	4.641E-07	4	1.206E-03	1.479E-03	6.228E-04	3.879E-07
N Mineralization Rate	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil/d	5	1.399	1.669	0.661	0.437	5	1.005	2.020	0.805	0.648
Nitrification Rate	mg NO_2^--NO_3^- /kg soil/d	5	0.130	0.322	0.142	0.020	5	0.244	0.467	0.197	0.039

A table of each variable measured, summarized across groups under the *H. helix* invasion presence cover factor in urban forest patch plots in Baltimore City, MD. The unit, number of samples (n), mean, range, standard deviation (SD), and variance (VAR) is shared for each variable.

Variable	Unit	No Invasion					Invasion				
		n	Mean	Range	SD	VAR	n	Mean	Range	SD	VAR
Daily Mean Soil Temperature	°C	5	13.982	0.821	0.318	0.101	15	14.241	2.799	0.802	0.643
Daily Low Soil Temperature	°C	5	12.817	1.476	0.556	0.309	15	13.331	3.190	0.886	0.786
Daily High Soil Temperature	°C	5	15.264	1.095	0.438	0.192	15	15.203	2.952	0.818	0.669
Daily Range Soil Temperature	°C	5	2.448	1.750	0.812	0.659	15	1.871	2.417	0.598	0.358
pH	pH	5	4.726	1.730	0.828	0.685	15	5.521	3.600	0.869	0.756
Soil Bulk Density	g/cm^3	5	0.913	0.285	0.121	0.015	15	0.817	0.714	0.195	0.038
Gravimetric Water Content	g water/g soil	5	0.189	0.060	0.026	7.022E-04	15	0.202	0.106	0.030	9.155E-04
Unsaturated Hydraulic Conductivity	cm/s	5	8.454E-05	2.021E-04	8.201E-05	6.726E-09	15	5.079E-05	2.319E-04	7.111E-05	5.056E-09
Soil TC	%	5	3.447	1.848	0.704	0.495	15	4.400	5.734	1.781	3.173
Soil TN	%	5	0.190	0.221	0.083	6.886E-03	15	0.265	0.280	0.084	7.038E-03
Soil C:N	C:N	5	19.892	12.730	4.994	24.937	15	17.048	14.305	4.895	23.966
Soil Organic Matter	%	5	8.980	6.800	2.937	8.627	15	8.493	6.800	2.333	5.442
Mineral N Pool	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil	5	9.436	7.991	3.174	10.075	15	10.144	18.073	5.107	26.085
Percent Canopy Openness	%	5	2.544	2.720	1.292	1.668	15	2.761	3.830	1.232	1.517
Effective LAI	Index	5	4.938	2.920	1.241	1.539	15	4.683	2.740	0.814	0.663
Canopy Gap Number	#	5	3684.600	2416.000	1035.683	1072639.300	15	3827.533	3095.000	922.986	851902.552
Litter Depth	cm/s	5	6.223	2.540	1.136	1.290	15	6.795	8.255	2.634	6.938
Litter TC	%	5	45.924	7.068	2.891	8.356	15	45.736	13.309	3.307	10.937
Litter TN	%	5	1.027	0.545	0.217	0.047	15	0.961	0.537	0.145	0.021
Litter C:N	C:N	5	45.881	17.995	6.929	48.017	15	48.338	21.296	5.715	32.657
Soil Respiration Rate	µmol CO_2 /m^2 soil/s	5	0.563	0.765	0.335	0.112	15	1.367	3.097	0.812	0.660
Herbaceous Litter Decay Rate	k coefficient	5	2.443E-03	3.651E-03	1.823E-03	3.324E-06	13	2.068E-03	4.079E-03	1.317E-03	1.736E-06
Woody Litter Decay Rate	k coefficient	5	1.578E-03	1.991E-03	7.719E-04	5.958E-07	14	1.159E-03	2.521E-03	6.857E-04	4.701E-07
N Mineralization Rate	mg NO_2^--NO_3^- & NH_3-NH_4^+ /kg soil/d	5	1.349	2.589	0.966	0.933	15	1.338	2.020	0.648	0.420
Nitrification Rate	mg NO_2^--NO_3^- /kg soil/d	5	-0.025	0.328	0.129	0.017	15	0.261	1.365	0.388	0.151

Appendix III. Coefficients of Variation

III.1 Ground Cover Presence

A table of the coefficients of variation for each group under the *H. helix* presence of ground cover factor in urban forest patch plots in Baltimore City, MD.

Variable	Control	No Ground Cover	Ground Cover
Daily Mean Soil Temperature	0.023	0.045	0.044
Daily Low Soil Temperature	0.043	0.049	0.044
Daily High Soil Temperature	0.029	0.052	0.049
Daily Range Soil Temperature	0.332	0.264	0.305
pH	0.175	0.187	0.137
Soil Bulk Density	0.132	0.121	0.311
Gravimetric Water Content	0.140	0.173	0.136
Unsaturated Hydraulic Conductivity	0.970	1.108	1.021
Soil TC	0.204	0.438	0.330
Soil TN	0.436	0.401	0.180
Soil C:N	0.251	0.349	0.234
Soil Organic Matter	0.327	0.241	0.238
Mineral N Pool	0.336	0.092	0.535
Percent Canopy Openness	0.508	0.435	0.406
Effective LAI	0.251	0.181	0.132
Canopy Gap Number	0.281	0.219	0.258
Litter Depth	0.183	0.204	0.269
Litter TC	0.063	0.096	0.046
Litter TN	0.211	0.157	0.131
Litter C:N	0.151	0.122	0.104
Soil Respiration Rate	0.595	0.322	0.641
Herbaceous Litter Decay Rate	0.746	1.236	0.303
Woody Litter Decay Rate	0.489	0.784	0.476
N Mineralization Rate	0.716	0.670	0.333
Nitrification Rate	-5.118	1.412	1.384

III.2 Canopy Invasion Intensity (Continued on next page)

A table of the coefficients of variation for each group under the *H. helix* canopy invasion intensity factor in urban forest patch plots in Baltimore City, MD.

Variable	Control	Low Invasion
Daily Mean Soil Temperature	0.023	0.045
Daily Low Soil Temperature	0.043	0.035
Daily High Soil Temperature	0.029	0.058
Daily Range Soil Temperature	0.332	0.330
pH	0.175	0.155
Soil Bulk Density	0.132	0.365
Gravimetric Water Content	0.140	0.169
Unsaturated Hydraulic Conductivity	0.970	1.062
Soil TC	0.204	0.395
Soil TN	0.436	0.361
Soil C:N	0.251	0.197
Soil Organic Matter	0.327	0.218
Mineral N Pool	0.336	0.651
Percent Canopy Openness	0.508	0.443
Effective LAI	0.251	0.178
Canopy Gap Number	0.281	0.232
Litter Depth	0.183	0.322
Litter TC	0.063	0.044
Litter TN	0.211	0.130
Litter C:N	0.151	0.111
Soil Respiration Rate	0.595	0.697
Herbaceous Litter Decay Rate	0.746	0.108
Woody Litter Decay Rate	0.489	0.525
N Mineralization Rate	0.716	0.241
Nitrification Rate	-5.118	1.587

Variable	Medium Invasion	High Invasion
Daily Mean Soil Temperature	0.062	0.056
Daily Low Soil Temperature	0.080	0.067
Daily High Soil Temperature	0.057	0.044
Daily Range Soil Temperature	0.476	0.141
pH	0.082	0.162
Soil Bulk Density	0.118	0.155
Gravimetric Water Content	0.099	0.192
Unsaturated Hydraulic Conductivity	1.195	0.616
Soil TC	0.256	0.414
Soil TN	0.348	0.271
Soil C:N	0.302	0.372
Soil Organic Matter	0.229	0.286
Mineral N Pool	0.451	0.101
Percent Canopy Openness	0.511	0.481
Effective LAI	0.218	0.150
Canopy Gap Number	0.155	0.127
Litter Depth	0.389	0.251
Litter TC	0.038	0.116
Litter TN	0.130	0.179
Litter C:N	0.105	0.125
Soil Respiration Rate	0.403	0.523
Herbaceous Litter Decay Rate	1.141	0.268
Woody Litter Decay Rate	0.800	0.516
N Mineralization Rate	0.472	0.801
Nitrification Rate	1.090	0.809

III.3 Invasion Presence

A table of the coefficients of variation for each group under the *H. helix* invasion presence factor in urban forest patch plots in Baltimore City, MD.

Variable	Control	Invasion
Daily Mean Soil Temperature	0.023	0.056
Daily Low Soil Temperature	0.043	0.066
Daily High Soil Temperature	0.029	0.054
Daily Range Soil Temperature	0.332	0.320
pH	0.175	0.157
Soil Bulk Density	0.132	0.239
Gravimetric Water Content	0.140	0.149
Unsaturated Hydraulic Conductivity	0.970	1.400
Soil TC	0.204	0.405
Soil TN	0.436	0.317
Soil C:N	0.251	0.287
Soil Organic Matter	0.327	0.275
Mineral N Pool	0.336	0.503
Percent Canopy Openness	0.508	0.446
Effective LAI	0.251	0.174
Canopy Gap Number	0.281	0.241
Litter Depth	0.183	0.388
Litter TC	0.063	0.072
Litter TN	0.211	0.151
Litter C:N	0.151	0.118
Soil Respiration Rate	0.595	0.594
Herbaceous Litter Decay Rate	0.746	0.637
Woody Litter Decay Rate	0.489	0.592
N Mineralization Rate	0.716	0.484
Nitrification Rate	-5.118	1.489

Appendix IV. Mean Separation Test Results (with Post-Hoc Values)

IV.1 Ground Cover Presence (Next page)

A table of results from mean separation tests, and associate post-hocs, for the *H. helix* presence of ground cover factor in urban forest patch plots in Baltimore City, MD for ecological characteristic (no fill) and nutrient cycling (gray fill) response variables. Parametric data was analyzed with ANOVA tests alongside Tukey's HSD post-hoc tests. Non-parametric data was analyzed with Kruskal-Wallis tests alongside Dunn's Test post-hoc test with the Holm stepwise adjustment. Degrees of freedom (df), R^2, and *p* value is reported for every ANOVA and Kruskal-Wallis result. Mean square is also reported for the ANOVA tests, and rank sum is reported for the Kruskal-Wallis tests. Significance of *p* values is noted as well, where significant (***** = $p < 0.05$) findings are bolded and suggestive findings (**.** = $p < 0.1$) are italicized. Significant post-hoc test results are also bolded, and suggestive post-hoc test results are italicized.

Response Variable	Mean Separation Test Results						Post-Hoc Test Reults		
	Mean Square (ANOVA)	Rank Sum (K-W)	df	R^2	*p* value	Significance	Control vs. No Ground Cover	Control vs. Ground Cover	No Ground Cover vs. Ground Cover
Daily Mean Soil Temperature	**2.009**	**NA**	**2**	**0.416**	**0.010**	*	0.696	*0.097*	**9.675E-03**
Daily Low Soil Temperature	**3.508**	**NA**	**2**	**0.530**	**1.62E-03**	*	0.891	**0.013**	**2.232E-03**
Daily High Soil Temperature	0.842	NA	2	0.166	0.214		NA	NA	NA
Daily Range Soil Temperature	**NA**	**6.488**	**2**	**0.292**	**0.039**	*	0.941	*0.075*	*0.081*
pH	NA	3.184	2	0.156	0.203		NA	NA	NA
Soil Bulk Density	NA	2.990	2	0.194	0.224		NA	NA	NA
Gravimetric Water Content	3.47E-04	NA	2	0.043	0.691		NA	NA	NA
Unsaturated Hydraulic Conductivity	**NA**	**6.967**	**2**	**0.223**	**0.031**	*	**0.048**	0.563	*0.074*
Soil TC	*NA*	*5.445*	*2*	*0.265*	*0.066*	.	0.767	0.188	*0.088*
Soil TN	**0.027**	**NA**	**2**	**0.361**	**0.022**	*	0.832	**0.032**	*0.068*
Soil C:N	NA	1.625	2	0.074	0.444		NA	NA	NA
Soil Organic Matter	11.180	NA	2	0.200	0.149		NA	NA	NA
Mineral N Pool	NA	3.457	2	0.170	0.178		NA	NA	NA
Percent Canopy Openness	1.587	NA	2	0.113	0.361		NA	NA	NA
Effective LAI	1.428	NA	2	0.182	0.181		NA	NA	NA
Canopy Gap Number	353351.393	NA	2	0.043	0.686		NA	NA	NA
Litter Depth	**NA**	**9.814**	**2**	**0.535**	**7.39E-03**	*	0.279	0.184	**5.194E-03**
Litter TC	NA	0.665	2	0.055	0.717		NA	NA	NA
Litter TN	0.034	NA	2	0.137	0.287		NA	NA	NA
Litter C:N	NA	0.714	2	0.132	0.700		NA	NA	NA
Soil Respiration Rate	**NA**	**6.096**	**2**	**0.285**	**0.047**	*	0.205	**0.042**	0.388
Herbaceous Litter Decay Rate	*NA*	*5.439*	*2*	*0.321*	*0.066*	.	0.151	0.786	*0.075*
Woody Litter Decay Rate	6.81E-07	NA	2	0.149	0.275		NA	NA	NA
N Mineralization Rate	0.044	NA	2	9.17E-03	0.925		NA	NA	NA
Nitrification Rate	NA	2.579	2	0.183	0.275		NA	NA	NA

IV.2 Canopy Invasion Intensity (Next page)

A table of results from mean separation tests, and associate post-hocs, for the *H. helix* canopy invasion intensity factor in urban forest patch plots in Baltimore City, MD for ecological characteristic (no fill) and nutrient cycling (gray fill) response variables. Parametric data was analyzed with ANOVA tests alongside Tukey's HSD post-hoc tests. Non-parametric data was analyzed with Kruskal-Wallis tests alongside Dunn's Test post-hoc test with the Holm stepwise adjustment. Degrees of freedom (df), R^2, and *p* value is reported for every ANOVA and Kruskal-Wallis result. Mean square is also reported for the ANOVA tests, and rank sum is reported for the Kruskal-Wallis tests. Significance of *p* values is noted as well, where suggestive findings (**.** = $p < 0.1$) are italicized. Suggestive post-hoc test results are also italicized. Mean separation tests yielded suggestive ($p < 0.1$) results for pH and Soil Bulk Density. However, due to a lack of statistical power (small n) and a high number of factor levels, the post-hoc tests were inconclusive in determining differences between pairs of groups.

Response Variable	Mean Separation Test Results						Post-Hoc Test Reults					
	Mean Square (ANOVA)	Rank Sum (K-W)	df	R^2	*p* value	Significance	Control vs. Low	Control vs. Medium	Control vs. High	Low vs. Medium	Low vs. High	Medium vs. High
Daily Mean Soil Temperature	0.672	NA	3	0.209	0.278		NA	NA	NA	NA	NA	NA
Daily Low Soil Temperature	1.184	NA	3	0.268	0.161		NA	NA	NA	NA	NA	NA
Daily High Soil Temperature	0.476	NA	3	0.141	0.476		NA	NA	NA	NA	NA	NA
Daily Range Soil Temperature	NA	3.366	3	0.161	0.339		NA	NA	NA	NA	NA	NA
pH	*NA*	*7.077*	*3*	*0.381*	*0.069*	.	1.000	0.288	0.237	0.276	0.260	0.873
Soil Bulk Density	*0.070*	*NA*	*3*	*0.337*	*0.080*	.	0.110	0.983	1.000	0.203	0.118	0.988
Gravimetric Water Content	NA	1.846	3	0.069	0.605		NA	NA	NA	NA	NA	NA
Unsaturated Hydraulic Conductivity	NA	3.583	3	0.231	0.310		NA	NA	NA	NA	NA	NA
Soil TC	4.444	NA	3	0.268	0.162		NA	NA	NA	NA	NA	NA
Soil TN	9.62E-03	NA	3	0.196	0.308		NA	NA	NA	NA	NA	NA
Soil C:N	NA	3.960	3	0.166	0.266		NA	NA	NA	NA	NA	NA
Soil Organic Matter	8.969	NA	3	0.241	0.208		NA	NA	NA	NA	NA	NA
Mineral N Pool	NA	0.463	3	0.091	0.927		NA	NA	NA	NA	NA	NA
Percent Canopy Openness	0.098	NA	3	0.010	0.982		NA	NA	NA	NA	NA	NA
Effective LAI	0.175	NA	3	0.033	0.905		NA	NA	NA	NA	NA	NA
Canopy Gap Number	*1818198.800*	*NA*	*3*	*0.335*	*0.082*	.	0.301	1.000	0.783	0.280	*0.061*	0.809
Litter Depth	NA	3.062	3	0.286	0.382		NA	NA	NA	NA	NA	NA
Litter TC	NA	0.669	3	0.105	0.881		NA	NA	NA	NA	NA	NA
Litter TN	0.025	NA	3	0.149	0.446		NA	NA	NA	NA	NA	NA
Litter C:N	NA	2.406	3	0.169	0.493		NA	NA	NA	NA	NA	NA
Soil Respiration Rate	NA	6.040	3	0.280	0.110		NA	NA	NA	NA	NA	NA
Herbaceous Litter Decay Rate	NA	5.479	3	0.298	0.140		NA	NA	NA	NA	NA	NA
Woody Litter Decay Rate	4.97E-07	NA	3	0.163	0.431		NA	NA	NA	NA	NA	NA
N Mineralization Rate	0.315	NA	3	0.098	0.636		NA	NA	NA	NA	NA	NA
Nitrification Rate	NA	3.594	3	0.202	0.309		NA	NA	NA	NA	NA	NA

Appendix V. NMDS Dimensions

A table of the NMDS axis dimensions for an NMDS analysis run using ecological response variables on the *H. helix* invasion factor presence of ground cover in urban forest patch plots in Baltimore City, MD, which was found to have significant differences between the groups No Ground Cover and Ground Cover from a PERMANOVA test and associated multilevel pairwise analysis (Tables 5 & 6). Some response variables were removed using a correlation matrix to prevent overfitting. Removal was based on having a correlation coefficient of > (+/-) 0.7.

Response Variable	NMDS1	NMDS2
Daily Mean Soil Temperature	-0.04273	-0.04415
Daily Range Soil Temperature	0.08966	-0.05144
pH	0.02689	0.10510
Soil Bulk Density	0.09523	-0.00318
Gravimetric Water Content	0.00304	0.13506
Unsaturated Hydraulic Conductivity	-0.10248	-0.03862
Soil TC	-0.07406	0.06449
Soil CN	0.01446	0.00153
Litter TC	-0.09151	-0.03640
Litter CN	0.07171	-0.00599
Soil Organic Matter	-0.07843	-0.04060
Mineral N Pool	-0.09244	0.05063
Percent Canopy Open	0.08532	-0.06008
Canopy Gap Number	-0.00784	-0.04040
Litter Depth	-0.11833	0.01277

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