

Early Root Structure and Growth of Japanese Barberry Seedlings

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ABSTRACT OF THE THESIS

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Japanese barberry (*Berberis thunbergii* DC.) is an invasive woody shrub that has invaded many different habitats throughout the northeast United States. Its ability to flourish under various environmental conditions gives it a tremendous competitive advantage when compared to indigenous flora. As a result, many indigenous plants are being displaced, ultimately causing changes in biodiversity and ecosystem function.

Since Japanese barberry is so prevalent under various environmental conditions I wanted to determine if Japanese barberry seedlings, first year plants, demonstrate different root growth patterns and structure based on local soil conditions. I also wanted to determine how early root development might contribute to invasiveness. My research was conducted at three locations in northeastern New Jersey, USA where all three locations were heavily invaded by Japanese barberry. I measured ten different soil components at each site to establish a soil chemistry and composition profile that I used

as a baseline for comparing sites. I also wanted to determine if variations local soil chemistry and composition were possible contributors to root structure and development.

Results indicate that Japanese barberry seedling demonstrated very distinct growth patterns and structure at each site during their first year. The Upland and Stream Bed seedlings showed relatively linear growth with the Upland seedlings having much greater plant mass and complex root structure opposed to the Stream Bed seedlings, which appeared poorly developed. The Great Swamp seedlings demonstrated very limited change in plant mass and root growth from July to December. The Great Swamp soil lay in between the Upland and Stream Bed soils and therefore had moderate root complexity.

Although Japanese barberry seedlings demonstrate different growth patterns at each site there is no indication soil composition is a key factor in my results. However, the difference among the three sites in hydrology was quite apparent, and may be the most important factor. I conclude that although Japanese barberry seedlings are clearly capable of germinating and surviving the first growing season in saturated or wetland soils, the conditions of these soils may help these areas avoid dense infestations because root growth is impaired compared to upland soils.

Dedication

To my wonderful wife Melissa for providing unwavering love and support through every moment of our life and enduring move after move through an exhausting military lifestyle . . .

. . . and to Ashley and Danielle for their love and understanding beyond what many children experience at their ages . . .

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Rutgers University is a great academic institution and EENR ensures the legacy continues by treating every student as a family member and caring. It has been my honor and pleasure to graduate from Cook Campus.

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Introduction

Ecological systems are dynamic and many processes occur simultaneously which contribute to their overall function. Additionally, within ecosystems there are population fluctuations of indigenous biota accompanied by invasions of non-native biota that occur randomly or intentionally, such as plant invasions. Plant invasions can affect ecosystems in various ways and the results could be positive, negative or neutral (Lockwood et al. 2007). Generally, plant invasions are considered negative because they displace indigenous plants and could alter ecosystems. A common plant responsible for invading many areas in the northeast United States is Japanese barberry (*Berberis thunbergii* DC.). Japanese barberry is an ecological threat because it has several means of reproduction and has been shown to alter soil chemistry (Ehrenfeld 2003) causing changes in biotic activity (flora and fauna) and its establishment of dense thickets profoundly alters understory structure. It is found in almost every habitat and can withstand various environmental conditions. Although there are many studies about Japanese barberry, they mainly focus on the aspects such as the above ground biomass or soil changes. A literature search yielded few published studies analyzing below ground biomass (roots) of Japanese barberry and very few studies involving invasive plant root systems in general. Roots are an essential component of plants because they transfer nutrients and water - in addition to providing support and stability. My research focused on early growth and development of the root systems of invasive Japanese barberry seedlings. More specifically, I looked at root growth patterns, structure and biomass of Japanese barberry in three different soil conditions over time. The seedling roots displayed unique physical

growth patterns at each location demonstrating plasticity in different soils. Perhaps even more significant was the differences in growth from the first harvest to the last.

The purpose for looking at early root development is threefold. First, there is lack of information and understanding about this key component of invasive plants. Secondly, understanding root development might lead to clues about how invasive plants establish and their survival strategy. Finally, understanding root development might lead to the assessment of similarities of root development in other invasive plants and therefore, lead to cost effective and common management techniques.

I have tested two related hypotheses in my research. First, I hypothesized that root development, as measured by a set of root architectural descriptors, will vary in soils of different types. Second, I hypothesized that root system structure will be highly correlated with above-ground biomass, such that the root system can be predicted by the measurements of the above-ground tissue.

I tested the first hypothesis by analyzing scanned seedling images, from each harvest, with WinRhizo software in order to measure the root length, number of forks, and number of tips. The second hypothesis was tested in two steps. The first step was to analyze soil from each site and establish a soil profile. The soil profile showed the variance of soil properties between sites. The second step was to statistically compare data from the Japanese barberry components. I compared root biomass to shoot biomass within sites and between sites. Finally I compared root to shoot ratios with the below and above-ground biomass.

Limitations

My research was conducted using a field study design at three separate locations in three different soil types where Japanese barberry invasions are well established. I chose a field study versus a greenhouse design for a few reasons. Although a field study is sometimes hard to manage, in this situation it was useful because it allowed me to analyze seedlings growing under natural soil conditions, which are not easily reproduced in the greenhouse. Also, from a logistics perspective it was easier to manage this study for the same set of reasons previously mentioned. This allowed me to focus on the plant harvests, soil collection, and plant analysis preparation versus spending time managing watering cycles or providing nutrients, which would have been a requirement in a greenhouse designed study. And although a greenhouse designed study would allow many variables to be managed easier such as herbivory, nutrients, hydrology, and sunlight, it does not represent natural conditions. A second consequence of a greenhouse study is the plants are removed from their natural environment, which could change their growth patterns. I would also lose the effect of the local tree canopy and hydrology. The field environment allows the natural tendencies of the environment to dictate the fate of the seedlings. Therefore, the results from this study are direct measurements of plant growth responses in their natural habitat. Also, it is unrealistic for this study to attempt to control these variables in the field due to the difficulty and extensive man hours required. The primary disadvantage in this field study is deciphering the results and determining causation because there are many uncontrolled variables in nature that will not be accounted for or measured. Therefore there is no definitive measurement or test to determine the most prominent influences of change in seedling growth or development.

However, there are techniques that can be used to elucidate possible contributing factors. For instance, I could transplant seeds and also seedlings and compare their growth response to their new environment. This would provide a qualitative assessment and confirm or deny the local conditions as a contributing factor.

An additional limitation is the soil nitrogen results were not incorporated in the soil chemistry profile because the soil was collected in a manner that comprised accurate testing. However, since nitrogen is a key component of plant growth, soil samples will be retested at a later time and incorporated into the soil profile data.

Background

Plant invasions

The term plant invasions can have different interpretations and trigger a wide range of different thoughts and visual images. Industries that produce herbicides might view plant invasions as good so they can reap the financial benefits of their products whereas agriculturists and horticulturists strongly despise plant invasions. There are different and conflicting interests and viewpoints regarding invasive plants, which could lead to ambiguity when defining the term. Therefore, it is important to accurately understand the term “invasive species” as it relates to plant invasions. The National Invasive Species Management Plan (NISMP) defines invasive species, under Executive Order 13112, as “a species that is non-native to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to human health” (National Invasive Species Council (NISC) 2006). Another suitable version consistent with the NISMP is an invasive species implies “their spread in space

has a negative effect on local species and ecosystems in the area they enter” (Alpert et al. 2000).

Once a single invasive seed germinates, it must survive a series of challenges in order to become established. In most ecosystems, there are many factors inhibiting this process but they do not always work. For instance, since plants are sessile, they must be able to tolerate new environmental conditions to include soil chemistry, soil structure and climate. They must also avoid other factors like herbivory and desiccation, while competing for nutrients and water. If they can balance all of these variables then they increase their chances to survive their first year. One thing to consider is at some point all plants invaded an area and were at that time invasive. But over time, they were “naturalized” and became indigenous. DeGasperis and Motzkin (2007) believe variations in plant invasiveness are due to the same conditions that once shaped the current indigenous plant populations.

This is precisely what is occurring in many areas throughout the northeastern United States by Japanese barberry. By surviving their first year, this common nursery shrub is spreading beyond its intended use as an ornamental shrub and slowly infiltrating deciduous forests across the mid-Atlantic region of the United States. The transformations taking place in these areas vary in magnitude and scope making it difficult to accurately document changes within ecosystems and more importantly determine how the ecosystem changed from pre-invasion. The exact mechanism or mechanisms of invasion ecology are yielding conflicting results. One proposal by Dietz and Edwards (2006) suggests that invasions occur in two phases the first where pre-

adapted species increase rapidly and a secondary phase, where plants expand their range based upon plastic responses or genetic adaptation to new ecological circumstances.

Japanese barberry

Japanese barberry is an ornamental shrub used by nurseries for residential and commercial landscapes. According to Steffey (1985), Japanese barberry was first introduced to the United States in 1875 in seed form by Russia to the Arnold Arboretum. In 1896 it was originally grown in the New York Botanical Garden. There is no definitive date when Japanese barberry became naturalized but some estimates suggest around 1910. It was not recognized as a serious threat to ecosystems until the 1980s (Silander and Klepeis 1999). Since its introduction in the United States it has become a widespread invasive shrub commonly found throughout the mid-Atlantic region of the United States. In the past 100 years it slowly infiltrated closed canopy forests displacing indigenous flora in many areas. *B. thunbergii* DC was first introduced as a suitable replacement for the European common barberry (*Berberis vulgaris* L.). It was discovered that young *B. vulgaris* plants were susceptible to black root fungus or black root rust caused by *Puccinia graminis*. Mature plants developed resistance as their leaves thickened but still served as a host plant (Leonard and Szabo 2005). Black root fungus is a major disease that infects small grain cereals such as wheat, barley and oats (Jin 2005). An intense effort to eradicate *B. vulgaris*, because of its effect on cereal grain plants, began during Colonial times and continued through the 20th century.

Its replacement, *B. thunbergii*, can withstand multiple environmental stressors therefore making it a good choice for its intended use as a landscape shrub. However, what made a good choice for horticulturists and landscapers made it a very poor choice

once it's devastating effects on the environment were recognized. In Morristown, New Jersey, Japanese barberry is widespread and does not appear to have any natural biological control. There are many plants that are susceptible to deer herbivory in the area due to the very high deer density in the area but there is little to no evidence of deer browse on this invasive plant species unlike other plant species in the area have been browsed to ground level. Insect herbivory on Japanese barberry is rarely observed and occurrences are infrequent. However, there is recent evidence that Japanese barberry might be susceptible to insect herbivory from Barberry Looper (*Coryphista meadii*) (Ehrenfeld 2007).

One possible reason why Japanese barberry plants deter herbivory is because each plant produces multiple stems that generally increase in number as the shrub matures (Ehrenfeld 1999) and along each shoot are defensive thorns. The thorns not only dissuade herbivory but also aid the shrub to form dense impenetrable thickets. The tips break off rather easily and embed in the skin of animals causing irritation and infection. As a result, shrubs develop into dense thickets that change the indigenous biodiversity and ultimately local ecosystem.

Masked by the thorns is inflorescence during the spring; its red fruit bears the seed that lasts throughout summer and fall. Additionally, along with the deep green foliage is the ability to produce multiple cultivars such as Aurea Bonanza, Aurea Nana, Emerald Pygmy, Monler, Kobold, and Silver Mile each producing spectacularly colored foliage throughout the year making this a very profitable plant for horticulturists and further enhancing its marketability. There is very little evidence suggesting the cultivars are invasive but there is no evidence suggesting they are not invasive.

Reproduction and seed dispersal

Multiple forms of propagation are just one characteristic of Japanese barberry. Although it was intentionally introduced into the environment as a landscape shrub it has several redundant means of reproduction to ensure its survival beyond the control of managed landscapes. It can sexually reproduce by seeds or under favorable conditions it can asexually reproduce by rhizomes or by decumbent branches.

The most visually obvious technique of reproduction occurs by seeds. There are no published studies quantifying invasive Japanese barberry seed production but there is one study that documented seed production in genotypically similar Japanese barberry cultivars. Lehrer et al. (2008) analyzed four ornamental genotypes of Japanese barberry and found that *Berberis thunbergii* 'Crimson Pygmy' produced up to 2968 seeds per mature bush. What is unclear from his research is the term mature bush. There was no dimensional data suggesting number of stems or height. Although the cultivar is discrete as a narrowly defined clone from the species, it demonstrates the seed producing potential in the recognized invasive species. What is also not addressed in his research is the viability of the seeds produced by the cultivars. Generally, seed production is dependent on size and maturity of the plant since smaller bushes tend to have smaller quantities of fruit whereas larger bushes have greater quantities of fruit. However, if smaller plants have a higher germination and survival rates than a larger, greater seed producing plants this could call into question the significance of seed production. The other three genotypes in his research produced considerable fewer seeds. In forested systems the seeds are primarily consumed and dispersed by turkeys and deer (Ehrenfeld 1997) and birds and small rodents (Silander and Klepzig 1999). The remaining seeds eventually

drop to the ground and either consumed by grainivores while unconsumed seeds may become part of the seed bank.

Japanese barberry can also reproduce asexually by vegetative propagation. The first form of vegetative propagation is by rhizomes. The rhizomes produce shoots at the internodes along the rhizome or at the terminal nodes. Shoots from rhizomes are similar in appearance to seedlings produced from seeds except they lack cotyledons during their first year. The lack of cotyledons was a definitive characteristic I used to distinguish between a first year plant originating from a rhizome and a first year plant originating from a seed. Decumbent branches are the second form of vegetative propagation although they were the least common form of propagation I observed in the field. During vegetative propagation new plants develop adventitious roots and eventually become independent plants. In each situation, the end state is a clone of the parent plant.

Modes of plant invasions

There are many modes of plant invasions that have been studied and are well documented. But despite the available research, involving all types of invasive plants, there is limited knowledge on the precise circumstances why invasions occur. Although there is no definite consensus why they take place there are several supported theories. Some theories involve spatial or temporal ideas such as physically separating two co-existing species. When the two species share a mutual habitat they keep each other in balance. But when one species is separated, the chemical or physical constraints they imposed on one another no longer occur or are reduced allowing excessive growth. As a result some plants uncontrollably proliferate. These situations arise when plants are imported, illegally smuggled, and accidentally or intentionally released into novel

locations. Although there have been increasing restrictions imposed by the United States Department of Agriculture (USDA), plant exportation and importation still occur and are two examples that facilitate disrupting a symbiotic plant-insect or plant-animal relationship. This is also referred to as the enemy release hypothesis (ERH). Keane and Crawley (2002) summarized several reports and concluded the general trend is that exotics grow larger, reproduce more and live longer in their novel regions. They also noted there was little empirical data to determine causation.

A second theory is plants have the ability to generate and to use chemicals (allelopathy) against other plant species to inhibit competitor fecundity or growth. Callaway et al. (2008) found that *Alliaria petiolata* (garlic mustard) and a coexisting plant inhibits mycorrhizal fungal mutualists of North American native plants and the effects on mycorrhizas on invaded North American soils is much greater than European soils where *A. petiolata* is native. The allelopathic effects of some plants were further supported by Weir (2006). She provided evidence that some knapweeds secrete the phytotoxic chemical (\pm)-catechin that contributes to their invasive success. She also noted that garlic mustard (*Alliaria petiolata*) produced glucosinolates that not only demonstrated antimicrobial effects but also deterred herbivory. This is referred to as the “novel weapons hypothesis” (Callaway and Ridenour 2004), which could incorporate spatial, temporal or both ideas. They suggested some plants developed chemical inhibitors they release into soil through the root system or from decomposing leaves. In either situation the chemicals released by invasive plants inhibit growth by reducing resource availability or resource acquisition. There are several studies that looked at (\pm)-catechin exuded by spotted knapweed (*Centaurea maculosa* Lam.) that support this

theory (Inderjit et al. 2008) (Weir 2003). Although some results from the (\pm)-catechin studies showed chemical influences on native plant growth not all results were definitive.

There are also situations that promote plant invasions that are not theories but rather events that occur such as disturbances or an array of situations that result in plant invasions. Disturbances are gateways for plant invasions to begin. A disturbance is any event that disrupts the normal daily function of an ecosystem. They can be categorized as a natural event or the result of anthropogenic activity. Natural disturbances can cover massive areas and be catastrophic such as wild fires or insect outbreaks or smaller in scale like a fallen tree or a rut mark. Anthropogenic activity can also vary in size but the end state is the same. One of the most obtrusive and significant causes of manmade disturbances are caused by highway or road construction. Not only do they compromise the integrity of the soil horizons but they also generate corridors allowing more means of seed dispersal of all plants. In either scenario disruptions in plant populations or any component of the biotic community could lead to a plant invasion. And if well functioning ecosystems are compromised they might not be able to prevent an opportunistic invasive plant from establishing and over time change the plant population and eventually change the community dynamics.

Regardless of the mode of establishment, invasions occur, and they occur at various paces, some are slow while others happen rapidly. For example, Kudzu (*Pueraria montana* Lour.) it is often seen along roadsides, especially interstates, but can be found throughout the eastern one third of the United States. It grows up to one foot per day and over time it topples trees under its immense weight. It also destroys understory vegetation by blocking out sunlight with their broad leaf area (Bergman and

Swearingen 2005). It primarily devotes resources to leaf growth and elongation versus woody tissue for support since it climbs vertically using existing structures such as trees, telephone poles, or buildings.

Bitou bush (*Chrysanthemoides monilifera* spp. *Rotundata* (L.) T. Nord. is a woody shrub planted by the Australian government along the Australian coast from 1946 to 1968 in order to stabilize sand dunes. Its progression is slow and rather uneventful but the long-term consequences became very evident along the country's coastal sand dunes. Ens and French (2007) demonstrated how bitou bush affected indigenous plant size and structure. They compared three native Australian plant species, Australian fuchsia (*Correa alba*), *Monotoca elliptic* (Sm.) R.B., and *Lomandra longifolia* in two different locations. The first location was a non-invaded habitat and the other location was a habitat invaded by the bitou bush. Ens and French (2007) found that bitou bush exerted dominance over the indigenous species in both invaded locations by significantly reducing juvenile plant quantities.

Effects of plant invasions on the ecosystem

Plant invasions often reduce indigenous flora richness and abundance (Collier and Vankat 2002) and drastically alter ecosystems including the soil food web structure (Belnap and Philips 2001). When indigenous flora is displaced the changes in the food web structure cause voids in trophic levels further changing species richness and composition (Heleno et al. 2008). Invasive plants do this by imposing physical or chemical stress on indigenous plants. They often have an arsenal of techniques they employ in order to tolerate various environmental conditions such as herbivory, light availability, shade tolerance, drought, and even invasions from other plants. Similarly,

growth characteristics may play an important role in plant invasions. For example, invasive plants that flower earlier than native plants have the ability to sequester nutrients and establish roots before increased nutrient and light competition. These characteristics are balanced in their native habitat where the environmental conditions manage plant growth and several species flower at the same time giving each species equal access to available resources.

Japanese barberry has specific traits that promote its establishment. For instance, Japanese barberry changes its ability to capture photosynthetic energy and acclimate to available light conditions. Xu et al. (2007) looked at invasive Japanese barberry and two co-occurring understory shrubs, including mountain laurel (*Kalmia latifolia* L.) and high bush blueberry (*Vaccinium corymbosum* L.) and found that Japanese barberry flushed its leaves twice, prior to canopy closure and after the canopy closure whereas both co-occurring species did not. This is an important trait because as a plant because Japanese barberry can also contribute to ecosystem function by providing shelter for birds and small mammals, stabilizing soil with their root system, and providing oxygen, in balance with the costs of its potential invasiveness.

Roots systems

Plants rely on their roots to provide a continuous supply of nutrients. Therefore, it is important for root systems to be efficient and maximize nutrient acquisition. Once roots begin proliferating, they develop into root cap, zone of division, zone of elongation zone of maturation wherein each region of a root system demonstrates plasticity. Each zone provides different services, for example, the root cap protects exploratory ends of the young root cells; a zone of division contains the meristematic cells; the zone of

elongation pushes the roots cap through soil; and a zone of maturation where cells differentiate to serve different functions. Genetic clones from rhizomes have very different root system architecture (RSA) depending on the environmental loadings and competition (Osmont et al. 2007). Root structure and architecture are heavily influenced by macronutrients, especially nitrogen and phosphorous and to a lesser degree some micronutrients. Fluctuations in both sets of nutrients can lead to vast differences in root structure. But there is also evidence of endogenous molecules such as vitamin C, auxin, ethylene, cytokinins, gibberellins, and abscisic acid found in various plant root systems (Osmont et al. 2007) that contribute to root architecture. Therefore, RSA may be a result of a set of factors, all working in unison to provide the best possible structure for plant survival.

One aspect of invasive plants infrequently studied is the root system. Despite the abundance of invasive plant literature there is a significant void regarding root systems and their ecological significance (Fitter 1987). This is also true today. The lack of information is striking considering the root system is arguably the most important structure to ensure a plants success. Even plants that are prolific seed producers need roots, if the root systems are inadequate or unable to establish the potential plant will encounter immense stress and severe attrition. After a seed germinates, the roots initially provide support and anchor growing plants to their substrate. As the plant develops, roots also serve as the interface between the soil where thin roots extract nutrients and water. Roots of invasive plants must be aggressive and rapidly proliferate in order to provide a continuous and substantial nutrient supply. Without a robust root system or the ability to provide the above ground biomass with nutrients invasive plants might not be as

aggressive or persistent. Clearly roots are an integral part of an invasive plants ability to dominate a landscape.

There have been significant amounts of research conducted trying to understand mechanisms of invasive plants and how they become established. New and novel research is conducted every year, leading to many published articles about invasive plants. Over the past few decades there has been extensive invasive plant research. It generally incorporates some or all of the following ideas such as competition either between plants species (Wilson and Tillman 1995; Gorchov and Trisel 2003), alterations in the soil microbial community and mycorrhizal symbiotic relationships with root proliferation (Hodge et al. 2000), short and long term impacts of invasive plants on ecosystems, or the effects of invasive plants on soil carbon and nitrogen (Ehrenfeld 2003, Kourtev et al. 1998). Other research involves manipulating litter treatments (Bartuszevige et al. 2007; Kourtev et al. 1998; Ross 2008).

There have also been studies demonstrating roots are symbiotically associated with soil microbes (van der Putten et al. 2007) (Calloway et al. 2004) and other biotic activity. However, most root system or root related research involves invasive grasses and trees and not invasive shrubs. However, a study by D'Antonio and Mahall (1991) found that ice plants, (*Carpobrotus edulis* (L.) N.E. Br) inhibited growth of two native coastal shrubs *Haplopappus ericoides* Less. and *Haplopappus venetus* H.B.K. in California. They noticed morphologic differences in both plants when it grew in the presence of ice plants. In the presence of ice plants the native plants root systems were more vertically arranged, penetrating soil deeper whereas the same native plants grown independently from ice plant were arranged more horizontally and closer to the soil

surface. After the ice plant was removed, both native species showed an increase in below ground and above ground biomass.

Even in the midst of the most sophisticated technological era, scientists cannot accurately determine where, how, when, and why a plant invasion will take place. Therefore, we must continue to investigate all possible aspects of invasive plant development. Roots have been neglected even though they play a significant role in growth and development.

Key components of soil in plant development

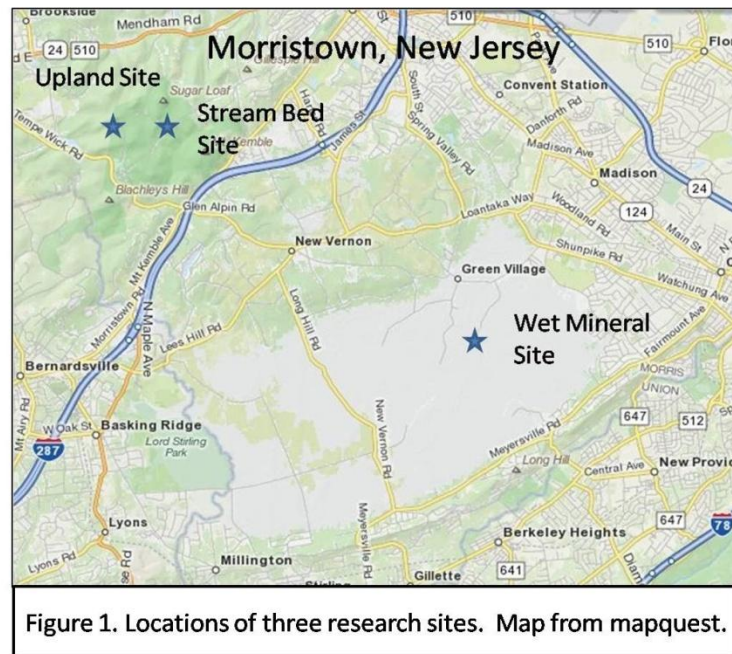
Soil is multifunctional and a key component to life on earth. Different regions possess unique properties that develop over time. Hans Jenny's work (1941) set the modern standard for soil formation principles. He determined the primary factors influencing soil formation are parent materials, climate, biota, topography and time. The location of my two research sites is a heterogeneous mixture of metamorphic schist and gneisses and post-glacial surficial deposits. The soil is mainly homogenous over small scales such as meters and hectares but changes are more likely to occur over large scales such as kilometers when influences such as biotic activity and slope take effect.

Understanding soil properties is also essential when studying root systems because different soil properties will determine root structure and development. Soil texture, pH, organic matter, and macronutrients were the key properties I measured at each site. These properties collectively influence root movement, hydrology, water holding capacity, and root growth. Additionally it will help with demonstrating plants do not grow equally, even within species plants possess plasticity allowing them to adapt to continuously changing environments.

Methods and Materials

Research Locations

Japanese barberry seedlings were harvested from three separate sites at two locations in northern New Jersey, USA, (see Figure 1). All three sites are similar in climate with an annual mean temperature of



10° C and receive the same annual precipitation approximately 1350 mm. The first site is Jockey Hollow, a portion of Morristown National Historical Park, in the vicinity of Morristown, NJ (Lat N40° 46' Long W74° 32'). At this location two soil types were present, an upland soil and the stream bed soil. They will be referred to as Upland (UP) and Stream Bed (SB), respectively. The vegetation at both sites in Jockey Hollow is characterized by mixed deciduous overstory at various ages of maturity (Kourtev et al. 1998). The native understory is extremely sparse, due to intense deer browse whereas the invasive plants rarely showed evidence of deer browse. There are two very abundant invasive plants present, *Microstegium vimineum* (commonly Japanese stiltgrass) and Japanese barberry. The first site is located on a gentle hill slope, and is designated as the Upland (abbreviated 'UP') site. This soil is characterized by the United States Department of Agriculture Web Soil Survey (USDA WSS) as a Parker gravelly sandy loam. The water table is generally greater than 203 centimeters with a mean organic

horizon depth of 2.54 cm. Its parent material is residuum weathered from granite and gneiss. The second site is located along a wetland area adjacent to the Primrose Brook, a first-order stream arising about 0.5 km upstream of the study area. This site is referred to below as the 'Stream Bed' (abbreviated 'SB') site. According to the USDA WSS, the predominant soil type in this area is Cokesbury loam, which is classified by the NRCS as a hydric soil. The parent material is till derived from gneiss and/or colluvium derived from gneiss. The water table at this site is generally less than 30 centimeters with the average organic horizon in the areas sampled of 6 cm. The organic horizon depth was the primary difference between SB and WM sites. The second location is at the Great Swamp National Wildlife Refuge, Chatham, NJ (Lat N40° 43' 36" Long W74° 27' 26"), a large mineral, flat, wetland. At this location, an invaded site on a contrasting wetland soil, the Parsippany silt loam, was located. This soil is characterized by sandy loam substratum, 0-3% slopes, and frequently flooded. Its parent material consists of fine glaciolacustrine deposits derived from basalt, shale and granitic gneiss material. The water table depth at this site ranges from 15-46 centimeters with a mean organic horizon depth of 1.5 centimeters.

Plant Collection and Processing

In April 2008 all three sites were surveyed to verify that adequate sample sizes of Japanese barberry seedlings were available to conduct a valid study. Based on my initial survey of each site I determined a total sample size of 30 seedlings, 10 seedlings per site per date would provide an adequate data set for accurate statistical analysis providing all data were normally distributed and passed a normality test. In May 2009 I identified 40 seedlings from each site and marked their locations with numbered orange flags. I

marked as many seedlings as possible to ensure I would have enough plants to harvest throughout the study. Identifying and marking all seedlings at the beginning of the study was priority while the cotyledons were still attached which confirmed they were 2008 seedlings. This would also ensure age continuity and make subsequent plant harvests easier. The plot size surveyed and used to harvest the prescribed 40 seedlings varied because seedling density varied at each site. In the UP site the area measured 50m by 100m, the SB site measured 25m by 200m, and the WM site measured 30m by 30m. The first 10 plants were harvested from each soil type in July 2008 during optimal growing conditions of maximum daylight, warm temperatures and moist soils. Based on prior observations, we estimated the seedlings were about 1-2 months post-germination at the time of harvest. The second harvest was conducted in October 2008 at the end of the growing season during decreasing daylight and cooler temperatures as plants were undergoing physical and chemically driven seasonal changes. The final harvest was done in December 2008 after above ground growth is complete for the season and dormancy is set. All plants were harvested by digging a 30cm by 15cm deep hemisphere around each plant. The larger than required area excavated ensured all roots were captured and to minimize root damage. The excess soil was removed by supporting the root mass and then gently agitating and shaking the root ball. Once all the loose soil was removed, the samples were placed in a labeled five-gallon bucket with approximately 1L of local stream water to prevent desiccation and to soften remaining soil. Each plant took roughly 20 minutes of preparation in the field. During the harvest if any plant roots were damaged during the initial field processing the sample was discarded. All samples remained in the water for 24-96 hours in order to soften the soil encasing some roots.

The samples were checked 2-3 times per day to agitate the buckets to help remove any additional attached soil. Once all the soil was removed from the roots systems the roots were cleaned a second time under water with a 5mm wide synthetic watercolor paintbrush. The paintbrush was ideal since it gently removed any remaining soil from roots forks and hairs revealing the true root dimensions. After all cleaning, each seedling was preserved in 70% isopropyl alcohol.

Plant Analysis

Based on the series of analyses I planned to perform on the seedlings, it was important to make sure the testing sequence did not damage the plants. If the seedlings were damaged, the plants structure would be compromised and the analyzed image would yield inaccurate results. The first series of testing was using the software package called WinRhizo. The WinRhizo package consists of a Hewlett-Packard scanner, computer workstation, and software. This was done first because it scans the entire plant and saves the image to a database. Each Japanese barberry seedling was removed from the preservative and blotted dry. In order to ensure accurate measurements each plant was divided into below-ground biomass (roots) and then above-ground biomass (leaves and stems). The above-ground biomass was further divided into two separate groups, the leaves and petioles and the stems. Not all plant sections were analyzed separately in this study. This will ensure accuracy, consistency, and also aid in organizing images during analysis. Once the seedlings are scanned they converted from analog to a digital .tiff file format. Once all seedlings were scanned and digitized the images were organized into separate folders. They were first categorized by soil type at their harvest location (Jockey Hollow Upland (UP), Jockey Hollow Stream Bed (SB), and Great Swamp Wet Mineral

(WM) and then by month harvested. The seedlings were further categorized into subfolders i.e. roots, leaves, and stems. The WinRhizo program analyzed the .tiff images by batch and established the output into a text file. For the below ground biomass (roots) I measured total root length, number of tips, and number of forks. For the stems I measured surface area, volume and total length. After completing each scan the samples were placed back into the preservative until I was certain all scans were accurate and no visual errors were made, for example overlapping leaves or stem touching the roots.

In the next step I prepared the samples for future arbuscular mycorrhizae analysis. The analysis was not carried out for this study but I extracted .5 cm of root tip from three different sections of the root system totaling 1.5cm from each plant. The purpose of obtaining three separate sections was the total root length for each plant was rather small, especially in the July SB seedlings. By using an analytical scale I determined I could remove 1.5cm of root without changing the scales digital display. Although roots tips were removed and the root mass was lighter, the precision of the analytic scale did not detect the change. If I removed any sections totaling greater than 1.5cm it would cause a change in the digital readout and therefore change the output of any statistical analyses. The second set of analyses I performed was determining the above-ground and below-ground biomass. I decanted the alcohol and left the entire plant in its container. The plants were placed in a rack in a drying oven for 72 hours at 65° C. After the plants were dry they were placed into a container with desiccants to reduce water absorption during transport and weighing process. Each plant was separated into its three parts and weighed using an analytical scale.

Soil Collection and Processing

Before collecting the soil samples I removed all leaf litter from localized forest surface where the soil would be extracted. This exposed the top soil layer, usually the organic horizon if present. Soils at all three sites were collected using a 2.54cm diameter soil corer. I collected the top 7cm of soil because that was the approximate maximum root depth I observed when harvesting the seedlings. I collected 15 subsamples for each sample within a one m² plot area. This technique was repeated so I had five samples from each site. I thoroughly mixed the 15 subsamples in a sealable bag. The purpose of collecting 15 samples was to ensure the soils collected accurately represented the harvest site and to reduce any spatial soil chemical variations or soil anomalies.

Soil Samples Analysis

The purpose of the soil analyses was to provide a chemical and texture profile of the soils. All soil samples were processed and tested at the Rutgers University Soil Testing Laboratory, New Brunswick, NJ. Samples were dried and sieved with a 2mm sieve prior to analyses. Each sample, 15 total, was tested for pH, %Sand %Silt and %Clay using a mechanical analysis (MA) technique, Nutrient extraction using the Melich III technique, and Organic Matter using the Walkley-Black procedure from methods for the determination of total organic carbon (TOC) in soil and sediments. From the previous procedures I was able to directly measure the soil for the following chemistries: pH, Phosphorus, Potassium, Magnesium, Calcium, Manganese, % sand, % silt, % clay, and organic carbon. I was able to estimate the Cation Exchange Capacity which is the total amount of extractable cations that can be held by the soil, expressed in terms of

milliequivalents per 100 grams of soil at neutrality (pH 7.0). Standard methods were used to determine the CEC (Anon. – SSSA reference).

Results

Soil Analyses

All three sites are unique in location, hydrology, and vegetation however the soil properties measured were remarkably similar. The average organic horizon (OH) depth for Upland (UP), Stream Bed (SB), and Wet Mineral (WM) soils were 0.5 cm, 1.0 cm, and 1.0 cm, respectively. Mean water level depth was not measured during the soil analysis but according to the USDA WSS the average water level at UP, SB, and WM are 203cm, 35cm, and 15-46cm, respectively. Based on observations and assessment of each location I confirmed their information. Table 1 summarizes all chemistries and physical analyses performed on each soil sample. Two chemistries that were significantly higher than normal averages were magnesium and calcium. But magnesium and calcium were elevated in all three soils types and therefore were not considered a significant contributor to growth or development.

Root Length

In the UP site, root length increased rapidly between July and October, but slightly decreased during autumn (Table 2). The SB site also showed continuous growth from July to October and continued increasing until December. In contrast the WM site, root length remained relatively unchanged from the first to the last sample, implying that no new root length was added after the initial flush of growth when the seedlings established.

Although Japanese barberry bushes are well established at all three locations, the seedling total root length varied considerably between sites. The greatest period of initial growth in July occurred in the UP soil with an average seedling root length of 423mm in contrast with the SB seedlings with an average root length of 49mm. Although the SB root length lagged behind both the UP and WM sites it demonstrated the greatest increase in growth from July to December, 78% (Table 3), in contrast with the WM seedlings that decreased by 50%, (Table 3). Although the UP seedlings overall length increased by 48% from July to October it was the only site that decreased, by 14% (Table 3), from October to December. Despite the aggressive initial growth by the WM seedlings they ended the growing season with the shortest overall root length of 31cm.

When comparing the differences in root length over time the analysis of variance (using SigmaPlot) followed by Holm-Sidak post-hoc tests showed there were significant differences in the SB seedlings from July to December and October to December, ($P<0.001$ and $P=0.021$), respectively but no significant changes in root length from July to October. The UP seedlings demonstrated significant growth from July to October and July to December, ($P<0.001$ and $P=0.004$), respectively, for differences between months but did not show any significant growth from October to December. There were no significant changes in root length during any period for WM seedlings.

When using the same method but looking within sites, during July, there was significant growth in the SB sites when compared to UP and the MW sites ($P<0.001$ and $P<0.002$) but there was no significant change between the UP and WM. In October a different pattern emerged. There was significant growth between SB and UP sites ($P<0.001$) and between the MW and UP sites ($P<0.001$) but no significant change

between SB and WM. The same pattern occurred in December. There were significant changes between SB and UP sites, ($P=0.006$) and the WM and UP sites, ($P<0.001$) but no significant changes between the WM and SB sites.

Root Tips and Forks

The number of tips and the number of forks showed the same pattern of growth as root length. Both the UP and SB seedlings increased in both tips and forks from July to October. However, the SB site seedlings continuously grew through autumn unlike the UP seedlings that decreased. The WM seedlings did not change in comparison to the seedlings from the other sites.

The greatest percent change from July –October occurred in the SB seedlings with an increase in tips and forks of 83% and 93%, respectively (Table 3). The UP and WM seedlings average number of tips and forks during July only differed by 1.9 tips and 9.5 forks (Table 2). However, the UP seedlings showed a much greater percent change from July-October in tips and forks, 73% and 73% (Table 3), respectively, in contrast with the WM tips and forks, 9% and 0% (Table 3), respectively. The WM and SB seedlings increased in both tips and forks from October to December unlike the UP seedlings that decreased by 12% (Table 3) in both tips and forks during the same period. Although the roots in the SB site started growing very slowly they continuously increased in tips and forks from July to December.

When comparing the differences in number of tips over time, the analyses of variance showed there were significant difference in the SB seedlings from July to December and October to December ($P<0.001$ and $P=0.015$), respectively but no significant changes in root length from July to October. The UP seedlings demonstrated

significant growth in tips from July to October and July to December ($P < 0.001$) and ($P < 0.001$), respectively but did not show any significant growth in tips from October to December. There were no significant changes in number of tips during any period for WM seedlings.

When using the same method but looking within sites, during July, there were no significant changes in number of tips. During October there were significant changes in the number of tips between SB and UP sites ($P < 0.001$) and between the MW and UP sites ($P < 0.001$) but no significant change between SB and WM. There were also significant changes between SB and UP sites ($P = 0.018$) and the WM and UP sites ($P < 0.007$) but no significant changes between the WM and SB sites.

Seedling Biomass

During seedling harvests, each shoot, to include stem and leaves, showed the same visual characteristics in appearance among all three sites. Each seedling, regardless of location, presented 2-4 leaves and the shoot height and diameter also appeared similar among sites. This was contrary to how the root structures appeared. The seedling roots clearly showed striking visual differences between sites over time (Figures 1-9).

Table 4 compares the below-ground-biomass, the above-ground biomass and the root to shoot ratio. The only seedlings to show increases in above-ground and below-ground biomass from July to December were from the SB site. However, the SB seedlings showed the smallest increases in the root to shoot ratio. The WM seedlings continued to demonstrate consistent growth trends similar to root length. The WM biomass stagnated or only slightly changed after the initial harvest and did not increase in mass through October. During the December harvest the overall mass of above and

below ground increased slightly from previous months. The WM seedlings with the greatest change in root to shoot ratio occurred from October to December. The UP seedlings above-ground biomass was relatively consistent but the greatest increases in below-ground and above-ground biomass occurring from July to October. The root to shoot ratio also increases the greatest from July to October.

Two way ANOVAs were performed on the data set but the normality test and the equal variance test failed for all biomass data sets, therefore making the results possibly invalid. Although the previous tests failed statistics based on the Holm-Sidak Method there was no significance between any months at the WM site. However, the UP site showed significance between all three months DEC vs. JUL and OCT vs. JUL ($P=0.017$ and $P=0.025$), respectively. There was also significance of variance between UP vs. SB in OCT vs. DEC ($P=0.017$, $P=0.017$) and UP vs. WM in OCT vs. DEC ($P=0.025$ and $P=0.025$), respectively. There were no significant interactions between the WM and SB during any month. For the below-ground biomass, the areas with significant variation in data are in the WM site between JUL vs. DEC and OCT vs. DEC ($P=0.017$ and $P=0.025$), respectively, and also at the SB site between DEC vs. JUL ($P=0.107$). For the below-ground biomass when comparing sites within months there is significant variance in JUL between WM vs. SB and UP vs. SB ($P=0.017$ and $P=0.025$), OCT between UP vs. SB and WM and SB and UP vs. WM ($P=0.017$, $P=0.001$, and $P=0.031$), respectively. There was also significance in DEC between UP vs. WM and UP vs. SB ($P=0.017$ and $P=0.025$), respectively. The Root to Shoot ratios showed the same patterns with significant variance at all three sites WM, SB, and UP between DEC vs. JUL ($P=0.017$, $P=0.017$, and $P=0.017$), respectively and also in the SB and UP sites between OCT vs.

JUL ($P=0.025$ and $P=0.025$), respectively. There was also significant variance in OCT and DEC between SB vs. UP ($P=0.017$ and $P=0.025$), respectively and in JUL and OCT between UP and WM ($P=0.025$ and $P=0.025$), respectively.

The below-ground biomass, shown in Table 4, compares seedling root biomass at each site over time. It shows a consistent pattern similar to root structure complexity (length, tips, and forks). However, unlike reductions in total root length, numbers of tips, and numbers of forks, the root biomass increased each month from July to December at each site (Table 4). The site with the greatest overall percent increase in seedling growth is the SB seedlings with a net increase in both below-ground and above-ground biomass of 50% and 91%, respectively (Table 5).

Discussion

Based on the results from this study I have concluded that my first hypothesis, that root growth pattern would be different in different soil types, is substantiated by the results. Root development, as measured by a set of root architectural descriptors, does vary in soils of different types. Why they grow differently is debatable. The soil, although different in proximity from one site to another, does not show any significant differences that would suggest why the roots developed like they did from July through December. My second hypothesis, that root system structure will be highly correlated with above-ground biomass, such that the root system can be predicted by the measurements of the above-ground tissue does not appear to be supported, at least by patterns of growth at the early stages of development.

As for root development, there are clear indications based on the results that given different growing conditions, Japanese barberry roots respond differently and employ

different growing strategies. For this study each site had unique environmental conditions that are defined by the local weather, soil composition, soil chemistry, soil texture, flora, hydrology, and canopy density, to name a few. However, not all of these factors were measured; instead, a select few were measured to determine the specific role, if any, they contributed to subterranean plant development. Of the measured factors, the soil composition including soil chemistry and texture were relatively consistent among all three sites. The percentages of sand, silt, and clay were consistent at all three sites and there were no apparent growing advantages between sites, i.e. the soil had a higher clay percentage and therefore had higher mineral availability. This was also the case for the soil chemistries measured. All of the micronutrients and macronutrient measurements were also relatively consistent among all three sites except for three chemistries. In the UP soil the potassium level was much higher, 22.6 kg/ha whereas the WM and SB soils were 5.0 kg/ha and 6.4 kg/ha, respectively. Although there is a great difference, the higher value is still very low. This is also the case for calcium and magnesium. It appears there is a great disparity among all three sites but even the high values are below the normal ranges. Ultimately, all of these soils have low nutrient availability for plant uptake.

After reducing the focus on soil nutrients as a main contributor to root development the other and more probable cause for changes in root growth and development was hydrology. Since each site was subject to the same environmental conditions and all three sites are within 10km of each other, all three sites experienced the same climate conditions (temperature, precipitation, light availability). The one aspect of hydrology that could contribute is the water table. Each area, based on the USDA WSS

has a distinct water table. And based on each sites water table, there is a direct correlation to root structure. In addition, two of the soils (Cokesbury in the SB site, and Parsippany in the WM site, are classified as hydric soils, implying that they experience prolonged soil wetness. The higher the water table the smaller the root structure. In the wettest area, the SB soil, the ground in the general area of the harvest is saturated during all three harvests but not at the other sites. The roots were most likely reduced in length due to anoxic conditions as a result of the saturated soil. In areas where water was restricted the seedling roots were required to explore for water and therefore their root structure became extensive. This is clearly evident by looking at Figures 1,4,and 7. They represent the July harvest and show a great difference in areas with limited water (UP) to increased water availability (WM) to a saturated soil (SB).

As for my second hypothesis, I initially thought I would be able to determine the below-ground biomass based on the above-ground biomass of invasive Japanese barberry in different soils. There are trends in the early stages of development that suggest that young seedlings have very little need for complex root structures if water is not limited, (Figure 1). This approach could provide an alternate management tool for controlling invasive Japanese barberry and even other species if clear conclusions can be drawn. Although there are many differences among plants there are many similarities. So any treatment would require a specific application to attack the plant in an area that makes it vulnerable. If a plant can be manipulated to recognize it is in a hydric soil, the plant roots will not proliferate in search of water and therefore dry out and wither. However, it is not apparent at this time that the trends seen in early growth are consistent at older plants and soil hydrology has not been proven to be a primary contributor to root structure. This

area would require additional research to determine how indigenous flora seedlings respond in comparison to invasive species.

Conclusion

Although there are variations in Japanese barberry seedling growth in different soil types it is not clear at this time why they occur. I tested various soil chemistry properties to determine if there was a significant difference between sites but found no conclusive evidence they were a primary contributor or contributed at all to root structure. But in order to ensure soil chemistries do not play a significant role, additional macronutrients and micronutrients should be tested to provide a comprehensive soil chemistry profile.

There are also many variables that were considered but not tested that collectively influence root structure and development. Variables such as canopy density may be highly correlated with root structure since solar radiation is a key component of any photosynthetic plant. Additionally, there are many community dynamics and interactions between plants and animals as well as plant-to-plant that contribute to the overall function of a habitat and may influence root development. To truly gain a full understanding of the factors contributing to invasive Japanese barberry seedling root development all of these factors need to be incorporated into a comprehensive study.

The primary conclusion I was able to determine from this study based on what I measured or observed is the role hydrology contributed to the over root growth. There are consistent trends in my data that suggest root growth is highly correlated to water availability might be the primary reason in the variations between sites. Looking at

hydrologic effects on invasive plants might be a key factor not only in root development but also in plant invasiveness.

	SB	WM	UP
pH	5.2	5.1	5.5
% Sand	49.8	53.0	45.0
% Silt	33.4	34.0	37.2
% Clay	17.0	13.0	18.2
P k/h	2.8	2.4	1.9
K k/H	6.4	5.0	22.6
Mg k/h	98.7	68.9	54.9
Ca k/h	536.8	365.0	306.0
% SOM	6.0	5.1	5.6
% SOC	3.5	2.8	3.3
*CEC	12.6	9.6	8.9
Table 1. Mean measured soil properties for three locations: Stream Bed (SB), Wet Mineral (WM), and Upland (UP). *calculated results			

	Site	% Change July-Oct	% Change Oct-Dec
Root length (cm)	SB	78	51
	UP	49	-14
	WM	-50	22
Root Tips	SB	83	55
	UP	73	-12
	WM	9	42
Root Forks	SB	93	57
	UP	73	-12
	WM	0	37

Table 3. Percent changes between sites over time.

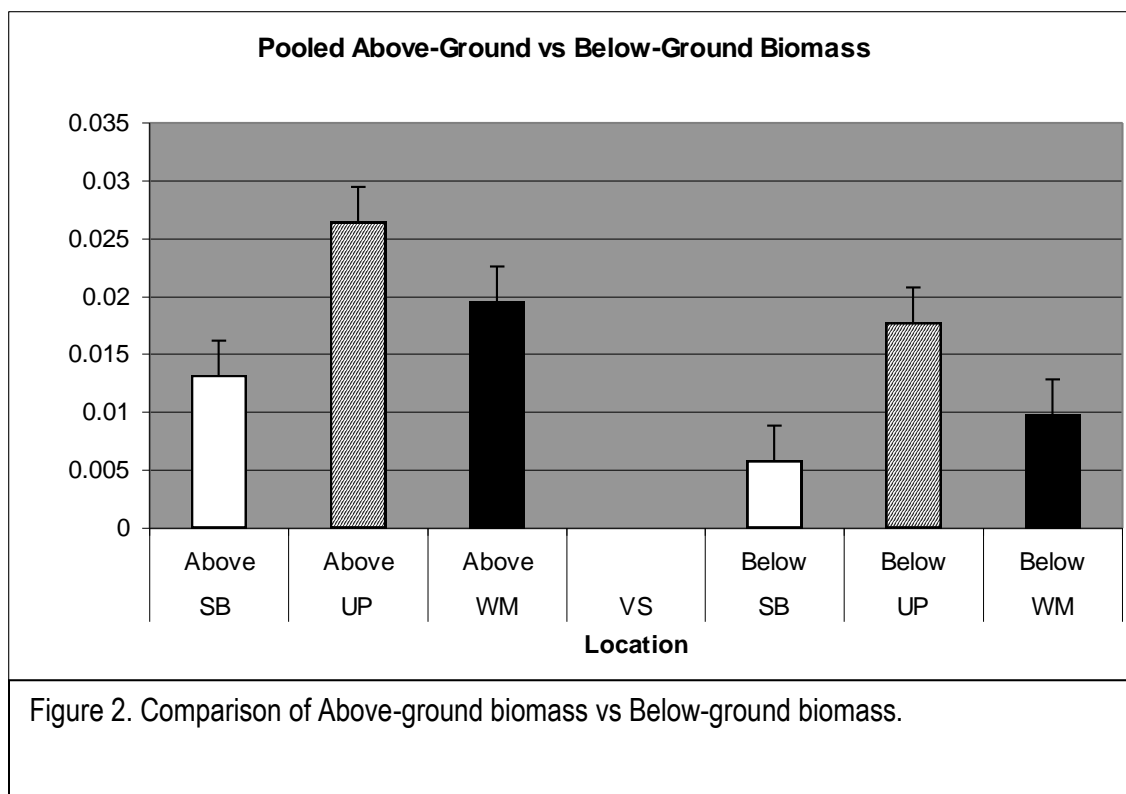




Figure 3 SB
July 08



Figure 4 SB
October 08

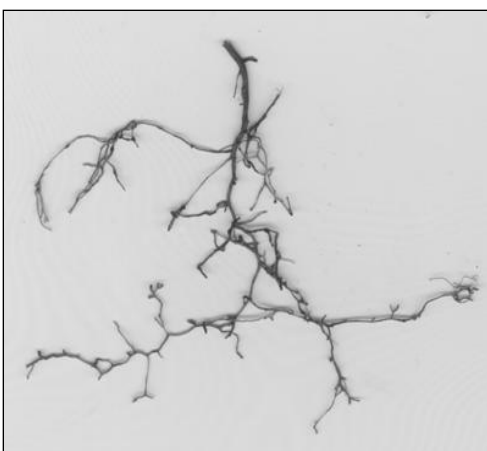


Figure 5 SB
December 08

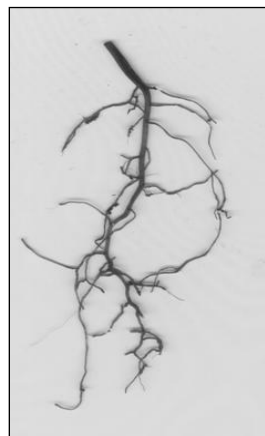


Figure 6 WM
July 08

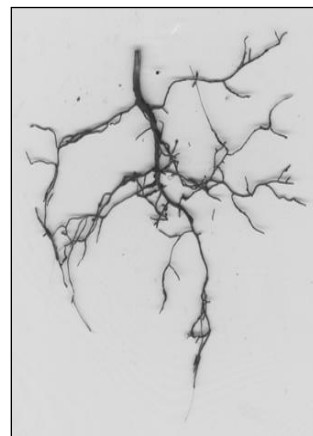


Figure 7 WM
October 08

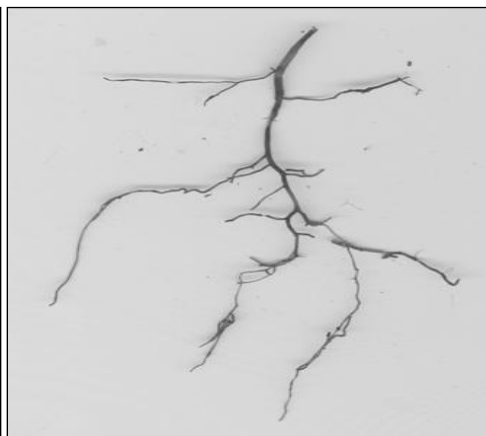


Figure 8 WM
December 08

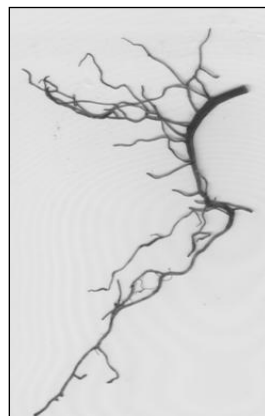


Figure 9 UP
July 08

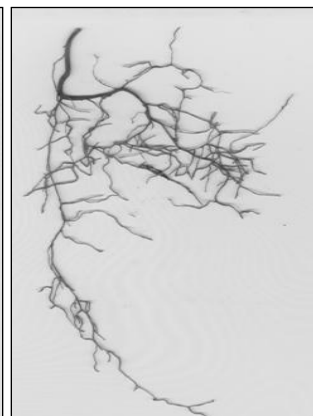


Figure 10 UP
October 08



Figure 11 UP
December 08

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