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Distribution and growth of autumn olive in a managed landscape

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To the Graduate Council:

I am submitting herewith a thesis written by Matthew Ruddick Moore entitled "Distribution and growth of autumn olive in a managed landscape." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

David S. Buckley, Major Professor

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Distribution and growth of autumn olive in a managed landscape

A Thesis Presented for
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Degree
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Matthew Ruddick Moore
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Dedication

This thesis is dedicated to my wife and family. Without your support and encouragement, Ellie, I would not have been able to successfully complete this work. You have helped me directly in the field, going with me to collect data, and at home, keeping everything running while I was buried in work. You truly are the only woman who could put up with me. To my parents, Keith and Rita, thank you both for making sure that I did things to the best of my ability and that I always had the opportunities that would help further me. To my sister, Sarah, thanks for showing me what it means to give something your all to achieve your goals. Finally, I want to thank my brother-in-law, Chase, for sharing my interest in comics and being one of the few people I can talk to about nerdy things of that nature.

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Abstract

Invasions by exotic plant species result in significant challenges for forest managers. Disturbance and increased light have been shown to facilitate the successful establishment and invasion of exotic, invasive plant species. Several studies have sought to determine which key factors lead to greater abundance of exotic, invasive plants on certain sites and this information is important for determining the likelihood for exotic plant invasions at broad scales. Site characteristics that may promote autumn olive (*Elaeagnus umbellata*) were studied. Our goal was to identify variables associated with forest road edges most important in explaining autumn olive abundance and growth. The objectives were to: 1) investigate whether southern aspects have greater abundance and height of autumn olive than other aspects, 2) determine if there is a negative relationship between the abundance and height of autumn olive and the abundance and height of native species, 3) determine if the relationship between autumn olive abundance and height and other invasive species abundance and height is positive and 4) document other site factors significantly related to the success of autumn olive. Larger autumn olive were more dense and patches of autumn olive were deeper on certain forest-road edges. Autumn olive height and abundance were positively related to both native and exotic, invasive plant height and abundance. Road canopy cover, slope, elevation, road opening width and road type were found to be important for autumn olive establishment and success. These factors will be investigated for future use in producing GIS based risk maps to assist managers in exotic, invasive species control.

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Introduction

Due to their economic and ecological impacts, exotic, invasive species represent one of the most significant challenges facing managers in the 21st Century. Estimates of the annual, direct cost of exotic species invasions in the United States alone range up to $137 billion (National Invasive Species Council 2001), and the total cost associated with the control and eradication of exotic species is unknown. Investments in direct removal or tactics to prevent the further spread of exotic, invasive species comprise only a portion of their overall costs, which also include costs associated with their detrimental impacts on native plant and animal species, crops, and changes in ecosystem properties and processes (Vitousek 1990). Emory et al. (2011) found that understories invaded by Japanese stilt grass (*Microstegium vimineum*) burned 300-400ºC hotter than understories without this species, and that these higher temperatures were sustained for 20-30 seconds. This change in fire behavior illustrates how the addition of one exotic species can directly alter ecosystem processes and properties, which, in turn, may impact co-occurring species and other ecosystem processes and properties.

Prevention, early detection, and eradication are preferable to mitigation measures applied long after an exotic species invades and becomes entrenched. As a result, a proportionally large share of the resources spent on exotic, invasive species has been invested in the development of identification guides, fact sheets, and control techniques (Darlington 1994, Haber 1997, Heffernan 1998, Miller 2003, Tennessee Exotic Pest Plant Council 2009). Clearly, these investments are extremely important in addressing invasions by exotic species, but it can also be argued that an increased

emphasis on understanding the ecology of many exotic species would help managers predict when and where a given species is most likely to invade and more effectively prioritize control efforts.

Although exotic species vary widely in terms of adaptations, strategies, and habitat requirements, some similarities have been identified through previous research. One such similarity is that many exotic, invasive plant species benefit from site disturbance (Bergelson 1993, McGlone 2009) where there are higher levels of photosynthetically active radiation (PAR) than those found in undisturbed sites in order for establishment (Spence 2011). Oswalt et al. (2007) found that invasion by Japanese stilt grass was aided by the removal of leaf litter. Further, Marshall et al. (2007) found that the rate of spread of Japanese stilt grass increased substantially with leaf litter removal and mineral soil disturbance. Although Japanese stilt grass is ranked as shade-tolerant (Winter 1982, Barden 1987), increases in the height and abundance of this species with decreasing canopy cover have also been reported (Winter 1982, Marshall 2007), suggesting the importance of the combination of both canopy and soil disturbance in the success of this exotic, invasive species. Garlic mustard (*Alliaria petiolata*), a species well known for its ability to invade shaded understories, has been shown to produce greater total biomass in environments with increased amounts of light (Meekins and McCarthy 2000, Myers et al. 2005). As a result, this species is also likely to benefit from canopy disturbance.

In managed forest landscapes, the combination of high PAR levels and soil disturbance most frequently occurs along forest road edges and in recently harvested

areas. In addition to the favorable PAR conditions and soil disturbance along their edges, roads act as conduits for the dispersal of plant and animal species. Roads connect cities, suburbs, and agricultural land with wildland areas and roadsides serve as the point of entry for many exotic species. The importance of roads as sources of exotic species is highlighted by the positive correlation between the abundance of invasive species and the presence of roads nearby (Watkins 2002, Yates 2004, Flory 2006, Ibañez 2009). Although shade-tolerant species such as garlic mustard may invade undisturbed forest adjacent roads, it is common for forest management activities such as timber harvesting and prescribed burning to facilitate the spread of exotic species into interior forest areas. Given the importance of roadside edges in serving as primary sources of exotic propagules for invasion of adjacent forest areas under management, managers need an increased understanding of the types of roadside edges that are most important in providing suitable habitats for different exotic, invasive plant species.

Forest road edges often have increased PAR levels and some form of soil disturbance in common, but can differ substantially in terms of factors such as aspect, the depth of edge effects, age of the edge, and species composition. Whether trees are removed to create roads or other, more extensive forms of development, anthropogenic reductions in forested land reduce the size of remnant forests and create new forest edges (Murcia 1995). A forest edge occurs where a narrow transition zone separates an ecosystem consisting of forest species and an adjacent ecosystem unique from that of the forest (Harris 1988, Chen 1992). The degree of change along forest edges

determines their effects on adjacent forests. Creation of a new forest edge has the potential to alter environmental characteristics of the forest (Wales 1972). Increased light can lead to an increase in air temperature and soil surface temperature (Geiger 1950, Chen 1995) and directly or indirectly cause a decrease in soil moisture within the forest edge (Oosting 1946). The importance of outside forces acting upon the forest can also increase. For example, the moderating effect of forest vegetation on wind is greatly reduced with the removal of trees, and the turbulence and windspeeds along forest edges often result in greater mortality of dominant over-story trees from windthrow (Chen 1992).

The depth of these edge effects depends upon several factors including the size of the adjacent opening, the age of the edge, management practices for the forest and adjacent lands, edge aspect, and the composition of the forest (Wales 1972, Matlack 1993, Gehlhausen 2000, Dignan 2003, Denyer 2006, Dale 2009). As edges age, the development of foliage throughout the vertical profile exposed to the edge increases and buffers the interior forest from edge conditions to some degree. Due to the elevation of the sun and predominant angles of incoming radiation, small openings and edges with a northern aspect result in less pronounced edge effects than large openings and south-facing edges (Williams-Linera 1990). Previous research suggests that in general, those forest edges that receive more direct sunlight have deeper edge effects (Gehlhausen 2000). In the northern Hemisphere, this leads to the conclusion that northern aspects should have the shallowest edge effects, southern aspects should have the deepest edge effects, and the depth of edge effects along edges with eastern and western

aspects should be intermediate between these two extremes (Burgess 1981, Palik 1990, Matlack 1993, Fraver 1994, Chen 1995, Gehlhausen 2000).

Forest edge characteristics directly impact microsite variables that, in turn, affect the forest biota. Altered microsite conditions can produce changes in forest species composition, woody and herbaceous stem density, and growth. Edge effects can result in microclimate regimes that favor shade-intolerant plants, such as native conifer and hardwood pioneer species, and also exotic, invasive plant species. These compositional shifts occur where there are increases in light as well as increased disturbance. Changes can also result in increased forest density towards the edge as both shade-intolerant (Wales 1972, Palik 1990, McDonald 2004) and shade-tolerant species (Williams-Linera 1990) respond with increased growth rates, taking advantage of higher resource levels. Greater levels of resource availability also benefit regeneration of shade-intolerant species (Ranney 1978) and some shade-tolerant species (Chen 1992) near a forest edge, causing additional increases in forest density.

The diversity of native plant species has been suspected of affecting the ability of exotic, invasive species to successfully infiltrate specific habitats. Several authors have purveyed the concept that the more diverse the native plant population, the fewer exotic, invasive plants are present (Elton 1958, Lodge 1993, Lonsdale 1999, Davies 2007). The reason for this negative relationship between native and invasive plants is that there are fewer niches available for exotic, invasive plants when native plant diversity is high. Researchers have found that the relationship between the diversity and abundance of native species and exotic, invasive plants can be negative, positive

(Howard 2004, Davies 2007) or have no relationship. In addition, native plants are thought to be outcompeted on sites with more exotic, invasive species, which decreases their abundance (D'Antonio 1998, Meiners 2001, Greene 2012).

The concept of native diversity repelling exotic invasion does not connect well with the mixed relationship found in experiments. Another theory is that certain sites have greater successful exotic, invasive species establishment because some characteristic makes them more susceptible to invasion than other sites. Invasibility is a term used to describe sites with specific characteristics that make them more vulnerable to exotic, invasive species establishment. Studies conducted on this topic have caused authors to conclude that broad site variables allow certain areas to be invaded more readily than others (Mosher 2009) or that no single group of site characteristics is sufficient to explain differences in exotic, invasive species success (Hill 2005). However, with disturbance of sites leading to successful establishment of many exotic, invasive plant species, more exotic, invasive species should be present at these sites assuming there are several inoculating populations proximal to the disturbance.

An important and often ubiquitous exotic, invasive shrub occurring along road edges is autumn olive (*Elaeagnus umbellata*). Autumn olive was introduced from Asia to North America in the 1830s. It was originally planted on disturbed sites to provide cover and food for wildlife and stabilize the soil (Fowler 1987, Darlington 1994). Once the distinguishing physical characteristics are known, the shrub is very easy to distinguish from most woody plants except Russian olive (*Elaeagnus angustifolia*). Having leaves with a dark green upper surface, a silvery underside with small orange flecks, and an

elliptical shape, this shrub stands out among the other plants in the central hardwood forest landscape. Autumn olive can attain heights up to 7m and their growth form can be upright, arching, or a mixture of upright and arching forms (Kohri 2011). The bark of autumn olive is usually smooth and brown, but occasionally becomes scaly as the plant matures (Darlington 1994). Typically single-stemmed as a seedling, the plant has the potential to produce many belowground offshoots from the main root as it becomes older. The main trunk produces a limited amount of branches, favoring instead the production of new stems at ground level. Both the branches and the main trunk produce sharp spines up to 2.54 cm in length. Autumn olive produces light yellow, campanulate, clustered flowers beginning in early spring. The flowers initially develop into small brown or olive green drupes that mature and turn bright red in late summer. These bright red fruits aid in identification of the species in late fall and winter after leaf abscission.

Generally, berry production begins in individuals aged 3 to 5 years (Fowler 1987). Berries of autumn olive do not readily separate from the plant. Instead, they persist on the branches into winter and provide a steady food supply for birds and small mammals when other sources of sustenance are less abundant (Fowler 1987, Darlington 1994, Kohri 2011). Once the fruit is consumed and the flesh has been removed, 99% of autumn olive seeds will germinate within 6 days. Those seeds that remain encapsulated within the fruit germinate over a period of one month at a rate of only 61% (Kohri, 2002). Kohri (2002) reports, from unpublished personal observations, that an autumn olive stem 5cm in diameter is capable of producing approximately 5,000 red

fruits, and that a stem with a height of 3m can produce as many as 10,000 berries in a season. In addition, frugivorous birds preferentially consume autumn olive fruits over those of other exotic species such as multiflora rose (*Rosa multiflora*) and Oriental bittersweet (*Celastrus orbiculatus)*, creating opportunities for autumn olive seeds to be spread to favorable locations and become entrenched there (Kohri 2011). Birds have been shown to disperse most autumn olive seeds within 200 to 300m of the nearest patch, but some seeds were found as far as 500m away (Kohri et al. 2011).

In addition to high fecundity and seed germination rates, autumn olive has the ability to reproduce asexually in two ways. The first is that autumn olive can reproduce by layering if branches become buried. In most cases, autumn olive does not produce stems long enough or arched enough to become buried (Kohri, 2002). However, in areas with regular soil disturbance such as steep slopes, this layering would increase the likelihood that autumn olive will be able to survive for a greater period of time, and potentially flower and produce fruit. Working in Japan, Kohri et al (2002) studied autumn olive on gravel bars in a river and found that branches would become buried after flood events and produce roots. Thus, it appears that layering in autumn olive is an adaptation to increase survival in the highly disturbed sites where it is usually found. Similar to its proclivity to root when branches become buried, autumn olive also produces multiple sprouts from the main rootstock (Kohri, 2011). With its propensity to spread and arch as it obtains greater heights, the crowns of autumn olive can envelope and shade out competing plant species. Known mostly as a shade intolerant species, previous research suggests that autumn olive is capable of germinating and expanding

in forest understories, making it a particularly problematic exotic, invasive species (Sanford 2003, Yates 2004). Autumn olive has been recognized as an invasive plant species in the United States for decades but further north, in Ontario, has escaped cultivation as recently as 1983 (Catling 1987).

Once present in an ecosystem, autumn olive's ability to fix nitrogen has the potential to impact other plant species and ecosystem processes such as nutrient cycling and primary production. In a greenhouse experiment, when an aqueous mixture of minced, live autumn olive leaves was used for watering non-germinated seeds, the rate of cottonwood (*Populus deltoids*) seedling survival was improved by 60%, whereas sugar maple (*Acer saccharum*) and sycamore (*Platanus occidentalis*) were not affected (Orr 2005). Although the effect of autumn olive leaves on cottonwood seedlings was positive, improvement only occurred with minced leaves that are unlikely to occur in nature. Ultimately the addition of autumn olive into a native forest ecosystem is likely to have at least some impact on forest dynamics and development. In terms of negative impacts on other species, a predominant concern is the potential for autumn olive to form dense patches once it becomes established, and the competitive exclusion of native forest species within these patches (Catling 1987).

Once autumn olive becomes established in an area there are several methods for control. Control methods work to varying extents depending upon the length of time between establishment and discovery of the invading autumn olive plant. When caught at the beginning stages of development and when the soil is moist enough to ensure successful extraction of a high percentage of the roots, hand pulling of plants is an

acceptable form of control (USDA Forest Service 2006, Missouri Department of Conservation 2010). However, once established, hand pulling results in greater density of autumn olive from vigorous resprouting, which also occurs after dormant season burns, and mowing. Autumn olive seed is also highly resistant to fire, and requires high temperatures for extended periods of time to destroy 90% of seeds (Emery 2011). More successful for autumn olive control is the use of herbicide treatments. Glyphosate can be used alone to reduce the success of autumn olive but requires multiple applications and is nonselective affecting all green plants that come in contact with the herbicide (USDA Forest Service 2006). A better method is to eliminate the root of autumn olive by cutting stems and applying 10 to 20 percent glyphosate directly to the stump (Missouri Department of Conservation 2010). Whichever treatment method is selected, follow-up treatments will need to be applied. Edgin and Ebinger (2001) reported on the use of glyphosate in eradication of autumn olive in forested sites. After five years, densities of autumn olive on treated sites were 3.9 stems m^{-2} compared to 12 stems m^{-2} on untreated sites. However, the above ground biomass of autumn olive was completely exterminated through treatment with glyphosate and still maintained a strong presence five years later. Therefore, autumn olive can be controlled, but requires vigilance in doing so.

Information on the relationships between autumn olive distribution and growth and different types of forest road edges is limited. Yates (2004) and Flory (2006) reported a general trend in which decreasing densities of autumn olive occurred with increasing distance from roads, but the differences were not significantly different. A

greater understanding of what variables associated with roadside edges such as aspect, slope, canopy cover, etc. are important predictors of the distribution, abundance, and growth of autumn olive would allow managers to predict when and where this species is likely to be a problem.

Chapter 1. Objectives

The overarching goal of this project was to identify variables associated with forest road edges most important in explaining autumn olive abundance and growth. The objectives were to: 1) investigate whether southern aspects have greater abundance and height of autumn olive than other aspects, 2) determine if there is a negative relationship between the abundance and height of autumn olive and the abundance and height of native species, 3) determine if the relationship between autumn olive abundance and height and other invasive species abundance and height is positive and 4) document other site factors significantly related to the success of autumn olive.

Chapter 2. Materials and Methods

Study Site

Research was conducted on Chuck Swan State Forest and Wildlife Management Area (CSSFWMA), a contiguous 9,997ha tract representative of central hardwood forests in the region that are managed for timber, wildlife, and recreation. Until 1934 when the Tennessee Valley Authority (TVA) acquired the land as part of Norris Dam construction, the area was privately owned with portions of the land being farmed. TVA turned the property over to the state of Tennessee in 1952 to be a multi-use property (Tennessee Department of Agriculture, 1999). Hardwoods are dominant on roughly 65% of the landscape and, before a recent pine beetle outbreak, pines were dominant on 35% of the land. CSSFWMA is located in the Ridge and Valley Province in eastern Tennessee, on highly dissected terrain. Chuck Swan is on a peninsula on Norris Lake and average annual temperatures range from 7.9ºC to 20.4ºC. Elevation on the site extends from 308m to 488m above sea level (Jackson, 2006).

Several woody, exotic, invasive species including multiflora rose, tree of heaven (*Ailanthus altissima*), mimosa (*Albizia julibrissin*), Japanese honeysuckle (*Lonicera japonica*), and water yam (*Dioscorea alata*) are abundant on CSSFWMA. Dominant canopy species consist of white oak (*Quercus alba*), black oak (*Q. velutina*), chestnut oak (*Q. montana*), blackgum (Nyssa sylvatica), pignut hickory (*Carya glabra*), mockernut hickory (*C. tomentosa*), red maple (*Acer rubrum*), and yellow poplar (*Liriodendron tulipifera*). Occasional loblolly pine (*Pinus taeda*) and Virginia pine (*P.* virginiana) were also encountered in some sites. Past and current timber and wildlife

management activities have resulted in a well-developed network of major and minor gravel roads and associated roadside edges maintained to varying degrees.

Sampling

Autumn olive sample plots were located along five main roads within CSSFWMA: Main Forest Road, Forks of the River Road, Longhollow Road, Big Loop Road, and White Creek Road (Figure 1). Along each of these roads, all autumn olive on forest road edges oriented within ±10° of one of the four cardinal directions (N, E, S, W) were logged using a Garmin eTrec Legend HCx (Garmin Ltd., Olathe, KS) GPS unit. Any patches separated from the initial plant by 5m or less were considered the same patch of autumn olive and were not logged separately. To ensure random sampling, an effort was made to collect at least twice as many sites as needed to achieve a representative sample (≥30 sites per forest-edge aspect). From these initial patches, sample sites were chosen randomly using Excel from Microsoft Office 2011(Microsoft, Redmond, WA) to assign each site a random number and then the 15 highest numbers were chosen as sample plots.

After site selection, sampling was conducted using 10m x 5m edge plots centered on the middle of the boles of the trees along the forest edge (Figure 2). At each site, autumn olive stems were counted and placed into one of five height-class categories: > 3m, 2.01-3.00m, 1.01-2.00m, 0.51-1.00m, and < 0.50m (hereafter refered to as: >3m, 2-3m, 1-2m, 0.5-1m, and <0.5m. Because of its clonal nature, stems were only considered separate if they were not clearly attached above ground.

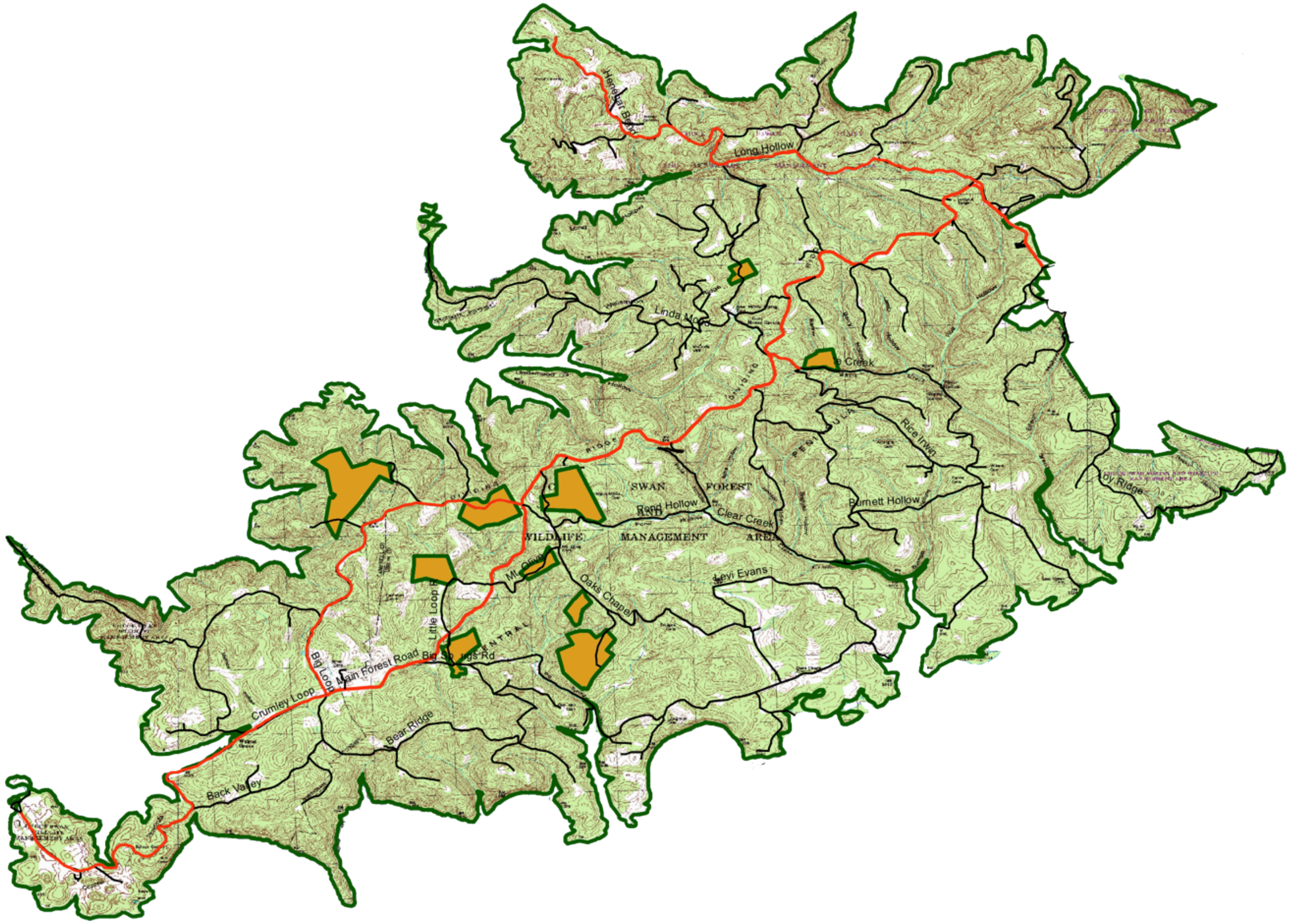

Figure 1. Chuck Swan State Forest and Wildlife Management Area. Roads used in the study are represented in red. Wildlife management fields are shown in orange.

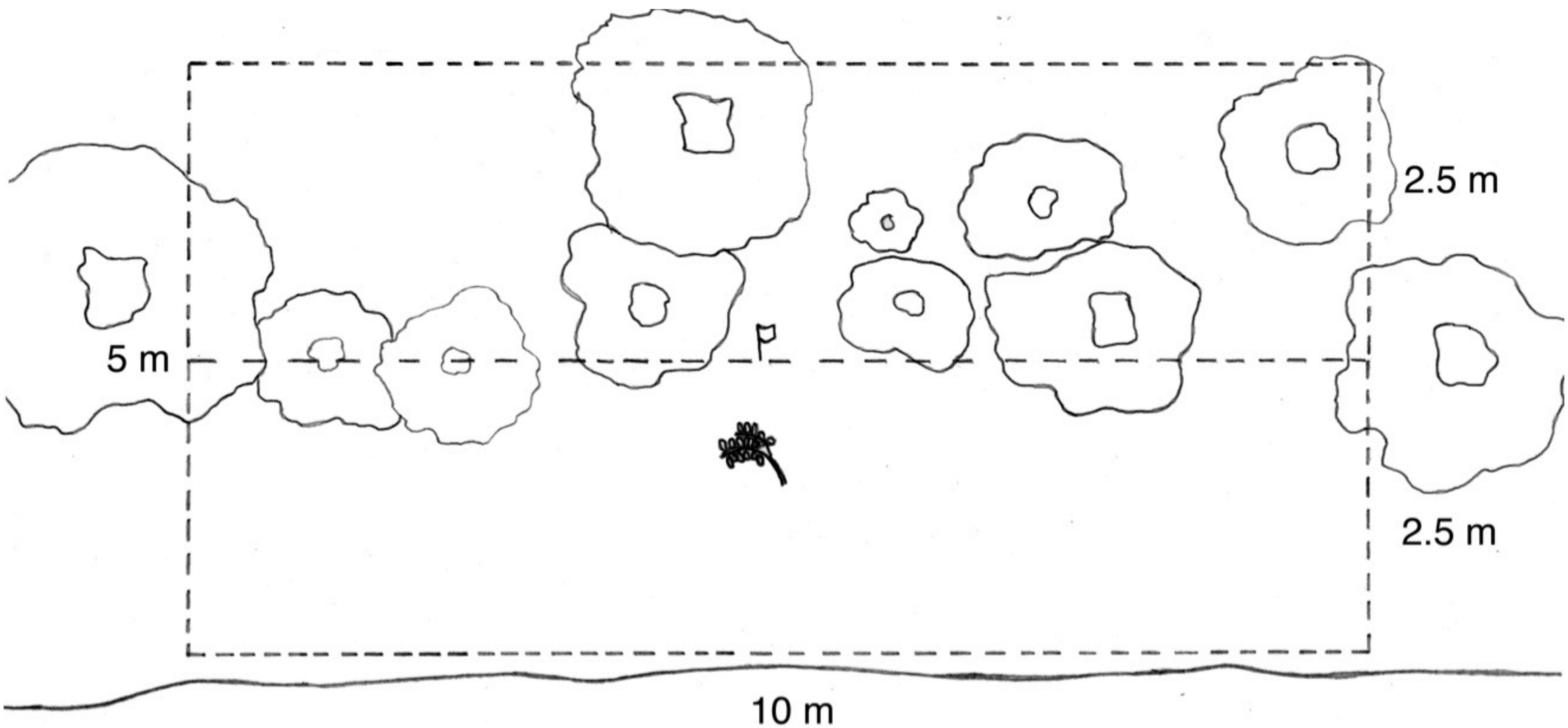

Figure 2. 10x5m rectangular sample plot design. *The flag represents the middle of the plot.*

Within the 10x5m plots, the breadth of the woody native and exotic, invasive flora was counted and sorted into the same height-class categories as autumn olive. If there were unknown woody species within the sample area, cuttings were taken and brought back to the lab in order to ensure proper identification and "Sample" used as a placeholder on the data sheet until an accurate ID was made and if no ID could be made then the species was listed as unknown.

In conjunction with the woody native and exotic, invasive species sampling and classification, the maximum patch depth autumn olive (m) was measured from the plot edge toward the road to the furthest autumn olive stem in the forest, given that each additional stem was within 5m of the previous stem (Figure 3). Elevation (ft), slope toward interior forest (%), basal area, and canopy cover (count) measurements were taken at plot center (Figure 2). Once 30 sites had been sampled, measurements of slope toward the road(%), and canopy cover at road center (%) were taken on the remaining sites and subsequently collected for completed sites (Figure 4). Forest edge aspect was determined using a Silva Ranger CL Compass (Johnson Outdoors Inc., Racine, WI) and elevation was measured using a Garmin eTrec HCx (Garmin International, Inc., Olathe, KS) GPS unit. Slopes were quantified with a Suunto PM-5 Clinometer (Suunto, Finland), basal area was measured with a 20x Prism (General Supply Corp., Jackson, MS), canopy cover was measured with a Spherical Densiometer Model-C (Forest Densiometers, Bartlesville, OK), and autumn olive patch depth and road widths were measured with a 100m Keson Fiberglass Measuring Tape (Keson Industries, Aurora, IL). Canopy cover was measured by taking four counts of canopy

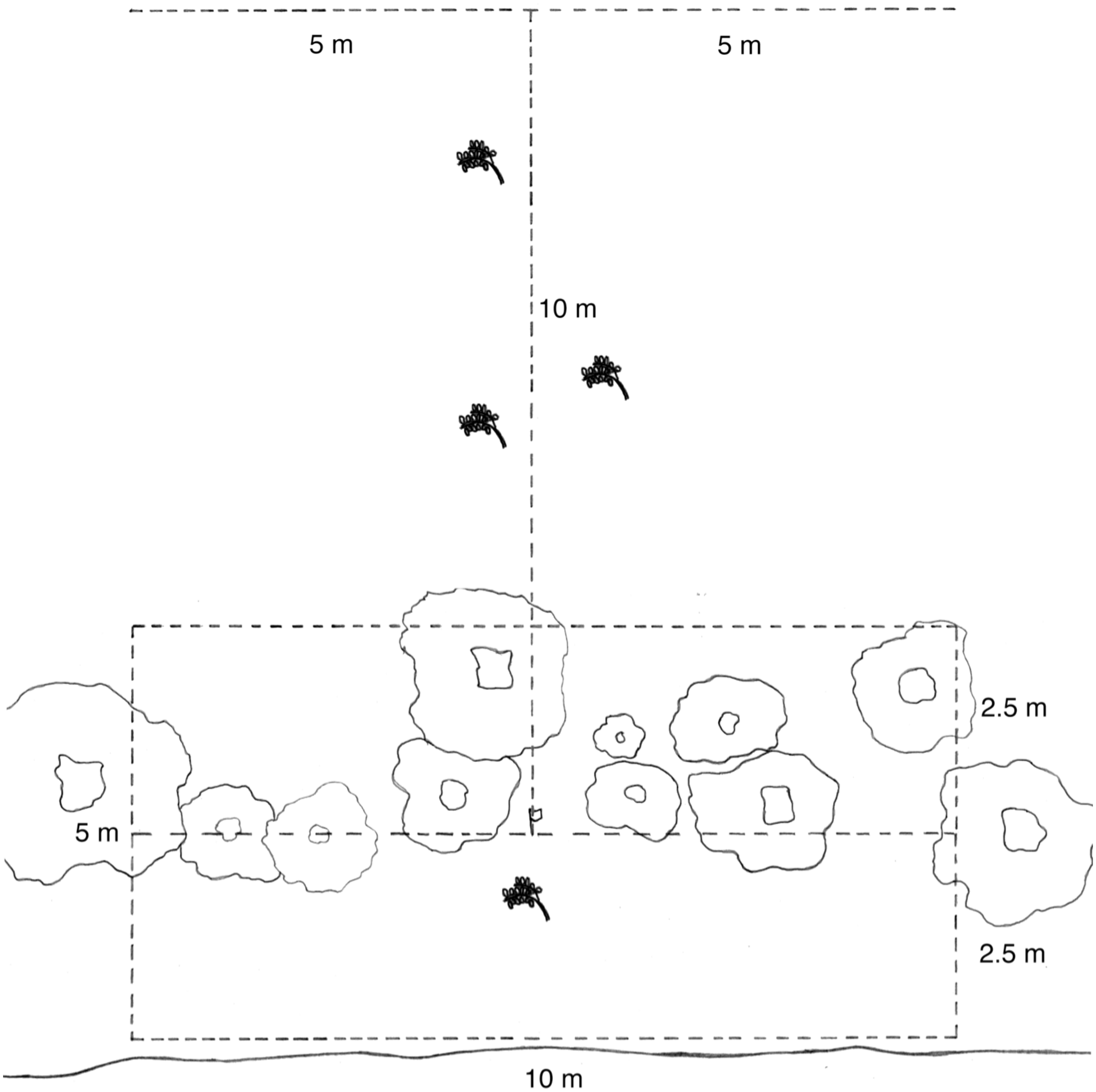

Figure 3. Patch depth and interior canopy sample design. Diagram of the sampling method for measuring maximum patch depth of autumn olive and interior canopy closure.

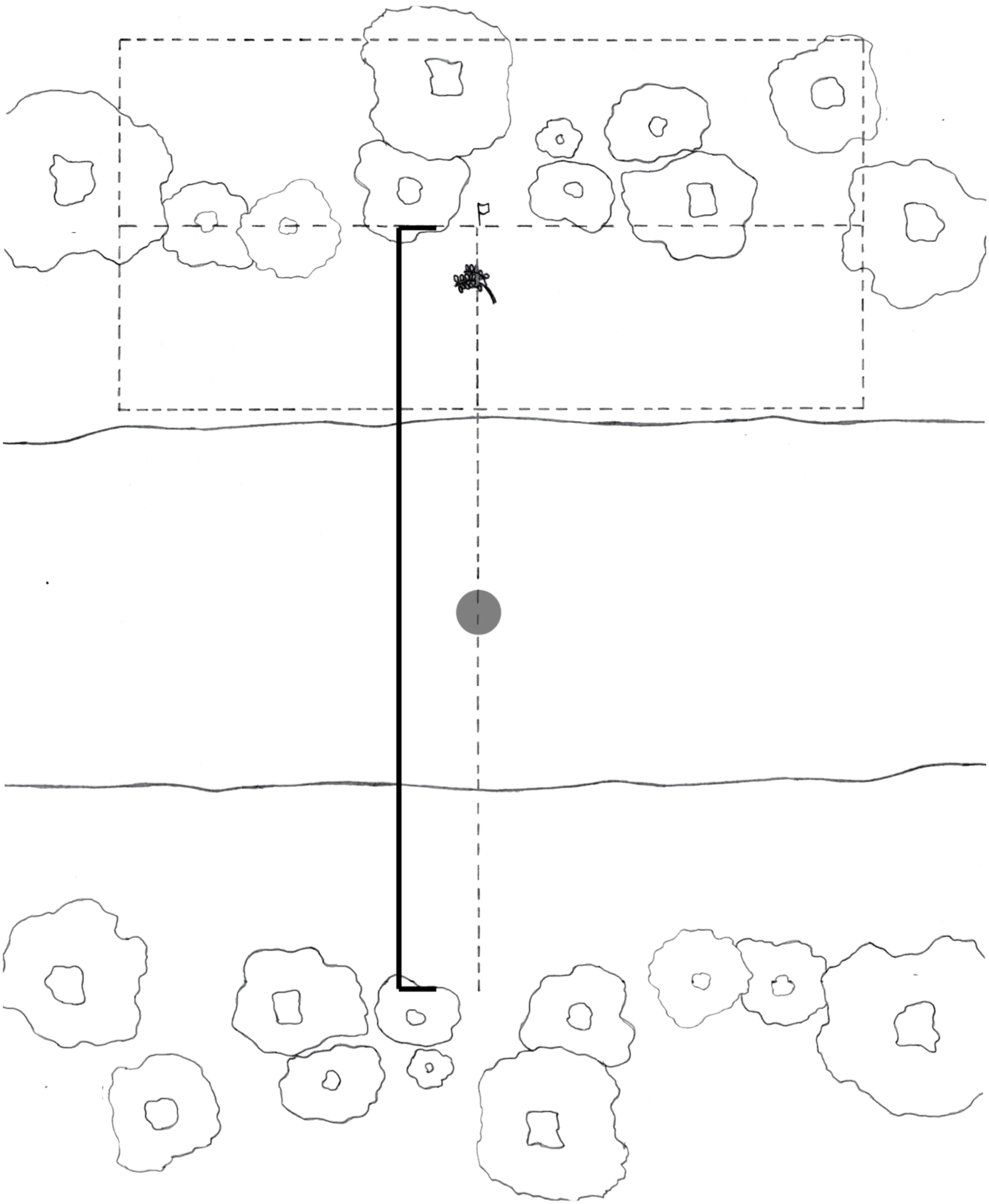

Figure 4. Road canopy and road opening width sample design. Diagram of the method for measuring road canopy closure and road edge opening-width.

opening at one sample point while facing each of the four cardinal directions. Measurements for canopy cover of the interior forest were taken 10m towards the interior forest from plot center and 5m to either side of that point parallel to the forest edge and averaged (Figure 3). During basal area sampling, trees were counted if the image of the bole sighted through the prism overlapped with the tree outside the prism at breast height on the bole, and every other tree was counted if the image of the bole sighted through the prism only overlapped the very edge of the same bole below the prism. Road edge opening-widths were measured from the center of tree boles on the forest edge of the established plot to the center of the boles of trees along the adjacent forest edge (Figure 4).

Several measurement conversions were carried out before any statistical analyses were performed. Elevation was converted from feet to meters by multiplying the measurement of elevation in feet by 0.3048 as in Equation A.

(Equation A) $\text{Meters} = \text{Feet} * 0.3048$

Basal area stem counts were converted by multiplying the number of in trees by the prism factor (20x). Canopy cover was calculated as percent canopy closure by averaging the four (4) canopy-count-values, multiplying by 1.04, and then subtracting this total from 100 as in Equation B.

(Equation B) $\%\,\text{Closure} = [100 - [(\text{V1} + \text{V2} + \text{V3} + \text{V4})/4]] * 1.04$

Each of the four counts measuring openings in the forest canopy are represented by V1, V2, V3, and V4, measurements in each one of the four cardinal directions.

After the first portion of the fieldwork was completed, a second sampling effort was initiated. In this second effort, the focus was on randomly sampling the major roads of Chuck Swan for the presence or absence of autumn olive, and also recording general conditions thought to potentially effect successful establishment by the invasive shrub. Main Forest Road, Big Loop Road, and Long Hollow Road were the three roads used in this study. These roads were chosen because they were all a part of the original study and are the largest roads in Chuck Swan. Road lengths were coarsely calculated using Google Maps (Google Inc, Mountain View, CA). These lengths were then doubled for round trip sampling. Once the length of each study road from the front gates of Chuck Swan was established (Table 1), they were divided so that observation points occurred every 0.16 kilometers. This portion of the study was designed to result in approximately 100 observation points. To accomplish this, total round trip road lengths were added together and then used to calculate how often observations would need to be taken to result in 100 sites. Measurements needed to be collected every 0.6 kilometers to obtain 100 sample sites. The number of points needed along each road was calculated by dividing the round-trip road length by 0.6km to yield a total number of sites per road. Once this was complete, distances along the roads to be sampled were selected at random for each of the four roads.

Table 1. Forest roads. List of forest road names, round trip kilometers used for sampling and the number of sample points along each road.

Road Name	Total Distance (km)	Sample Points
Main Forest Road	41.8	65
Big Loop Road	10.6	17
Long Hollow Road	15.4	24

Using a 1991 Chevrolet Suburban (General Motors Company, Detroit, MI) the road was driven until the trip odometer reported that the required distance had been travelled from the current to the subsequent sample point. When the correct tenth of a mile value was centered the truck was stopped, and the front bumper used as an invisible sampling line. At each point, both sides of the road were sampled to avoid biasing data and to provide a second dataset for validation. The presence or absence of Autumn olive (1 or 0), road name, road type (primary, secondary, or tertiary), GPS coordinates in degree and minute notation (ww°xx.yyy), elevation (ft), edge orientation (°), road canopy closure (%), slope towards road (%), and slope towards interior (%) were recorded. Qualitative forest age estimations were recorded at each site, but ultimately, were removed due to inability to obtain accurate stand records. The road type was determined subjectively based on the relative density of traffic on each road and the amount of road maintenance performed. GPS coordinates and elevation were obtained using a Garmin eTrec Legend HCx (Garmin International, Inc., Olathe, KS), and all other measurements were recorded as stated previously. Presence or absence of autumn olive was recorded as 1 for present and 0 for absent. Autumn olive individuals were only recorded as present if they were within 5m of the observation point. Once collected, elevation and canopy cover were transformed with Equation A and Equation B, respectively. It was also necessary to convert the GPS degree and minute notation to degree-decimal notation appropriate for use in ArcGIS. Transformation was accomplished using Equation C.

(Equation C) $\mathrm{ww°xx.yyy} = \mathrm{ww°}\left(\frac{\mathrm{xx}}{60}\right) + .\mathrm{yyy} = \mathrm{ww.zzzzzz}$

W's represent the degree measure of either latitude or longitude. X represents minutes, and Y is the decimal portion of the minute measure. Once calculated, W remains the same as in the original measure but Z is a new decimal measure for location.

A diameter by age study was also completed as a part of the investigation into factors affecting autumn olive success. On northern and southern facing forest road edges, 5 autumn olive stems in the 2-3m height class were collected right at the forest edge (0m) and 10m into the forest from the edge. All stem samples were collected 6 inches above the ground. Each autumn olive stem was measured to the nearest millimeter using calipers and ages gauged by counting growth rings.

Statistical Analysis

Autumn olive across forest-road edge aspects

To determine 1) whether autumn olive colonizes forest-road edges of particular aspects preferentially, mixed model analysis of variance (ANOVA) in SAS 9.3 (SAS Institute, Inc., Cary, North Carolina) was used with Tukey mean separation. Comparison of maximum autumn olive patch depth, total autumn olive stems, and an index of stem abundance and height, a value calculated using Equation D, were completed to determine differences between autumn olive for the four edge orientations. To calculate the index of average height, the number of stems in each height class, > 3m, 2-3m, 1-

2m, 0.5-1m, and < 0.5m, were multiplied by the central measure for that height class. Height class values were then added together for the total plot height. This total was then divided by the total number of trees for that species or category of species, in this case autumn olive.

In addition, individual height class means for each of the four edge aspects were compared. However, autumn olive stem counts were collected at each plot point and with this type of data collected as the response variable, it was more likely to fit a Poisson distribution rather than a normal distribution. Therefore, it was necessary to use another method of statistical analysis. Towards this end, PROC GLIMMIX (SAS 9.3) was used to determine whether N, E, S, or W forest-road edge aspects differed based on mean stem counts for Poisson distributed data.

(Equation D) $[(> 3m * 3.5) + [(2\ to\ 3m) * 2.5] + [(1\ to\ 2m) * 1.5] + [0.5\ to\ 1m) * 0.75] + [(0.0\ to\ 0.5m) * 0.25]] \div Total\ Species\ Stems = Index$

In addition to the univariate method of variance analysis based on edge aspect, multivariate analysis of variance (MANOVA) was also employed to determine if forest edge aspects were significantly different based on a combination of response variables. Although completed here as a second step in determining significant differences based on forest-road edge aspect, MANOVA incorporates all response variables into the analysis. Using combinations of variables more accurately establishes whether significant differences exist based on all pertinent data. However, this type of analysis requires that variables be distributed multivariate normal and that the variance-

covariance matrices of each group be equal. In addition to MANOVA, the use of polynomial regression in conjunction with dummy regression allowed the determination of whether regression equations explaining autumn olive response variables differ by edge aspect.

From here, principal component analysis (PCA) was used to create principal components, or linear combinations of the original variables, that explained the greatest amount of variation with the fewest possible principal components. This type of variable simplification enabled visualization of the data based on the combinations of variables, which in some cases aids in the interpretation of relationships.

Diameter by age information was analyzed using linear regression with data divided four ways. First, the overall trend of the data was analyzed to determine general growth rates regardless of aspect or depth into the forest. The data were then split by north or south forest-road edge aspect using indicator variable to determine growth rate differences based on aspect. Differences in the growth rates based on the depth of the patch were then analyzed with linear regression using an indicator variable. Fourth, using linear regression with an indicator variable, groups were broken up by aspect and depth to determine how growth rates vary.

Relationship between autumn olive and native plant species

To determine 2) whether colonization by autumn olive on a forest-road edge adversely affects the abundance of native plants on that edge, simple linear regression analysis was performed. Using linear regression allows the strength of a relationship

between two variables to be understood, but also allows for the prediction of one variable by the other. Therefore, the abundances and indices of autumn olive were evaluated using linear regression for its effect on the abundances and indices of native trees, other woody native plants, and all woody natives.

Relationship between autumn olive and other exotic, invasive plant species

To determine 3) whether the presence of autumn olive on an edge correlated with the colonization of other invasive species on the same edge, a second set of simple linear regression was completed. Using linear regression, abundances and indices of autumn olive were compared to abundances and indices of other woody invasive plants, and all woody invasive plants. Invasive tree species were observed in so few plots that they were left out of this analysis.

Significant site characteristics

In addition to the previously stated hypothesis driven analyses this study also sought 4) to investigate relationships that exist between autumn olive and plot site characteristics. To achieve this, site characteristics were split into logical groups based on those observed. All canopy closure measurements were grouped into four categories. For edge canopy cover 70% - < 80%, 80% - < 90%, 90% - < 95%, and > 95% canopy closure were considered and for road canopy cover 0% - < 35%, 35% - < 50%, 50% - < 75%, and > 75% canopy closure. Interior canopy cover groups had less variation and were 80% to < 89%, 89% - < 93%, 93% - < 96%, and > 96% canopy

cover. Basal area was placed in three groups, 0-80, 100-160, and 180-260 BA. Both slope measurements were categorized as either upslope or downslope and also combined to determine whether the plot toward the interior forest from the road was a uniform upward slope, uniform downward slope, convex slope, or concave slope (Figure 5). Five groups were used for edge to edge width, 9m - < 12m, 12m - < 14m, 14m - < 16m, 16m - 25m, and > 25m. For elevation, groups were 320m - < 375m, 375m - < 425m, 425m - < 475m, and > 475m. Groups were then analyzed for significant differences in the abundance measures and maximum patch depth of autumn olive using MANOVA.

Autumn olive presence/absence data was evaluated with MANOVA to find significant site characteristic differences between plots with and plots without autumn olive. PCA was again used to simplify the presence/absence variables. Potentially PCA would provide a clear visualization of reasons for autumn olive establishment.

All statistical tests were calculated and considered statistically significant if the probability was less than or equal to 0.05 ($\alpha \leq 0.05$).

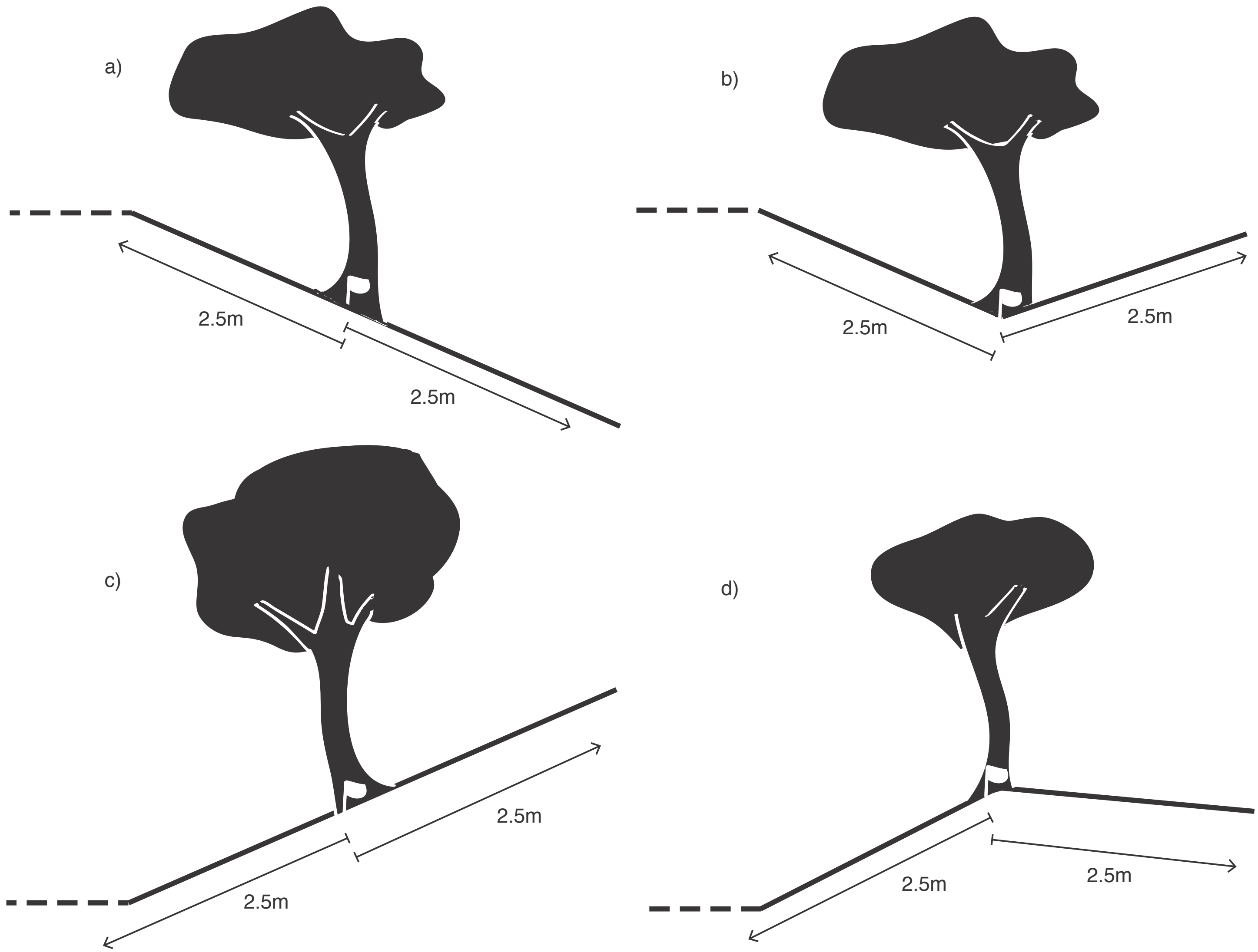

Figure 5. Diagram of slope type. a) uniform downward slope, b) a concave slope, c) a uniform upward slope, d) a convex slope.

Chapter 3. Results

Autumn olive across forest-road edge aspects

Of the autumn olive variables measured, maximum patch depth, density in the >3m, 2-3m, 1-2m, 0.5-1m, and <0.5m height classes, density of autumn olive in all height classes combined, and index of average autumn olive height, only four did not violate the ANOVA assumption of univariate normality. Maximum autumn olive patch depth, autumn olive density in the 2-3m and <0.5m height classes, and the average height of autumn olive were normally distributed. Of the four normally distributed autumn olive variables, maximum patch depth ($\rho < 0.0324$), and autumn olive stem counts in the 2-3m height class ($\rho < 0.0345$) differed across forest-road edge aspects (Figure 6, Table 2). North and south aspects had the deepest average autumn olive patch depth (17.3m and 14.9m, respectively) and east edges had the shallowest average, (4.7m). Density of 2-3 m autumn olive stems was greatest (5.5 stems) along south-facing forest-road edges and lowest (2 stems) on north-facing edges (Figure 6, Table 2).

Analyses of the densities of autumn olive stems by height class and the density of autumn olive in all size classes combined conducted with the assumption of a Poisson distribution indicated that aspect had an impact ($\rho = 0.0325$) only on stem density in the 2-3m height class. Autumn olive density and height means and standard deviations were consistent with previous mixed model ANOVA results. Of the eight autumn olive response variables, autumn olive stem density in the >3m height class, 1-

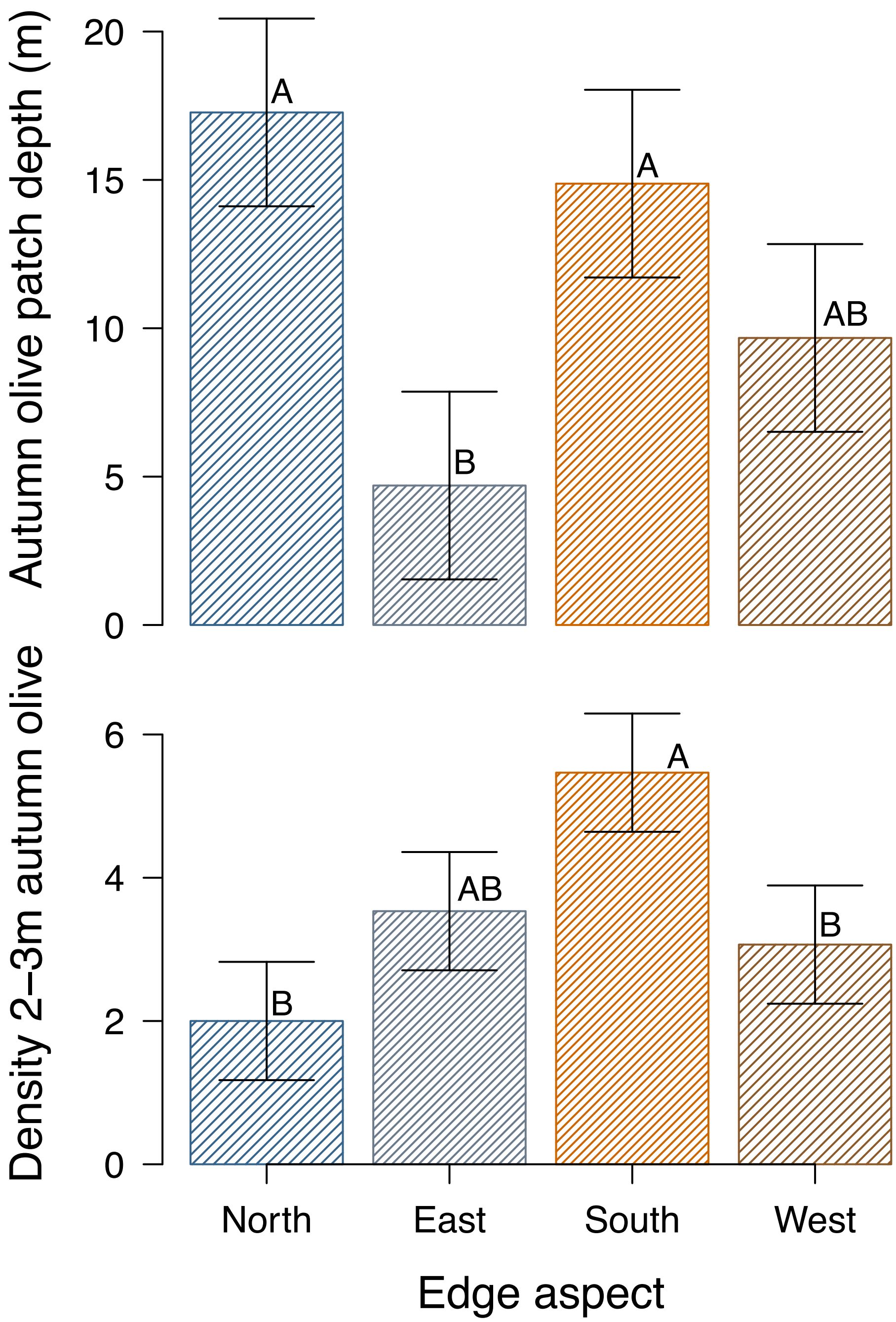

Figure 6. Aspect differences bar chart. Bar chart of autumn olive maximum patch depth and stem counts in the 2-3m height class, organized by aspect. Edge aspects with the same letter group are not significantly different at α = 0.05. Groupings based on Tukey's method. Error bars represent one standard error.

Table 2. Differences by aspect. Statistically significant autumn olive response variables as determined by ANOVA, with corresponding mean variable estimates by forest road edge aspect. Edge aspects with the same letter group are not significantly different at $\alpha \leq 0.05$. Groupings based on Tukey's method.

Edge Aspect	N	Maximum Patch Depth (m)	Density of 2-3m Stems
N	15	17.3m [a]	2.0 [a]
E	15	4.7m [b]	3.5 [ab]
S	15	14.9m [a]	5.5 [b]
W	15	9.7m [ab]	3.1 [a]

Table 3. MANOVA differences by aspect. Statistically significant response variables, as determined using MANOVA, corresponding variable estimates by forest road edge aspect. Edge aspects with the same letter group are not significantly different at $\alpha \leq 0.05$. Groupings based on Hotellings Two-Sample T2.

Edge Aspect	N	Maximum Patch Depth (m)	Density of 2-3m Stems
N [a]	15	17.3m	2.0
E [b]	15	4.7m	3.5
S [ab]	15	14.9m	5.5
W [a]	15	9.7m	3.1

2m class, 0.5-1m class, 0-0.5 class, all height classes combined, and the average height of autumn olive did not differ across aspects ($p = 0.5534$, $\rho = 0.8700$, $\rho = 0.8702$, $\rho = 0.3948$, $\rho = 0.8673$, and $\rho = 0.3276$, respectively). In contrast, aspect affected the maximum patch depth of autumn olive and density of 2-3m tall autumn olive stems ($p = 0.0228$ and $p = 0.0325$, respectively).

MANOVA indicated similar differences in maximum patch depth and density of 2-3m autumn olive based on the orientation of the forest-road edge. Although all test statistics were significant (Wilks' Lamdba, Hotelling-Lawley Trace, Pillai's Trace, Roy's Largest Root) with $\rho < 0.02$, Roy's Largest Root ($\rho < 0.01$) is the more pertinent test because the highest eigenvalue is three times that of the next highest value, suggesting that only two or three variables explain the majority of variation within the data. As in the other analyses, maximum autumn olive patch depth ($\rho = 0.0324$) and density of autumn olive stems in the 2-3m height class ($\rho = 0.0345$) were the only variables that differed among forest-road edge aspects (Table 3).

Polynomial regression, in conjunction with indicator variable regression, indicated that maximum patch depth of autumn olive, density of 2-3m tall autumn olive stems, and the average height of autumn olive had significant regression models ($\rho < 0.0001$, $\rho < 0.0001$, and $\rho = 0.0002$, respectively) that differed based on orientation of forest-road edges. Maximum patch depth of autumn olive decreased linearly with greater downward slope from the road toward plot center. Patch depth also decreased with increasing upward or downward slope toward the interior forest (Figure 7). The relationship between maximum patch depth of autumn olive and slope toward the road

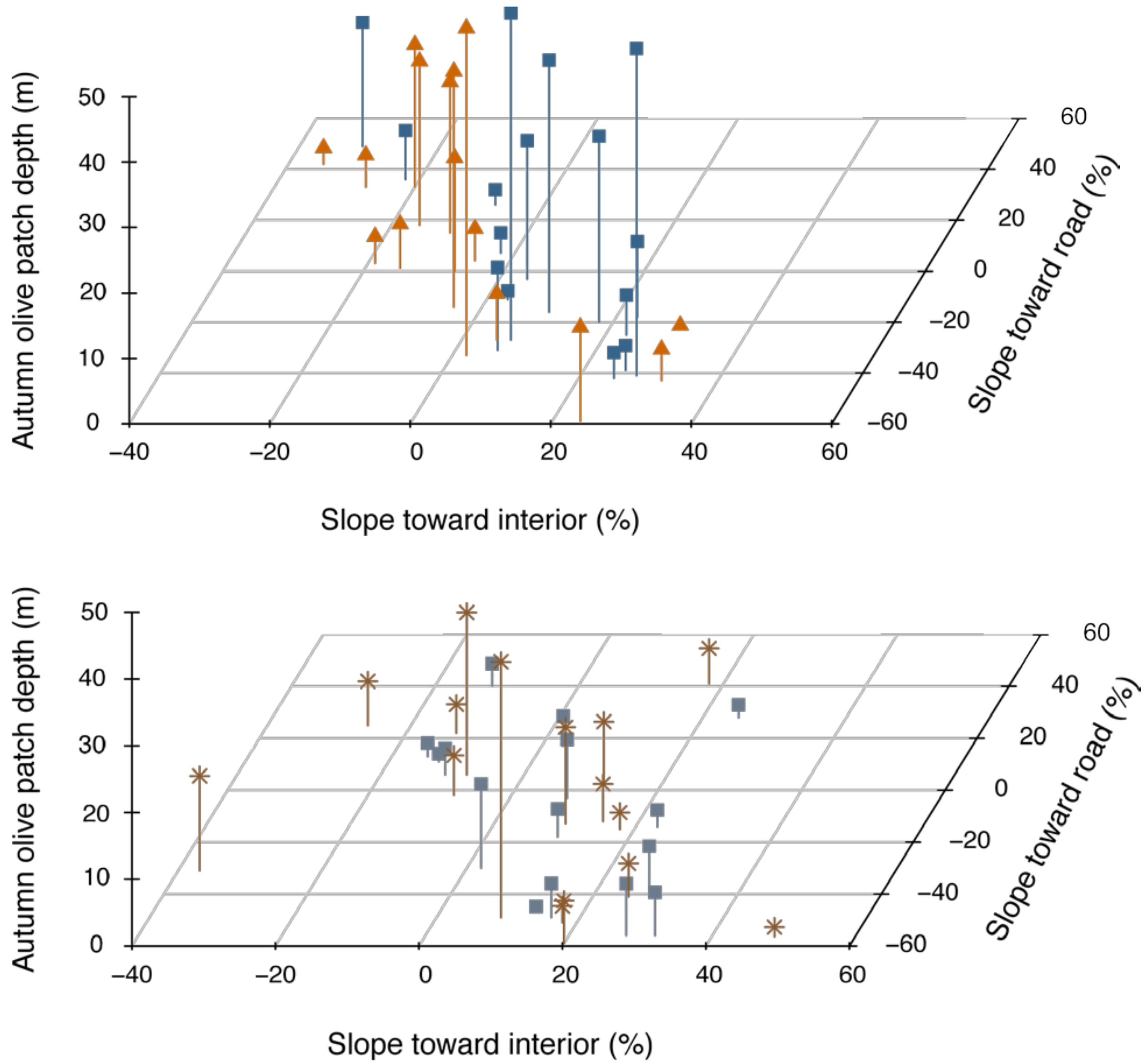

Figure 7. Patch depth by slope. 3D scatterplots of the maximum patch depth values of autumn olive plotted against both slope toward the interior forest (%) and slope toward the road (%). Observations are divided by aspect: blue (■) represent north forest-road edge aspects, gray (●) east, orange (▲) south, and brown (✳) west.

and slope toward the interior forest indicate that autumn olive patch depths are greatest on sites with greater downward slopes toward the road and level from plot center toward the forest interior (Table A-1). Linear slope toward road and quadratic slope toward interior forest explained 23% of variation in maximum patch depth of autumn olive.

Road opening width affected the density of 2-3m tall autumn olive ($\rho < 0.0001$). The width of the road opening explained 36% of the variation in 2-3m tall autumn olive density. On north-facing edges, a strong negative relationship existed between 2-3m tall autumn olive abundance and road opening width. No 2-3m autumn olive were predicted at road widths 22m and greater along north-facing edges. Density of 2-3m tall autumn olive had the strongest positive relationship to road opening width along south-facing edges where approximately 20 2-3m tall autumn olive stems were predicted with a 50m road opening width. Densities of 2-3m tall autumn olive were related to road opening widths to lesser extents along eastern and western edge aspects. Along forest-road edges with an eastern aspect, density of 2-3m autumn olive had a positive relationship with road opening width with a predicted increase from 3 to 9 autumn olive stems as road opening width changed from 10m to 50m wide. The density of 2-3m tall autumn olive had a slight negative relationship with increased road opening width along west-facing edges, but autumn olive density in this size class was predicted to decrease by only half a stem from the narrowest to the widest widths (Figure 8, Table A-2).

The average height of autumn olive was related to slope toward the forest interior ($\rho < 0.0001$), and slope toward the interior explained 42.5% of the variation in average

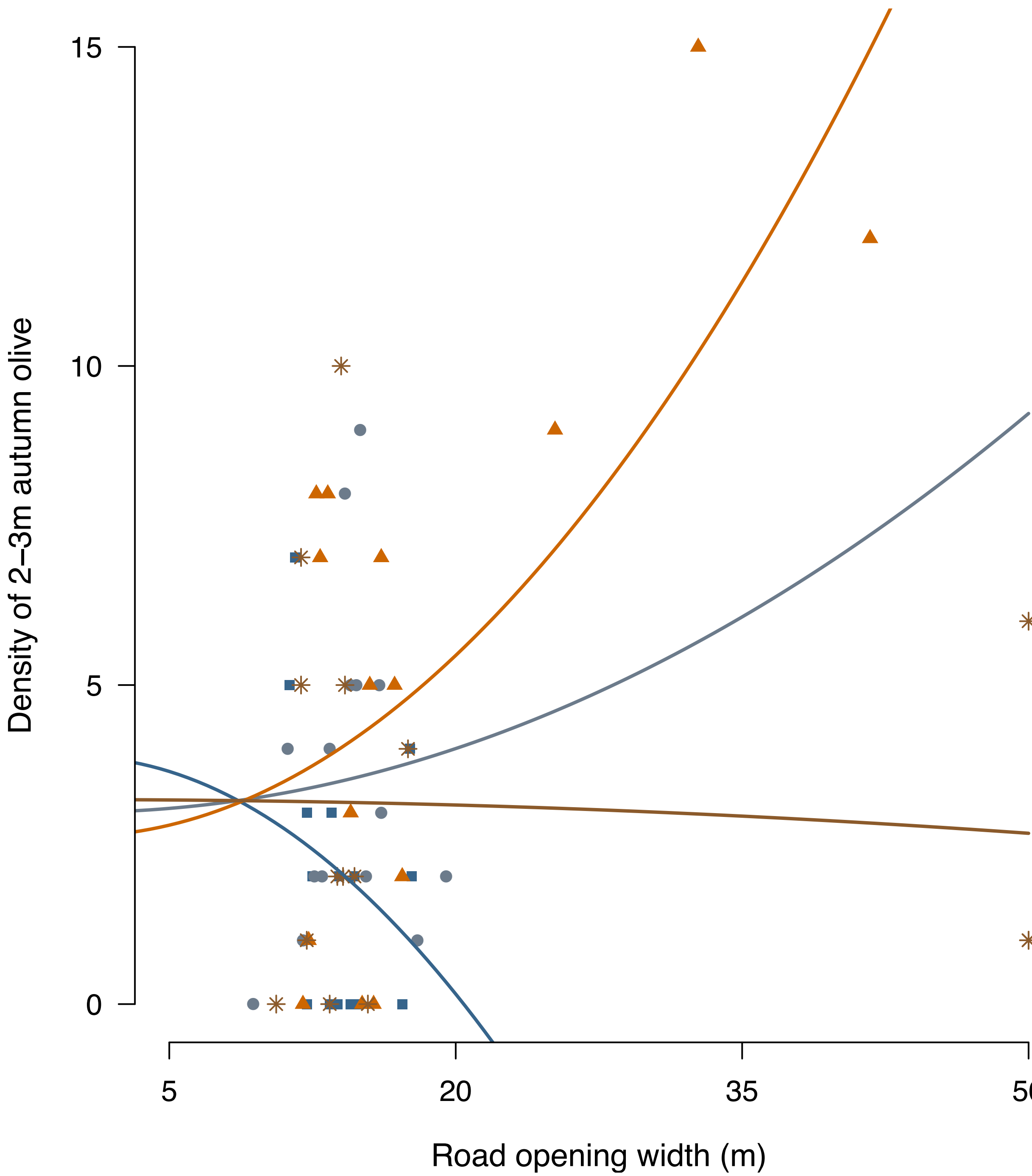

Figure 8. Density of 2-3m autumn olive by opening width. Scatterplot of values for 2-3m autumn olive density plotted against road opening width. Observations are divided by aspect: blue (■) represent north forest-road edge aspects, gray (●) east, orange (▲) south, and brown (✳) west. Polynomial regression lines are distinguished by color.

height. Polynomial regression incorporating data collected along northern, eastern and southern aspects predicted that minimum average autumn olive height (about 1.25m) would occur on sites with a 10% slope. Maximum average autumn olive height (approximately 4m) was predicted to occur along south-facing forest-road edges with steep downward or upward slope values. Along northern and eastern aspects, average autumn olive height increased by roughly 0.5m and 0.75m, respectively, with the same changes in upward and downward slopes. In contrast, average autumn olive height on western aspects decreased from a maximum of 1.3m on level sites to approximately 0.8m on steep upward or downward slopes (Figure 9).

Densities of 1-2m tall autumn olive were also related to certain site characteristics ($\rho < 0.0001$) (Table A-4), but these relationships did not vary across aspects. Densities of >3m ($\rho < 0.0001$)(Figure A-1), 0.5-1m ($\rho < 0.0001$), 0-0.5m ($\rho < 0.0001$), and all autumn olive height classes combined ($\rho < 0.0001$) (Figure A-2, Table A-5) were also related to certain site characteristics, but the models had either too little explanatory capability or were too complex to be considered further.

Density of 1-2m tall autumn olive was predicted to increase as slope toward the interior became more level ($\rho < 0.001$). A maximum of 36 autumn olive stems per plot were predicted on flat sites, and decreased to about 17 stems on sites with 40% downward slopes or 60% upward slopes. Density of 1-2m tall autumn olive was predicted to be 36 stems at 0% canopy cover, 14 stems at 100% cover, and 6 stems at 60% canopy closure (Figure 10, Table A-4). The model for 1-2m autumn olive explained 29% of variation in the data ($\rho < 0.0001$).

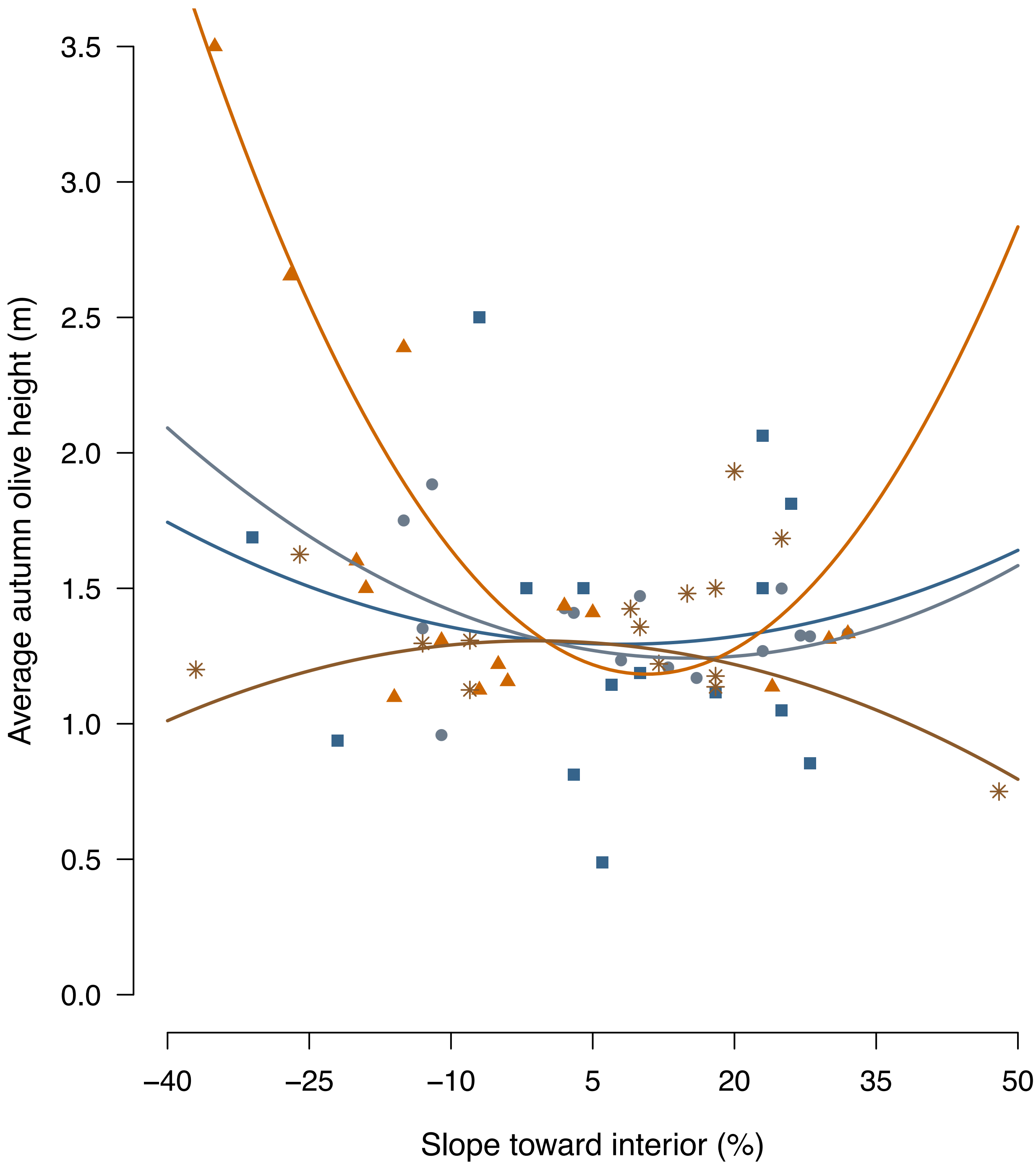

Figure 9. *Average autumn olive height (m) by slope. Scatterplot of the values for average autumn olive height (m) plotted against slope toward the interior forest (%). Observations are divided by aspect: blue (■) represent north forest-road edge aspects, gray (●) east, orange (▲) south, and brown (✳) west and polynomial regression lines are distinguished by color.*

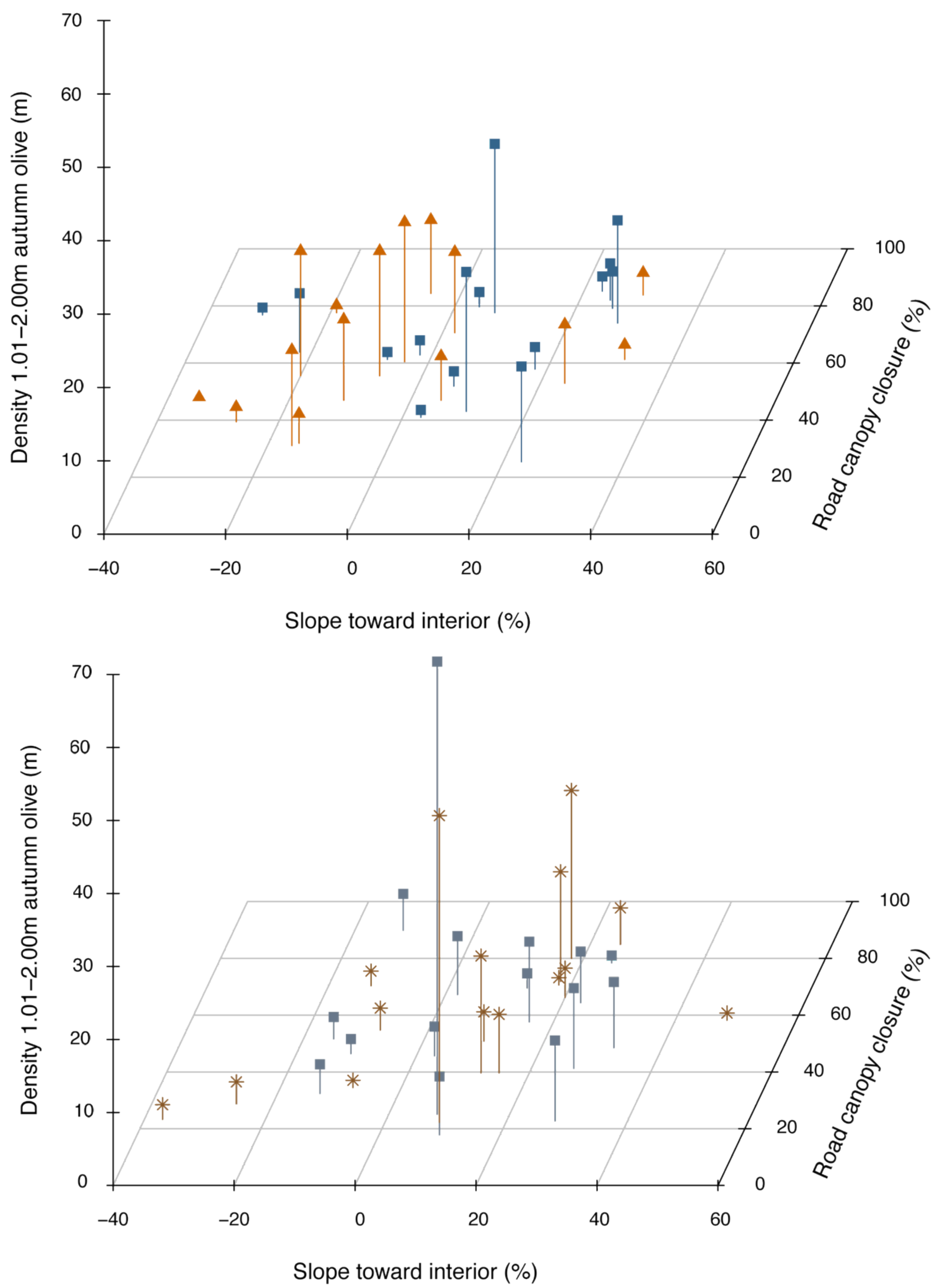

Figure 10. *1-2m autumn olive abundance by slope and canopy closure. 3D scatterplot of values for abundance of autumn olive plotted against road canopy closure (%) and slope toward interior forest (%). Observations are divided by aspect: blue (■) represent north forest-road edge aspects, gray (●) east, orange (▲) south, and brown (✳) west.*

Diameter by age data indicated there was a positive relationship between the age of autumn olive and the diameter of autumn olive stems $(\rho < 0.0001, r^2 = 0.5314)$ (Figure A-3). Differences occurred based on aspect $(\rho < 0.0001, r^2 = 0.5656)$ (Figure A-4, Table A-6), distance from the road $(\rho < 0.0001, r^2 = 0.5559)$ (Figure A-5, Table A-7), and site position dependent on aspect $(\rho < 0.0001, r^2 = 0.6025)$ (Table A-8). In general, sites with northern aspects had higher autumn olive growth rates than did sites with southern aspects. When divided by position within the forest, autumn olive right along the forest edge grew at the same rate as autumn olive 10m toward the interior forest but were generally larger than autumn olive grown within the forest. Based on aspect and position, autumn olive is initially larger on sites with a southern aspect that are on the forest edge. However, growth rates are greatest for autumn olive on northern aspects on the forest edge, and second greatest on northern-aspects 10m into the forest interior. Growth rates differ by about 0.5mm per year between 0m northern aspects (4.6mm), 10m northern aspects (4.0mm), and 10m southern aspects (3.5mm). Growth rates for autumn olive on sites where growth is slowest (0m southern aspects) is roughly half the growth rate of 0m north-facing edges where growth rates are greatest (Figure 11).

Relationship between autumn olive and native plant species

Regression analysis conducted with observations pooled across all aspects indicated linear relationships $(\rho = 0.0498, r^2 = 0.0647)$ between the average height of all species of native trees and the average height of autumn olive (Table 5). When

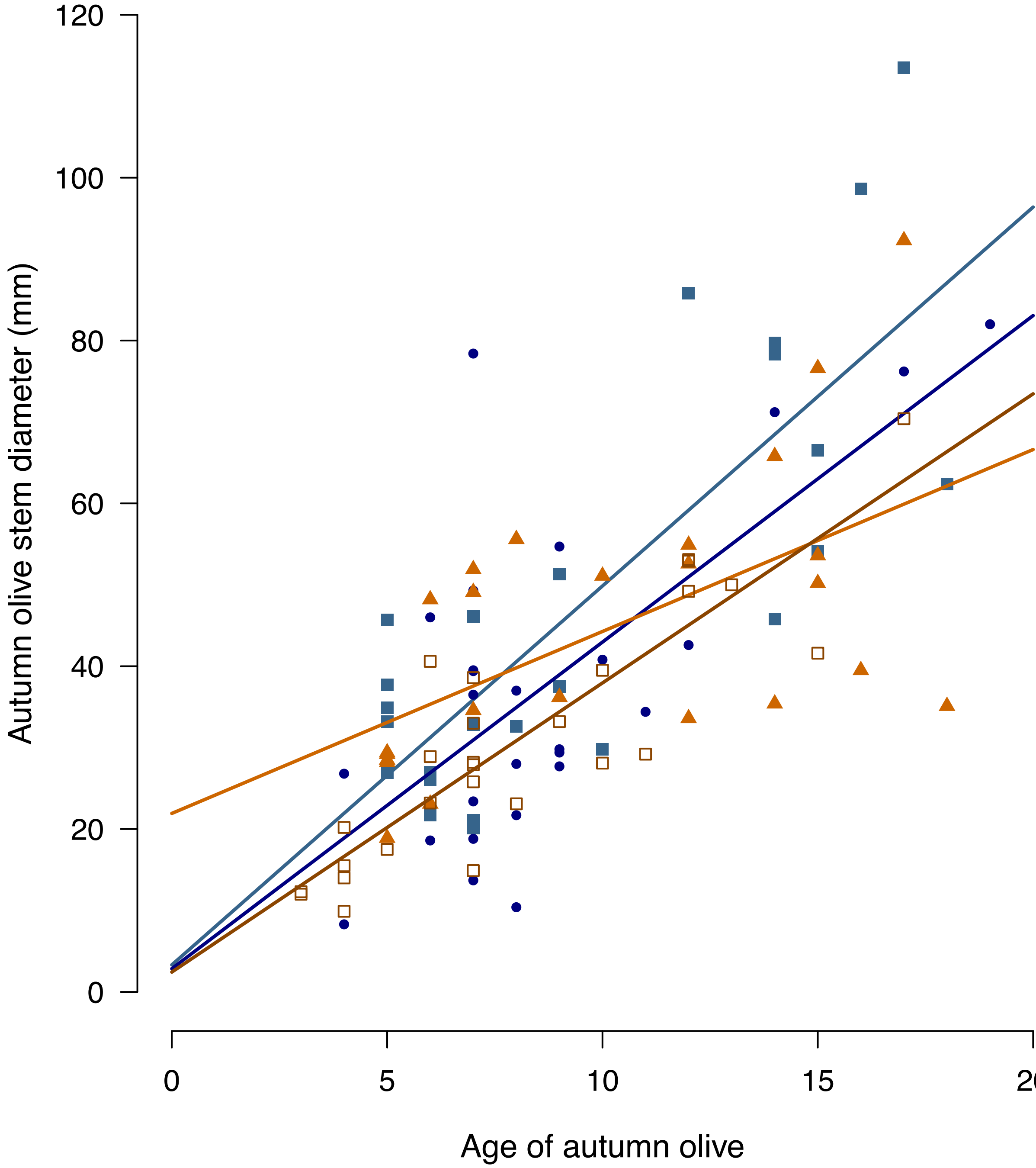

Figure 11. *Diameter by age dependent on edge aspect and location. Scatterplot of the diameter of autumn olive stems 6" above the ground plotted by the age of the plant with corresponding linear regression line. All slopes differ. Lighter blue (■) represent observations for northern aspects at 0m, dark blue (•) northern aspects at 10m, light orange (▲) southern aspects at 0m, and dark orange (□) southern aspects at 10m.*

observations of average autumn olive heights were divided and analyzed by aspect, the average height of autumn olive was positively related ($\rho = 0.0200\ r^2 = 0.3509$) to the average height of native tree species on south-facing forest-road edges only (Table 5, Figure 12). The relationship between the average height of autumn olive and the average height of native tree species predicts that southern forest-road edges with greater average autumn olive height should also have greater average native tree height. When native woody vines and shrubs were included with native tree species in regression analysis, the relationship between the average height of autumn olive and the average height of all species of native plants was also positive ($\rho = 0.0377\ r^2 = 0.0724$) (Figure 13). Again, subdividing and analyzing observations by aspect resulted in a relationship ($\rho = 0.0380\ r^2 = 0.2910$) between the average height of autumn olive and the average height of all species of native plants on southern aspects only. The average height of all native woody plant species on southern forest-road edge aspects is predicted to increase with increasing average autumn olive height. Densities of native species and densities of autumn olive were not related to any measures of autumn olive and native species average height or density (Table A-9, A-10).

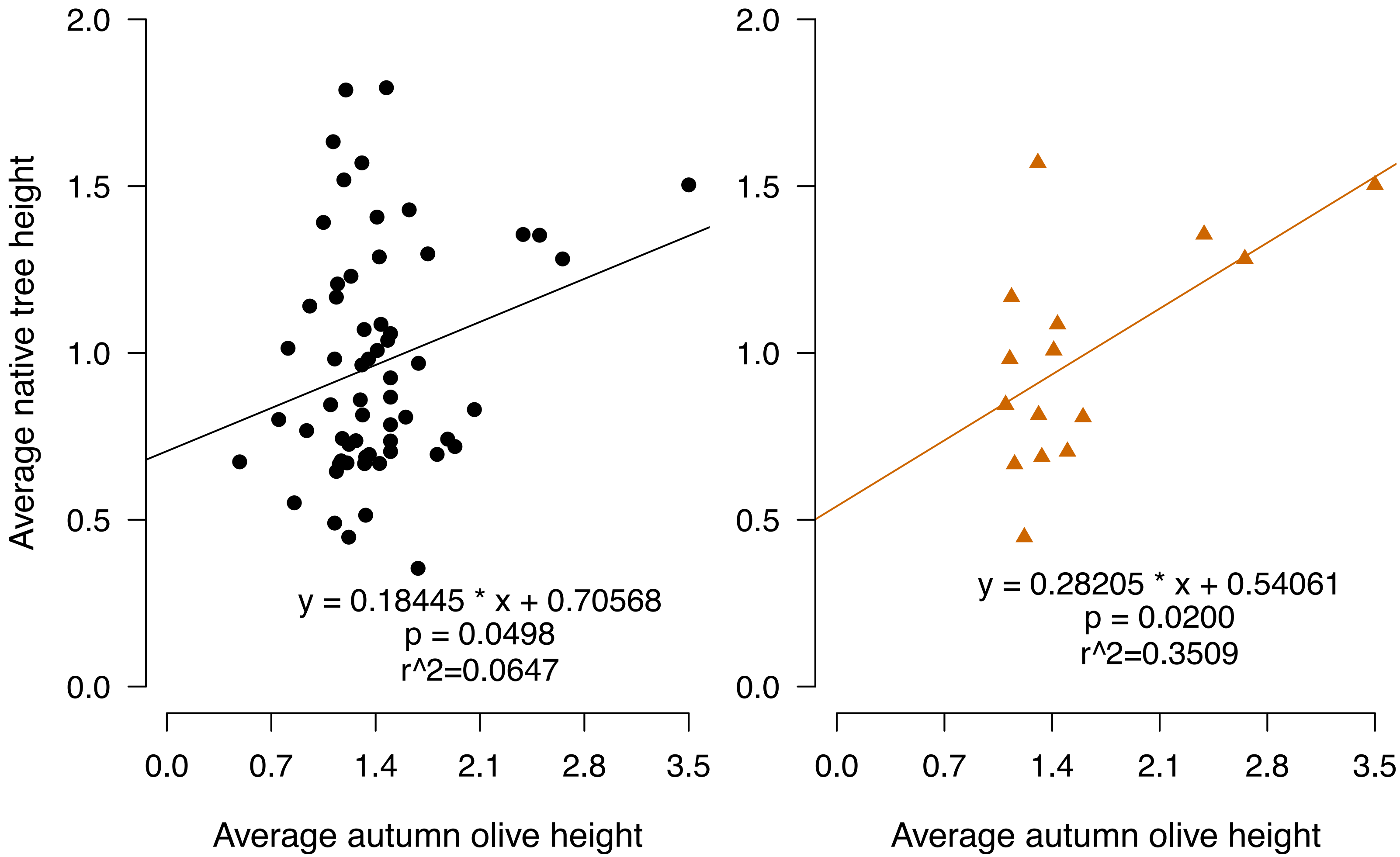

Figure 12. *Average height of autumn olive versus average height of native trees. Scatterplot of all species of native trees plotted by the average height of autumn olive with linear regression line. Black (●) represent observations for all aspects, orange (▲) represent observations for south aspects.*

Table 5. *Native species by average height of autumn olive. Linear relationships between the autumn olive average height index and native plant density and average height index. Variables with significant relationships are bold and italicized. Comparisons completed for all measurements regardless of aspect and for average heights and densities based on aspect. R-square values present for all relationships with p-values indicating their significance.*

Variables	All Aspects	North	East	South	West
Average height of native trees	***ρ = 0.0498*** ***R^2=0.0647***	ρ = 0.6602 R^2=0.0153	ρ = 0.7240 R^2=0.0099	***ρ = 0.0200*** ***R^2=0.3509***	ρ = 0.9596 R^2=0.0002
Density of native trees	ρ = 0.1951 R^2=0.0288	ρ = 0.3137 R^2=0.0779	ρ = 0.1846 R^2=0.1312	ρ = 0.6446 R^2=0.0169	ρ = 0.7579 R^2=0.0076
Average height of all native plant species	***ρ = 0.0377*** ***R^2=0.0724***	ρ = 0.5881 R^2=0.0232	ρ = 0.8733 R^2=0.0020	***ρ = 0.0380*** ***R^2=0.2910***	ρ = 0.9395 R^2=0.0005
Density of all species of native trees	ρ = 0.2630 R^2=0.0216	ρ = 0.4826 R^2=0.0386	ρ = 0.3593 R^2=0.0649	ρ = 0.6285 R^2=0.0185	ρ = 0.7586 R^2=0.0075

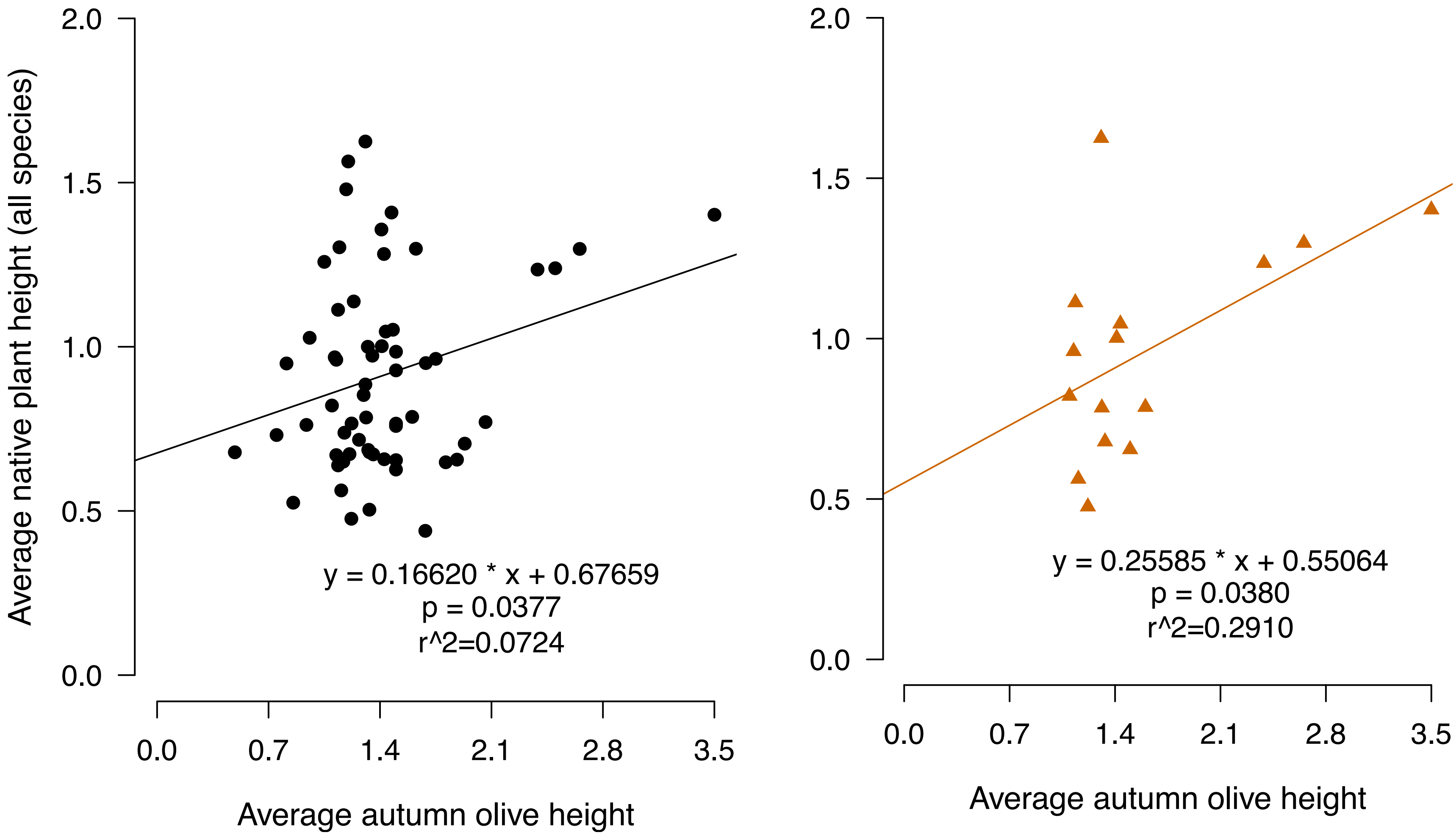

Figure 13. *Average native plant height by average height of autumn olive. Scatterplot of the average height of all species of native plants plotted by the average height of autumn olive and the corresponding linear regression line. Black (●) represent observations for all aspects, orange (▲) represent observations for southern aspects.*

Relationship between autumn olive and other exotic, invasive plant species

Relationships were also found between exotic, invasive plant species and autumn olive. Both the average height and density of all species of exotic, invasive plants were positively related to the density of autumn olive. However, this was only the case when observations were divided and analyzed by aspect (Table 6). The average heights of all exotic, invasive plant species were positively related ($\rho = 0.0271$) to the total abundance of autumn olive on eastern forest-road edge aspects. Therefore, exotic, invasive plant heights were greater when autumn olive, in any height class, was more abundant. Also, the density of all exotic, invasive species combined (all size classes combined) had a positive relationship ($\rho = 0.0128$) with the density of autumn olive (all size classes combined) on southern forest-road edges. The relationship between the density of autumn olive and the density of other exotic, invasive species suggests that an increase of one autumn olive stem corresponds to a one stem increase in other exotic, invasive plant species on south-facing forest road edges (Figure 14).

Significant site characteristics

MANOVA indicated statistically significant effects of road canopy closure, slope toward interior forest, slope toward the road, slope shape, road opening width, and elevation on autumn olive. Edge canopy closure, interior canopy closure, and basal area did not affect autumn olive height, abundance, or maximum patch depth. Although there were differences between grouped road canopy closure measures, differences between autumn olive variables were not significant overall. The average height of

Table 6. *Relationships between invasive species and total native and invasive species by density of autumn olive.* *P-values indicating significance* with *R-square values present for linear relationships between the abundance of exotic, invasive species and total species combined by the density of autumn olive. Variables with significant relationships are italicized and bold. Comparisons were completed for all observations regardless of aspect and also divided based on aspect.*

Variables	All Aspects	North	East	South	West
Average height of exotic plants (all species)	ρ = 0.1472 R^2=0.0359	***ρ = 0.0271*** ***R^2=0.3229***	ρ = 0.3643 R^2=0.0637	ρ = 0.9231 R^2=0.0007	ρ = 0.6883 R^2=0.0128
Density of all exotic, invasive plant species	ρ = 0.7596 R^2=0.0016	ρ = 0.2756 R^2=0.0906	ρ = 0.5416 R^2=0.0293	***ρ = 0.0128*** ***R^2=0.3902***	ρ = 0.4688 R^2=0.0411
Average height of all trees (native and invasive)	ρ = 0.5428 R^2=0.0064	ρ = 0.4373 R^2=0.0471	ρ = 0.5327 R^2=0.0306	ρ = 0.3737 R^2=0.0613	ρ = 0.6731 R^2=0.0141
Density of all trees (native and invasive)	ρ = 0.9551 R^2=0.0001	ρ = 0.8375 R^2=0.0034	ρ = 0.9683 R^2=0.0001	ρ = 0.6380 R^2=0.0175	ρ = 0.3883 R^2=0.0577
Average height of all plant species (native and invasive)	***ρ = 0.0218*** ***R^2=0.0874***	***ρ = 0.0197*** ***R^2=0.3521***	ρ = 0.3114 R^2=0.0786	ρ = 0.7814 R^2=0.0061	ρ = 0.3165 R^2=0.0770
Density of all plant species (native and invasive)	ρ = 0.6554 R^2=0.0035	ρ = 0.4275 R^2=0.0491	ρ = 0.6604 R^2=0.0153	ρ = 0.4231 R^2=0.0500	ρ = 0.9608 R^2=0.0002

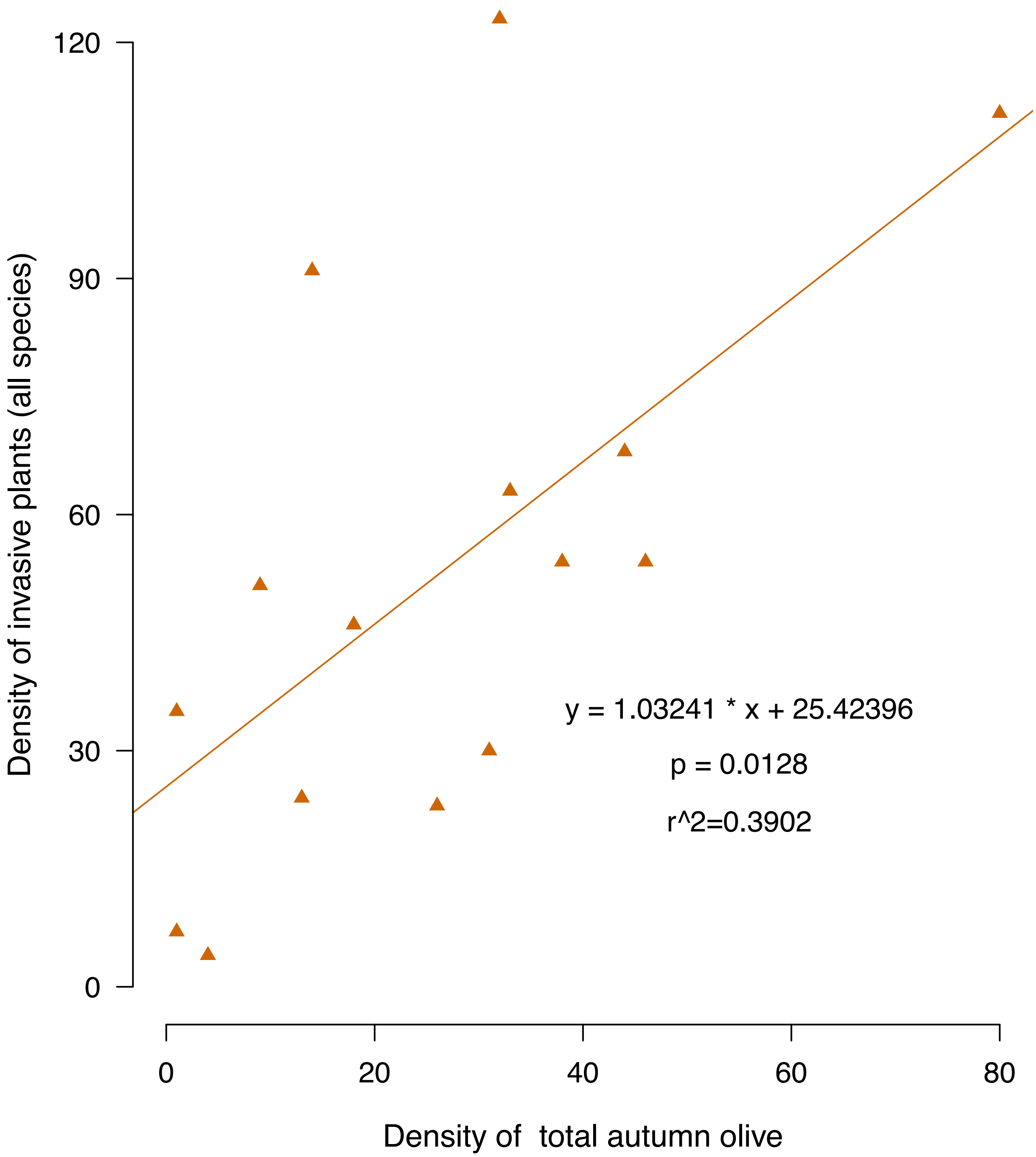

Figure 14. *Exotic invasive plants by density of autumn olive. Scatterplot and linear regression for the density of autumn olive versus other exotic, invasive plants. Linear regression equation, p-value, and* r^2 *included.*

autumn olive differed significantly between upward and downward slope for both slope toward the interior ($\rho = 0.0221$) and slope toward the road ($\rho = 0.0120$). Autumn olive average height increases on downward slopes toward the forest interior and upward slopes toward the road from plot center (Figure 15). Therefore, a uniform downward slope from the road would result in greater average autumn olive height.

The density of autumn olive 0.5-1m differed ($\rho = 0.053$) between an upward slope and a downward slope toward the road. Sites with a downward slope tended to have greater 0.5-1m autumn olive densities (Figure 16). Also, autumn olive in the 0.5-1.m tall height class differed $\rho = 0.0204)$ based on the overall, within-plot, slope shape (Figure 16). Relative to the road, uniform downward slopes had the lowest abundance of autumn olive 0.5-1m tall and convex slopes had the greatest abundance of 0.5-1m tall autumn olive plants. Density of 0.5-1m height class autumn olive on uniform upward slopes had different ($\rho = 0.0236$) values only from densities of 0.5-1m tall autumn olive on steady downward slopes. Slopes that were convex did not have different values of 0.5-1m autumn olive densities for any group (Figure 17).

Autumn olive densities of the 2-3m height class differed depending on the road opening width ($\rho = 0.0340$). The greatest abundance of 2-3m tall autumn olive occurred on sites with the widest road openings, which were greater than 25m wide (Figure 17). Sites with large road openings had greater numbers of 2-3m height class autumn olive than all other road opening widths except the narrowest, which were 9 to 12m wide (Figure 18). In addition, areas at CSSFWMA with the highest elevations, 475-525m, had the deepest average maximum patch depths of autumn olive ($\rho = 0.0196$).

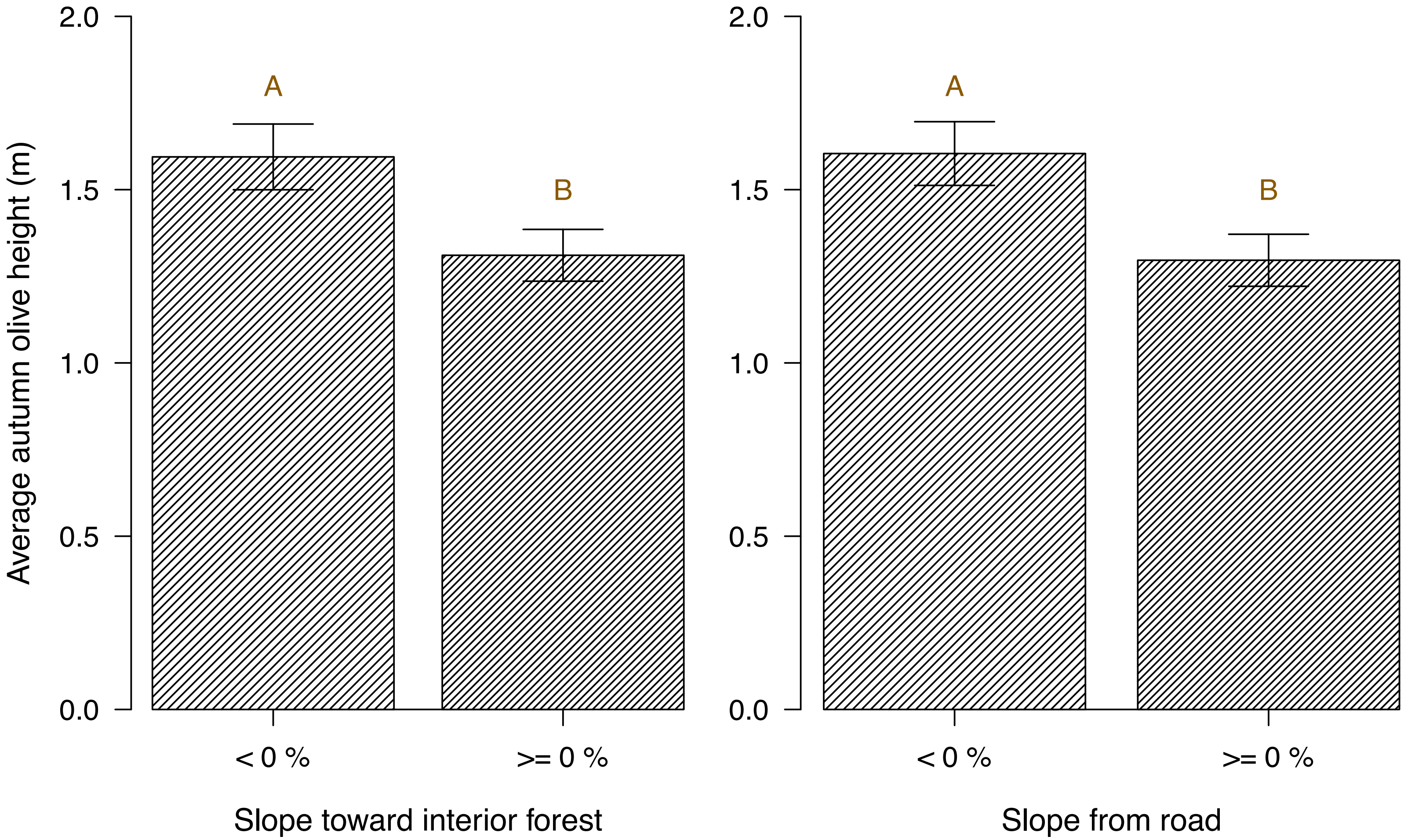

Figure 15*. Barplot of height differences by slope. Barplots of the significant differences in the average height of autumn olive based on slope directionality from plot center toward the interior forest and toward the road. Differences calculated using MANOVA with a significance level of* $\alpha \leq 0.05$.

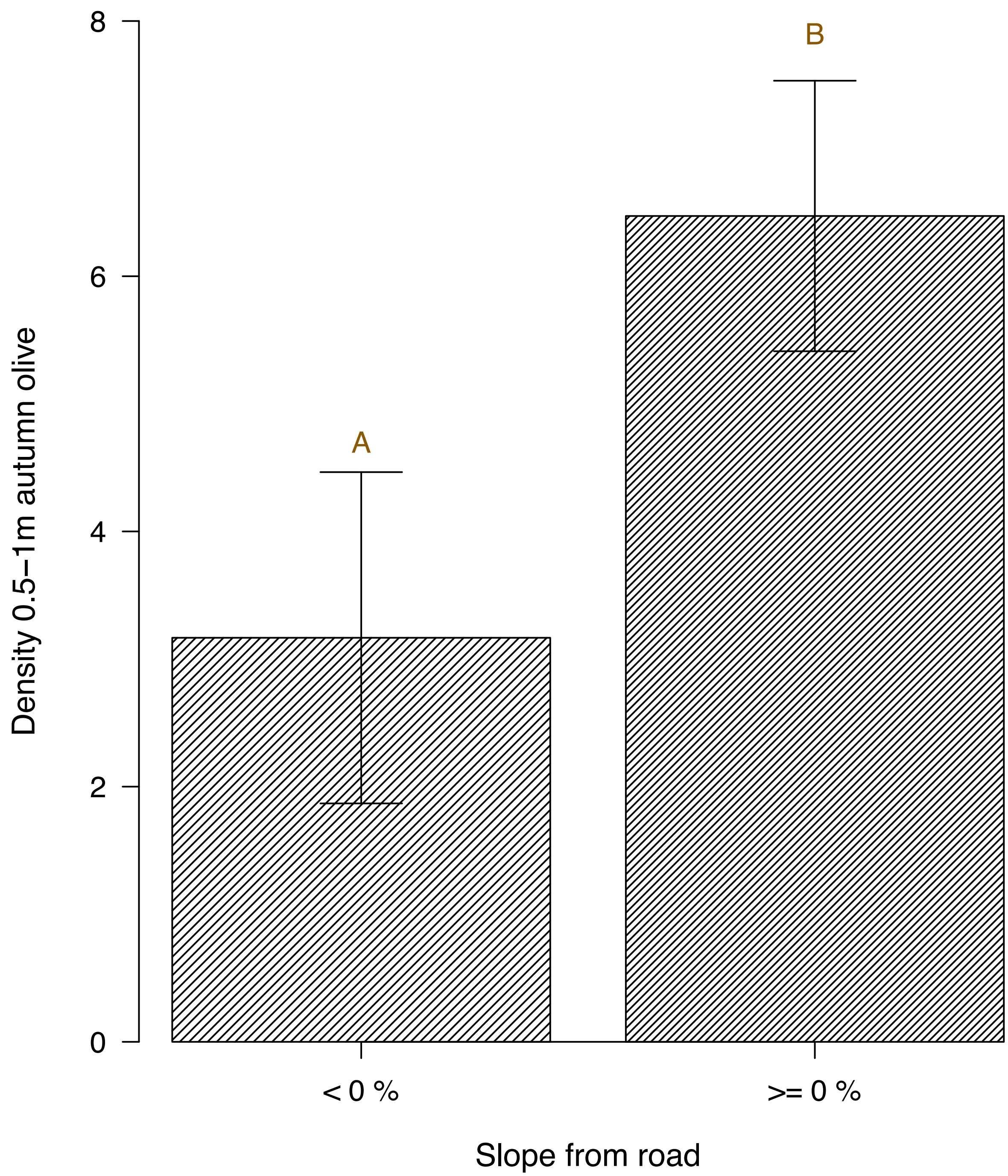

Figure 16. *Barplot of 0.5-1m autumn olive density by slope. Barplot of significant differences in the density of 0.5-1m autumn olive based on slope directionality from plot center toward the road. Differences calculated with MANOVA with a significance level of* $\alpha \leq 0.05$.

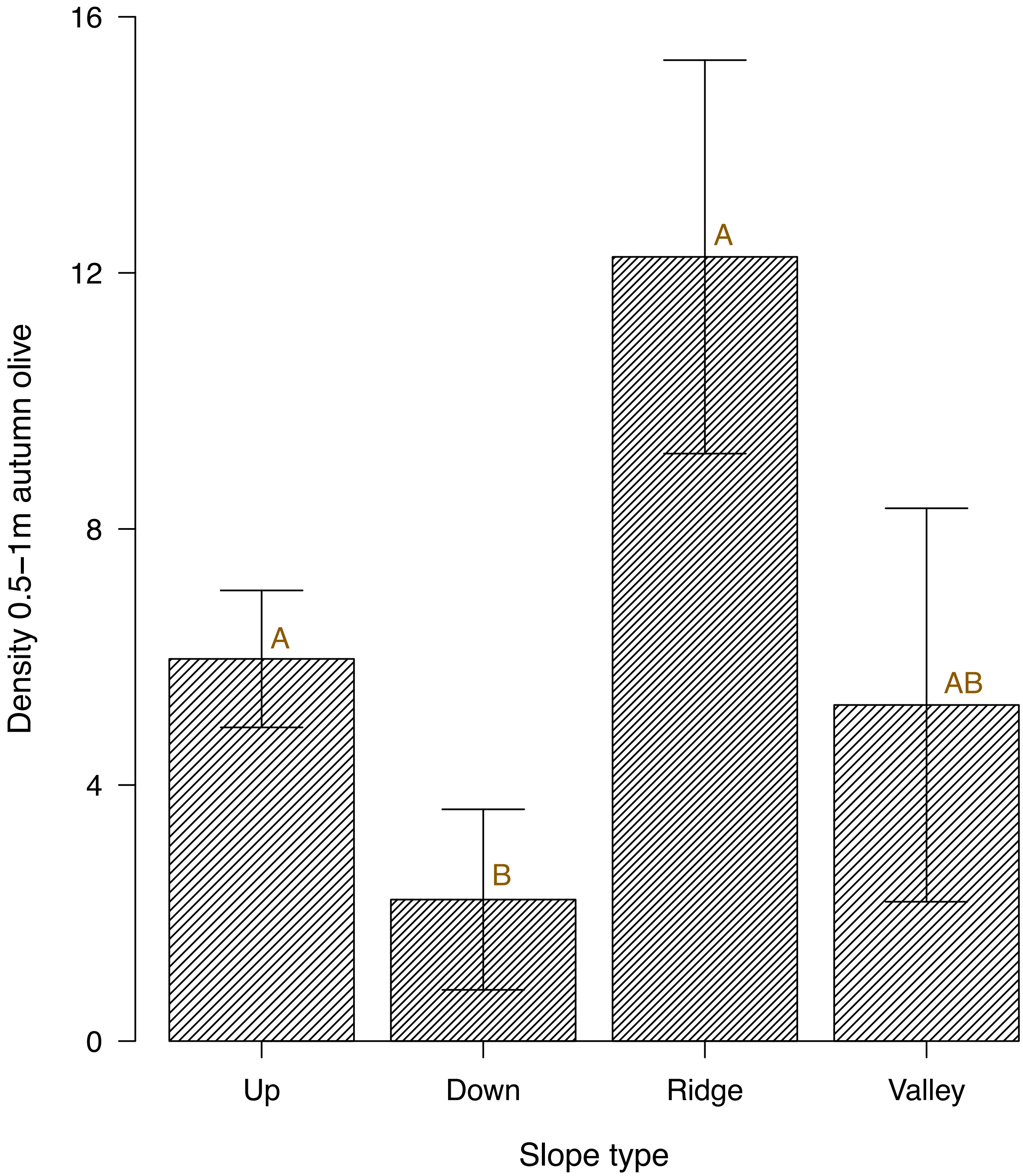

Figure 17*. Barplot of 0.5-1m autumn olive density by slope type.* *Barplot of significant differences in the density of 0.5-1m autumn olive based on slope type from the forest-road edge toward the forest interior. Slope types with the same letter group are not significantly different. Differences calculated using MANOVA with a significance level of* $\alpha \leq 0.05$.

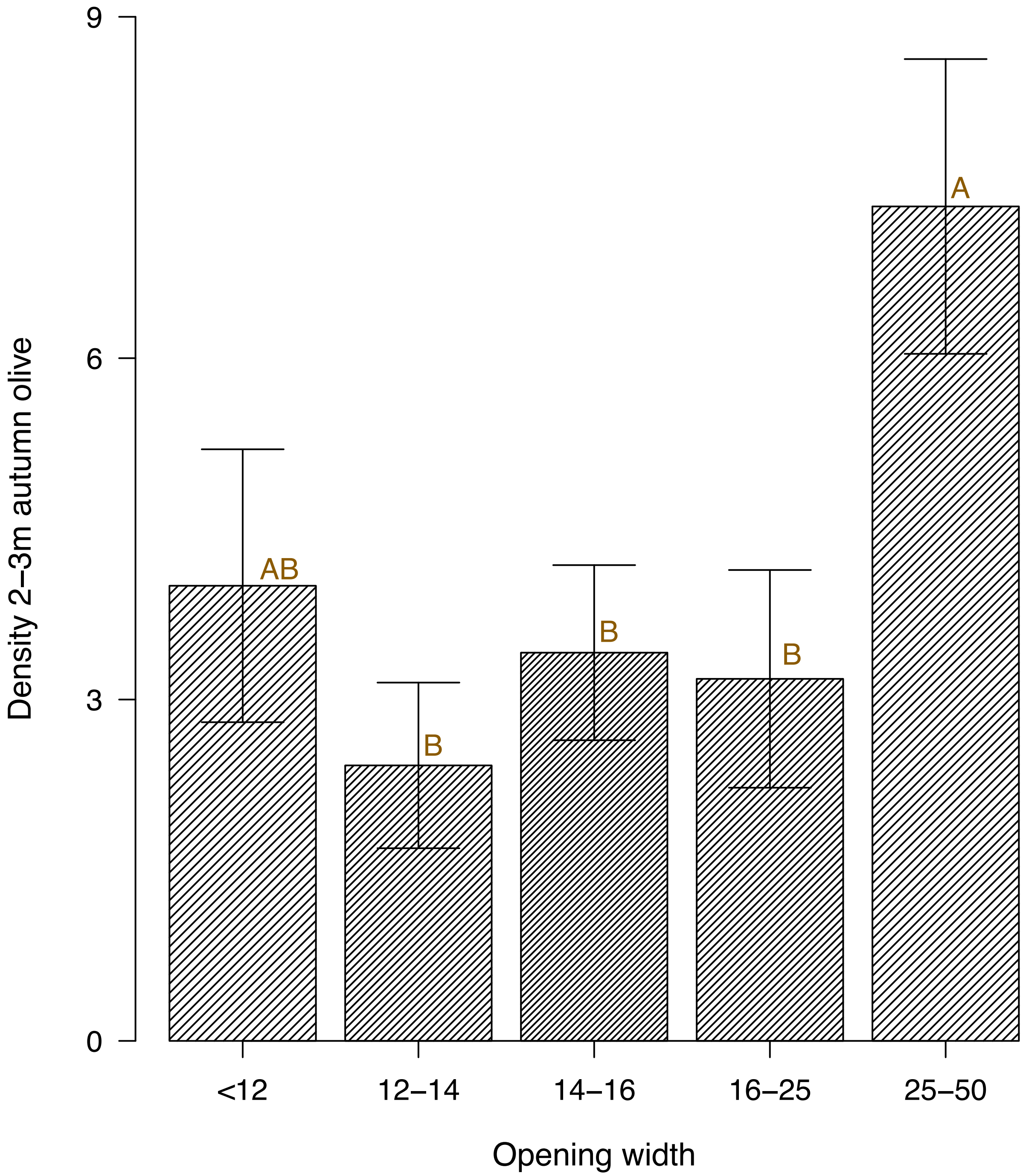

Figure 18. *Barplot of 2-3m autumn olive by opening width. Barplot of significant differences in the density of 2-3m autumn olive based road opening width. Road opening widths with the same letter group are not significantly different. Differences calculated using MANOVA with a significance level of* $\alpha \leq 0.05$.

Sites with the lowest and highest elevations did not differ significantly in autumn olive maximum patch depths. However, 475-525m in elevation had significantly greater autumn olive patch depths than elevations between 375 and 475m (Figure 19).

Analysis of variable relationships using PCA

Evaluating all of the physical site characteristics and autumn olive variables with PCA resulted in all autumn olive variables except density of >3m autumn olive and the average height of autumn olive loading onto the first principal component (PC) (Figure 19). The density of autumn olive for all size classes combined was left out of PCA.. The majority of the autumn olive variables loading onto the first PC indicates that density of 2-3m, 1-2m, 0.5-1m, and 0-0.5m autumn olive and maximum patch depth variables are responsible for the greatest proportion of variation in the data, and that they are correlated. The second PC had slope toward the interior negatively related to slope toward the road and interior canopy closure (Figure 20). PC 3 had a positive linear combination of both and basal area and interior canopy closure while PC 4 had a combination of elevation, density of autumn olive > 3m tall, and the average height of autumn olive (Figures 21). Comparing the first and fourth PCs, density of >3m autumn olive showed some relationship to both elevation and the other autumn olive variables. A comparison of the fifth PC with the first PC, indicated a relationship between density of 2-3.m tall autumn olive and road opening width (Figure 22).

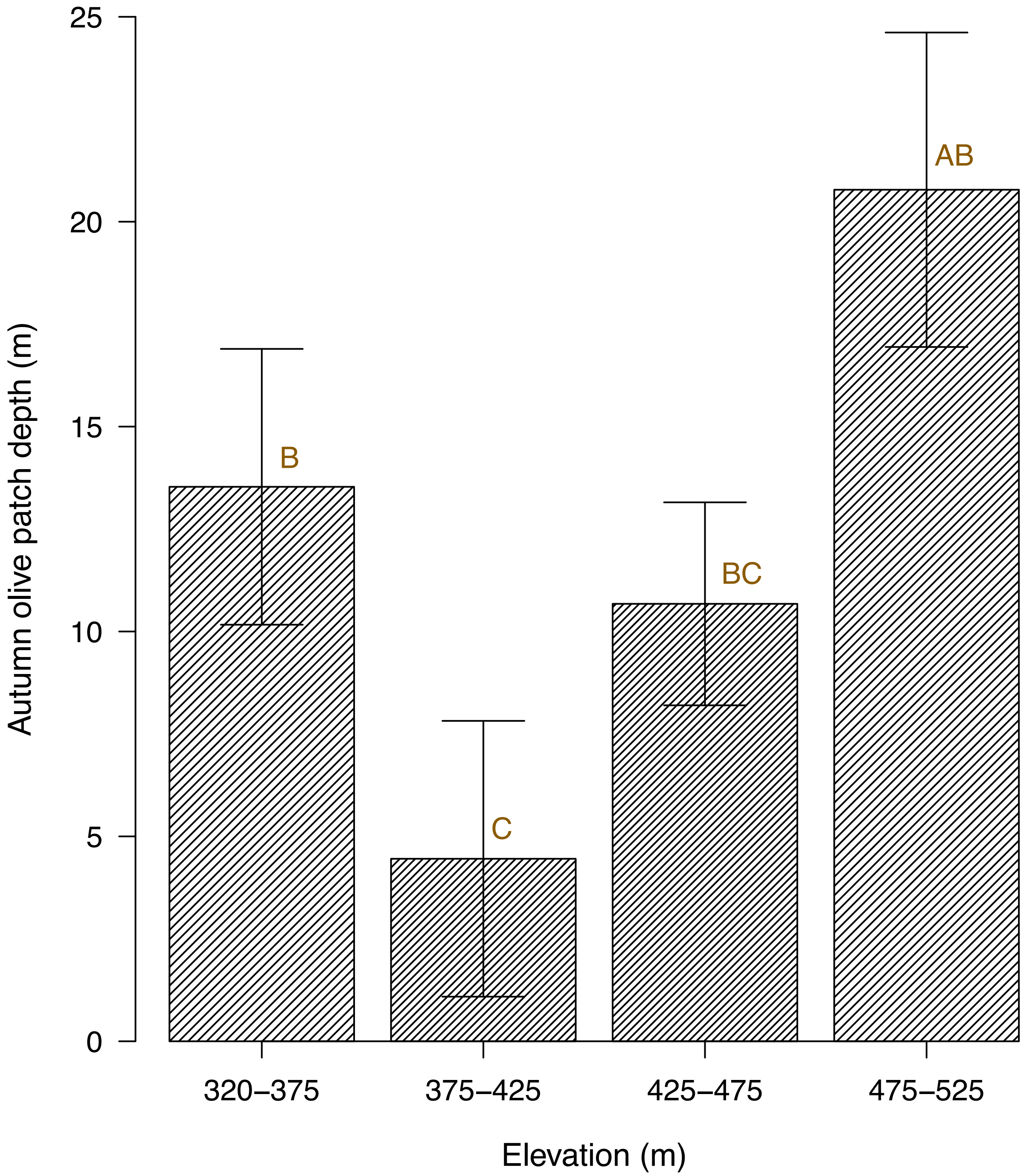

Figure 19*. Barplot of patch depth of autumn olive by elevation. Barplot of significant differences in the maximum patch depth (m) of autumn olive based on elevation (m). Elevations with the same letter group are not significantly different. Differences calculated using MANOVA with a significance level of* $\alpha \leq 0.05$.

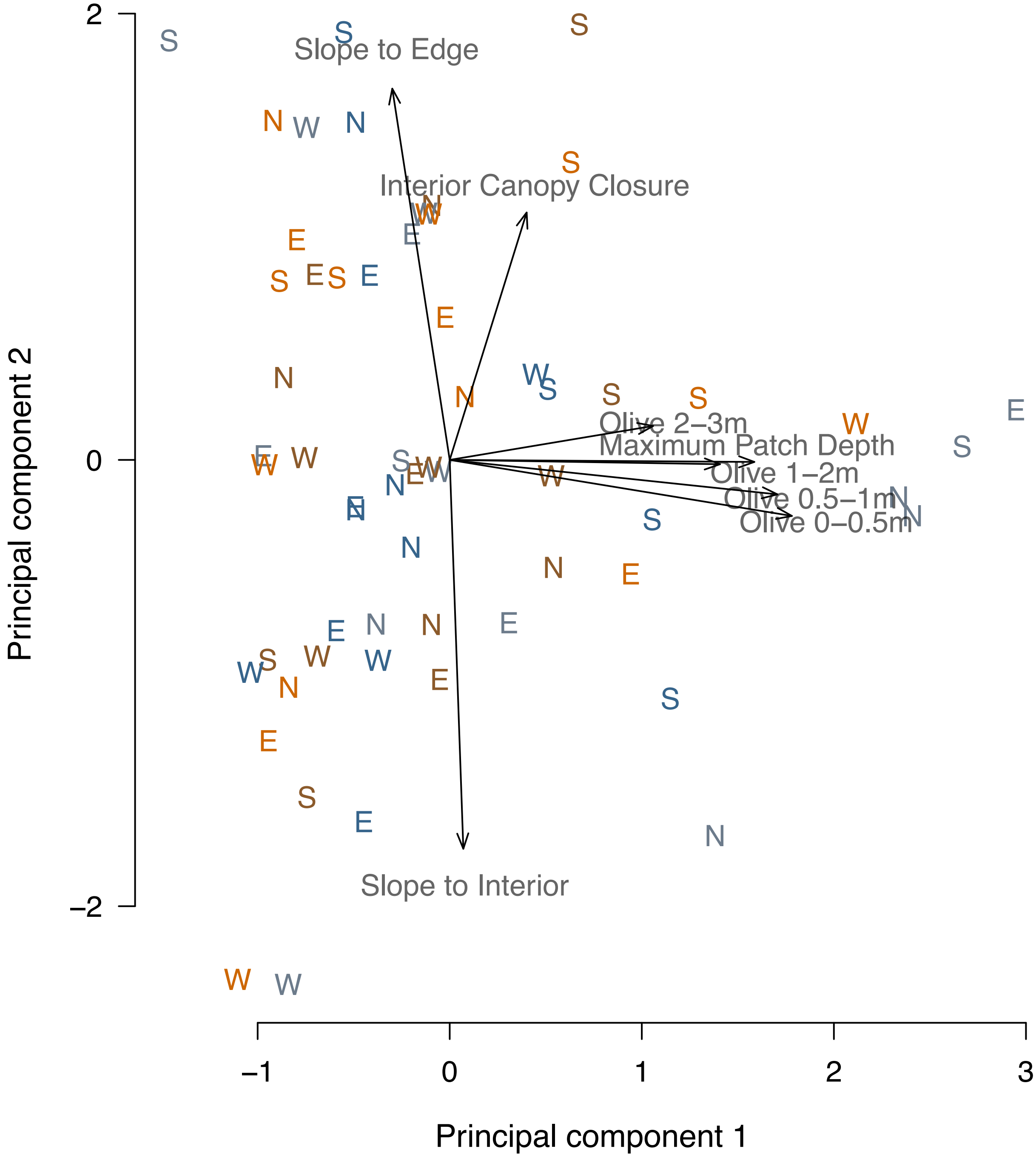

***Figure 20**. PC1 vs PC2 for all autumn olive variables and site variables.* *Principal component (PC) 1 versus PC2 for all autumn olive and physical site characteristics. Length and direction of arrows represents the strength and relationship combined variables have with observations and each other.*

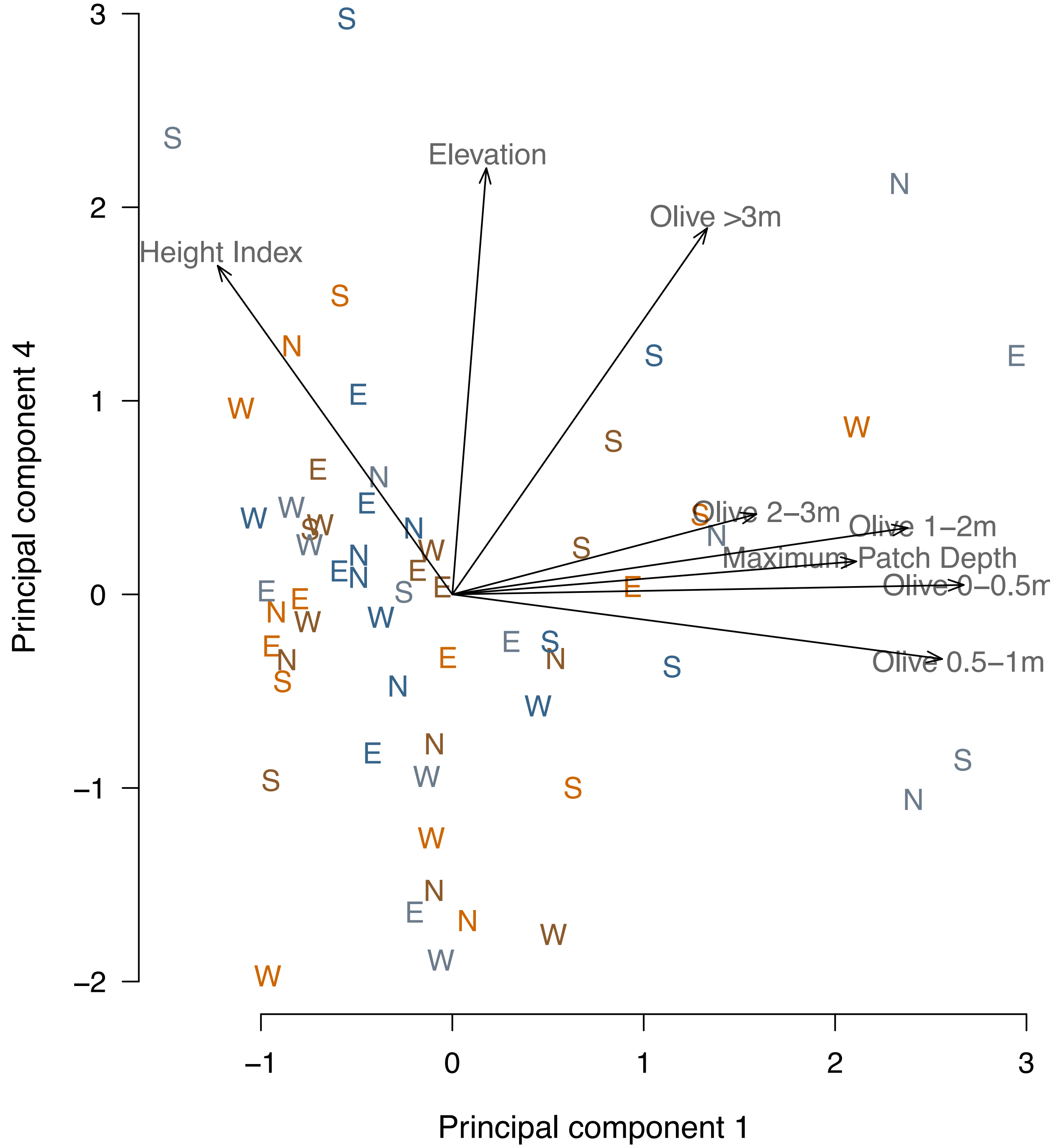

***Figure 21**. PC1 vs PC4 for all autumn olive variables and site variables. PC1 versus PC4 for all autumn olive and phys4cal site characteristics. Length and direction of arrows represents the strength and relationship combined variables have with observations and each other.*

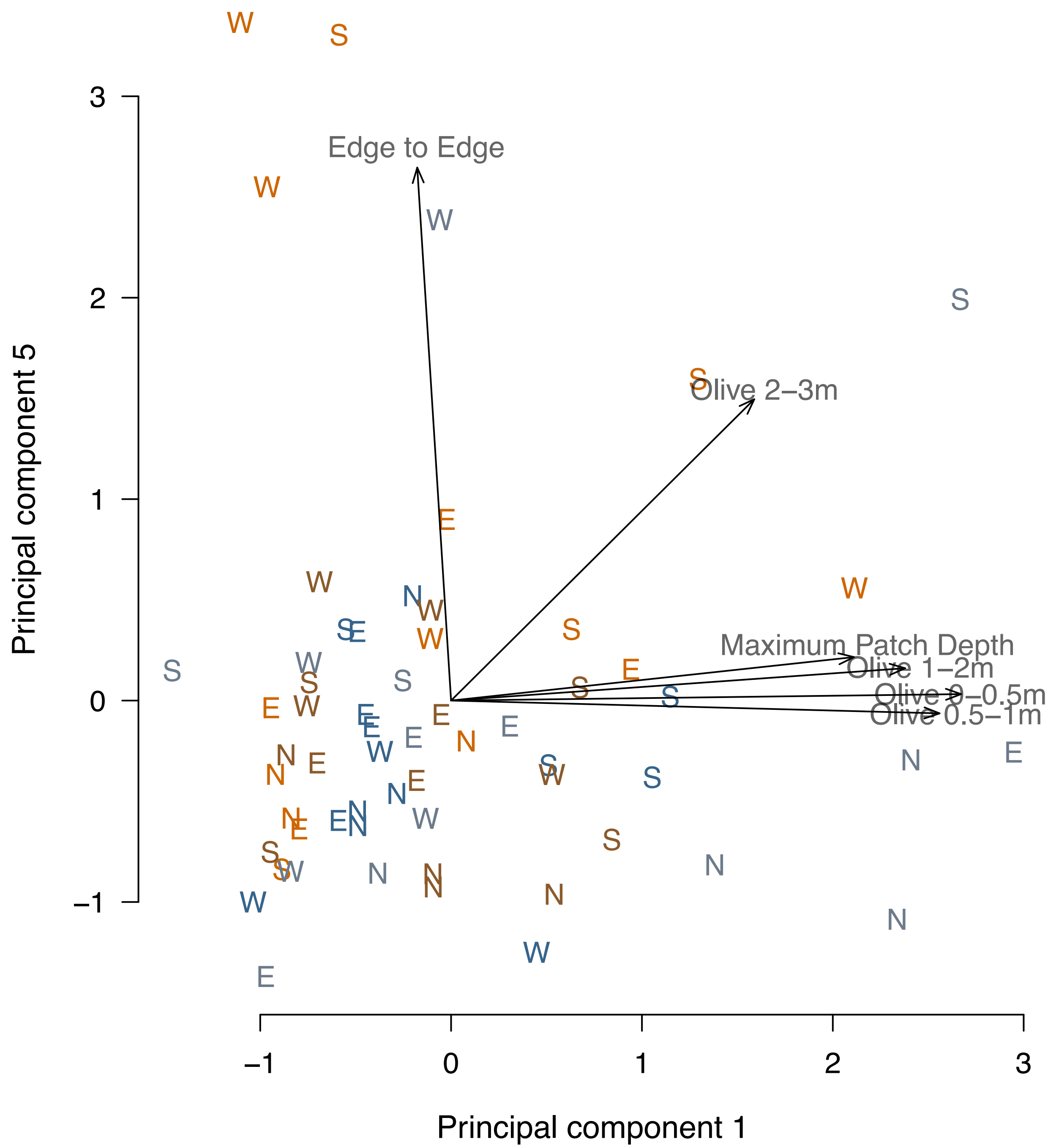

Figure 22. *PC1 vs PC5 for all autumn olive variables and site variables. PC1 versus PC5 for all autumn olive and physical site characteristics. Length and direction of arrows represents the strength and relationship combined variables have with observations and each other.*

When each of the eight autumn olive variables was analyzed individually against all physical site characteristics using PCA, the density of autumn olive >3m, 2-3m, 1-2m, <0.5m, and total autumn olive were each negatively related to road canopy closure (Figure 23). Autumn olive 0.5-1m densities did not associate strongly with any PC but had a positive relationship to elevation and a negative relationship to road opening width. Maximum patch depth of autumn olive associated positively with elevation, and the average height of autumn olive was positively related to slope toward the road and negatively with slope toward the forest interior.

Autumn olive presence or absence

Analysis of the autumn olive presence or absence data with MANOVA indicated significant differences ($\rho < 0.0001$) existed between the types of sites where autumn olive was present and the types of sites where it was absent. Presence or absence of autumn olive depended on the amount of road canopy closure, the road type (Figure 24), latitude and longitude. Differences in the presence or absence of autumn olive were not found to depend on changes in elevation, edge aspect, slope toward the road, and slope toward the interior forest. Running PCA on the presence or absence of autumn olive and physical site characteristics suggested that autumn olive presence was related to road type, with presence more likely on the more heavily used main roads (Figure 25).

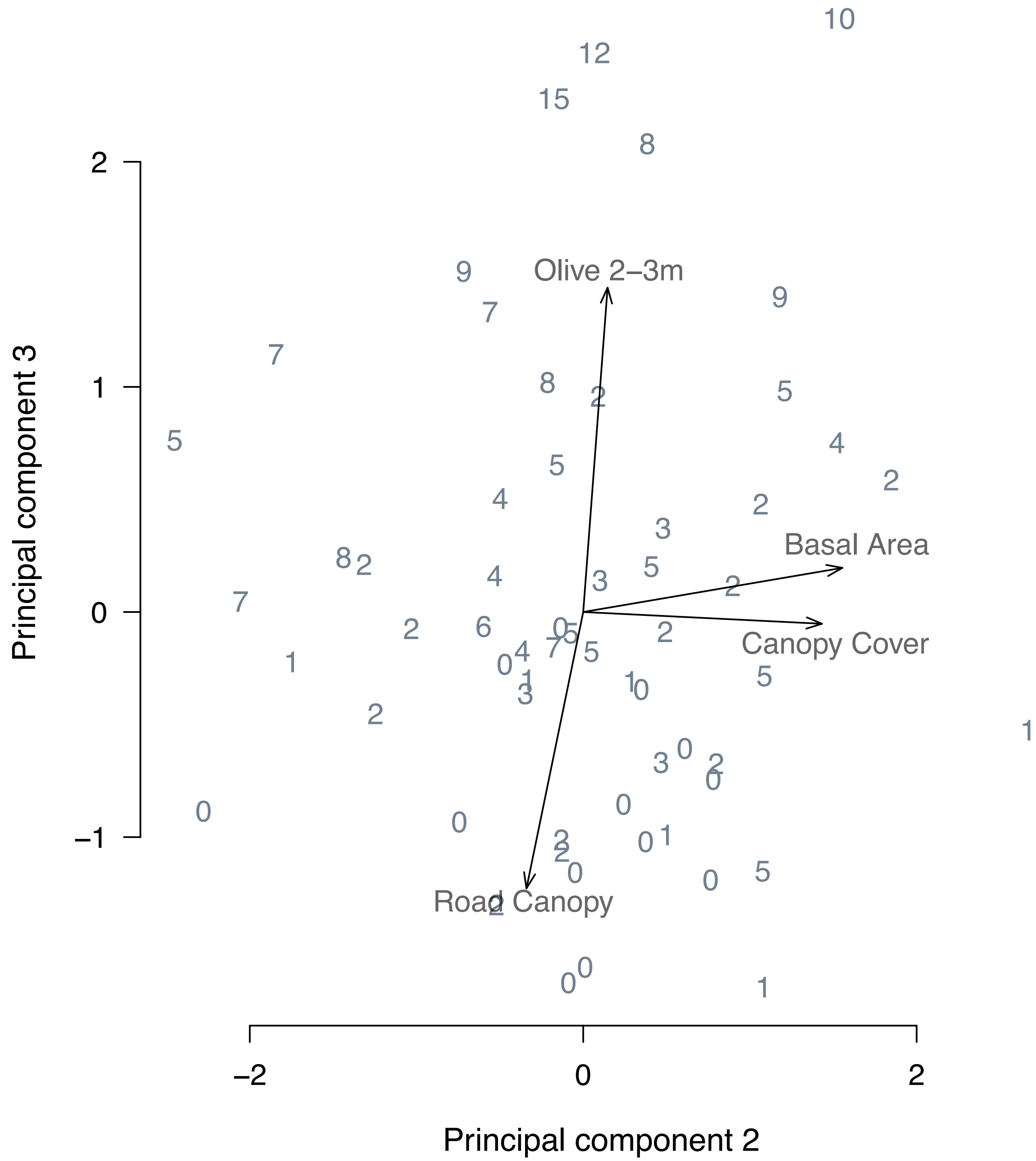

Figure 23. *PC1 versus PC2 for 2-3m autumn olive density and site characteristics. Length and direction of arrows represents the strength and relationship combined variables have with observations and each other. Numbers within plotted area represent number of autumn olive stems 2-3m.*

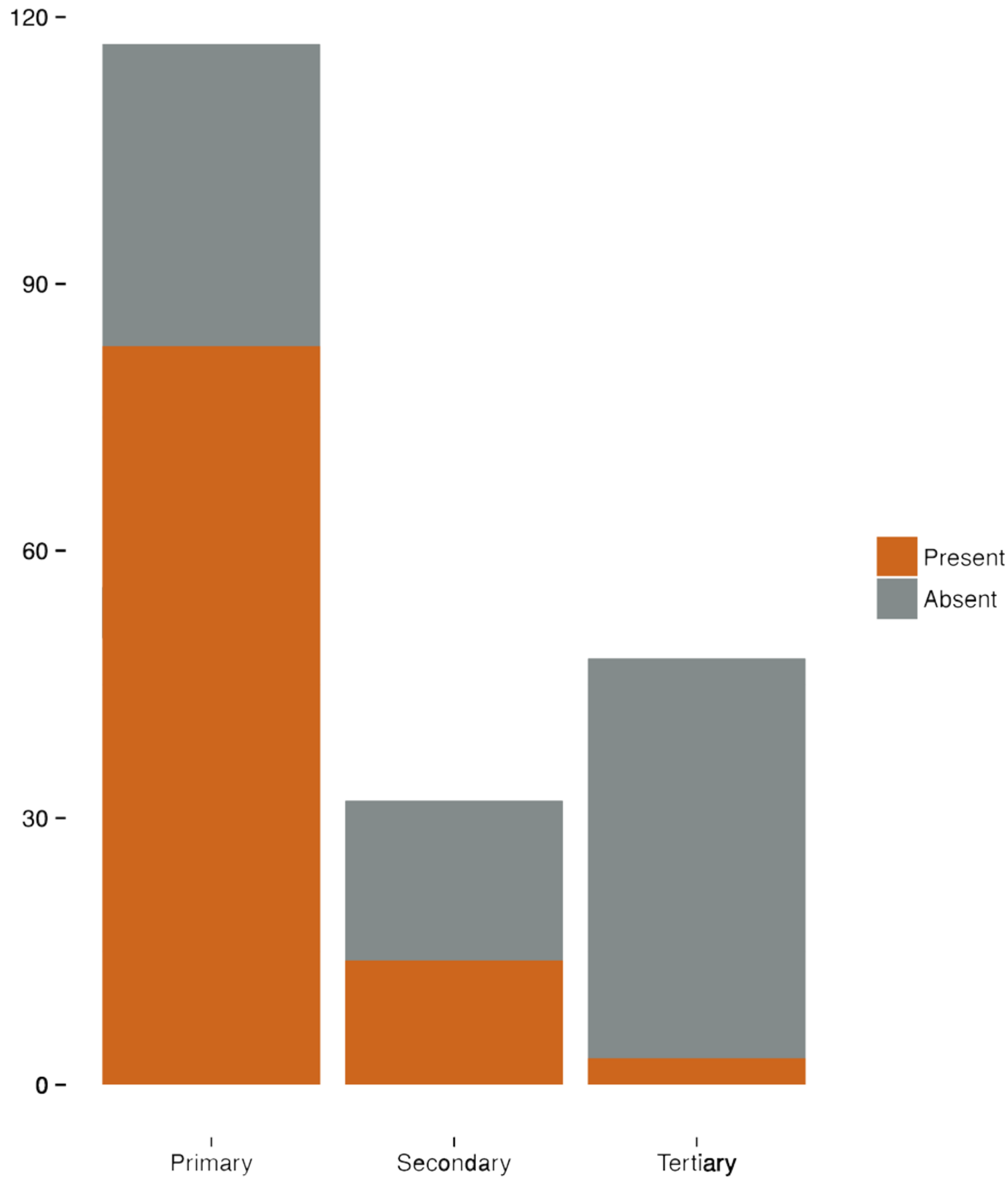

Figure 24. *Stacked barplot of autumn olive presence by road type. The color orange denotes sites with autumn olive present, and gray denotes sites where autumn olive was absent.*

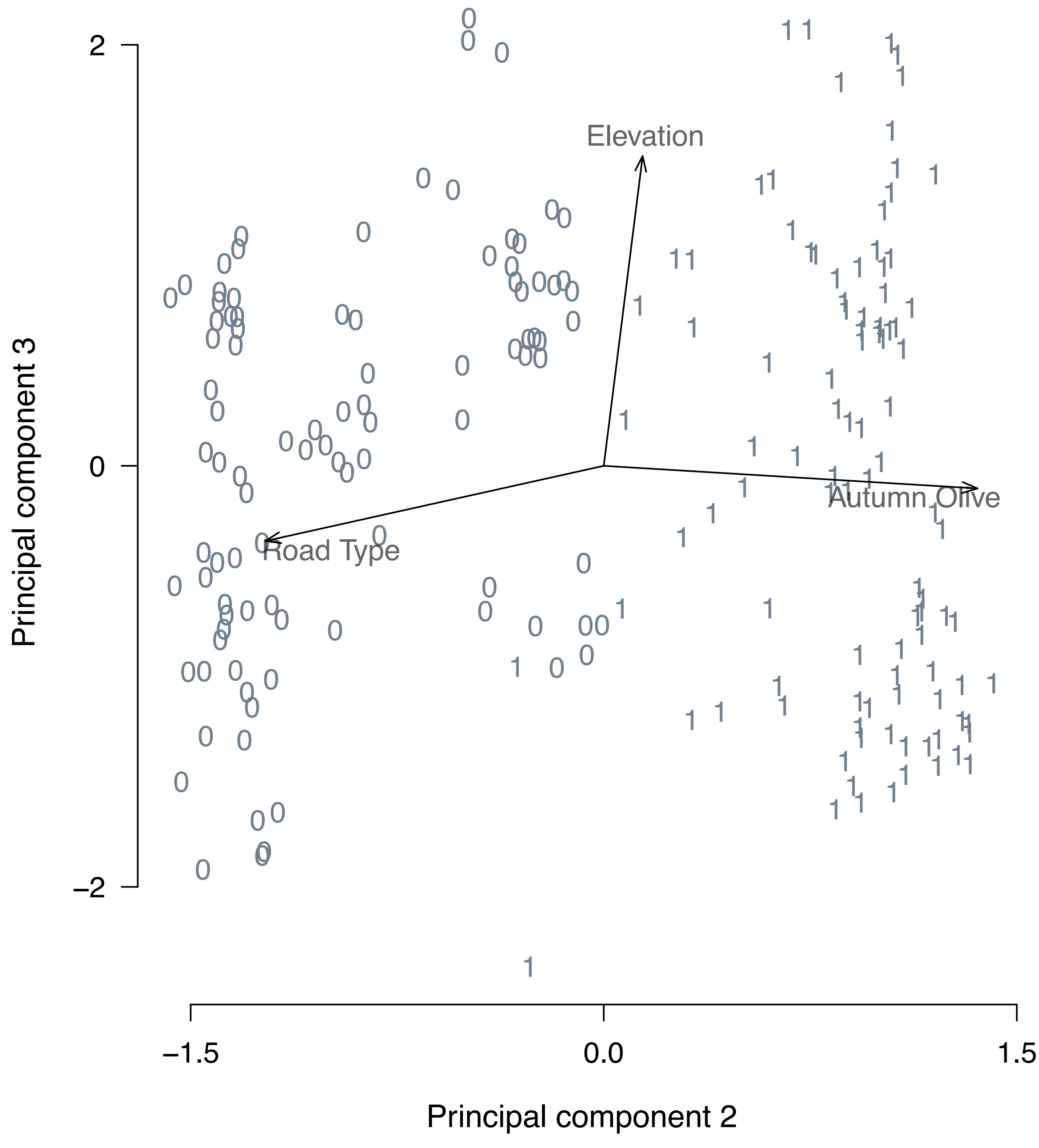

Figure 25. *PC2 versus PC3 for presence/absence of autumn olive by site characteristics. Length and direction of arrows represents the strength and relationship combined variables have with observations and each other.*

Chapter 4. Discussion

Autumn olive across forest-road edge aspects

Only maximum patch depth of autumn olive and the density of 2-3m autumn olive differed by aspect, and only the density differences for 2-3m autumn olive supported our hypothesis that autumn olive would be more abundant on southern aspects. In turn, higher numbers of taller autumn olive may reflect greater access to sunlight on southern aspects. Although PAR was not measured in this study, previous studies reported that south edge aspects received higher light levels than other forest edge aspects (Matlack 1993, Gehlhausen 2000). Presence of lower numbers of taller autumn olive on northern forest edge aspects further support this theory that light may optimize autumn olive growth, yielding taller height on south facing sites.

Our hypothesis that maximum patch depth would be greatest on south forest-road edge aspects was not supported by the data. On average, southern, northern, and western edge aspects all had autumn olive patches extending deeper into the interior, and aspects did not differ. In a study of the depth of microclimate effects on two forests in Illinois, both south- and west- facing forest edges had canopy closure percentages that did not change from the forest edge to the forest interior (Gehlhausen 2000). Having similar canopy openness from the forest edge toward the forest interior could explain why no significant differences in autumn olive height, abundance or patch depth existed between south and west forest-road edge aspects in our study. It does not, however, explain why north facing forest-road edge aspects failed to demonstrate

shallower penetration of autumn olive patches. With that result, our findings differ from those of previous studies in North Carolina that showed the penetration of edge-associated species was less on north-facing forest edges (20m) compared to south forest edges (60m) (Fraver 1994). Because we studied forest-road edges, which are shaded by adjacent forests creating a buffer, the capacity of the adjacent forest to buffer the edge could limit extreme microclimate differences between forest-road edges based on aspect (Gehlhausen 2000, Denyer 2006). Forest-road edge aspects would have greater microclimate similarities when shading decreases light attenuation. With various microclimate variables responsible for determining autumn olive's ability to establish, proliferate, and spread, greater microclimate similarities between forest-road edges would result in similar autumn olive patch depths. Additionally, with slower growth of all plants on north oriented forest edges, side canopy could remain open longer, allowing for greater seed dispersal further into the interior forest (Cadenasso 2001). Decreased side canopy closure resulting in greater seed rain further into the interior forest could also help explain why northern forest-road edge aspects actually had greatest maximum patch depth averages.

As birds consume autumn olive berries, the aril is removed. Autumn olive seed germinates at a rate of 99.3% when fruit is separated from seed (Kohri 2002). A 99% successful germination rate coupled with greater seed movement through the forest edge into the interior would increase the likelihood of autumn olive encountering and establishing in a suitable site as deep on northern forest-road edge aspects as southern and western forest-road edge aspects (Kohri 2002). The idea that on north facing

edges greater seed rain results in a better chance of autumn olive seed being dropped in more suitable sites for growth also would not confound our theory that greater 2-3m autumn olive densities on southern forest-road edge aspects are related to increased sunlight. Because height of autumn olive could simply be a product of amount of available sunlight, which would still occur on buffered southern forest-road edge aspects, maximum patch depth and height could be impacted by different environmental factors.

The greater initial size of autumn olive diameters edge forest sites with southern aspects reinforces the thought that light benefits growth of autumn olive. However, after 8 years, northern forest-road edge sites obtain sizes equal to those of 0m southern patches. The trend of increased initial growth on forest edge sites with a southern aspect eventually being overtaken by all other sites contributes to the theory autumn olive has differing environmental requirements at different life stage.

Relationship between autumn olive and native plant species

The positive linear relationship between the average height of autumn olive and the average height of native tree species, and all native plant species in general, did not support our hypothesis that the density and height of autumn olive would be negatively related to the abundance and height of native plant species. A positive relationship between native plants and autumn olive solely on south facing forest-road edges suggests that sites beneficial for autumn olive height growth are also beneficial for native plant height growth. Considering previous findings of greater light availability on

southern forest edge aspects (Burgess 1981, Matlack 1993, Chen 1995, Gehlhausen 2000), this relationship of increasing height is likely a response to higher PAR levels on south forest-road edge aspects. In areas of high light, taller autumn olive stems tend to bend towards the ground adding to the likelihood that potential competitors will experience additional shading from autumn olive. If autumn olive and other plant species establish at the same time, the 7m height maximum of autumn olive (Kohri 2011) would prevent it from shading out competitors past that height (Schlesinger 1984) and typically autumn olive reaches a height of approximately 4.5m in the southeast (Darlington 1994). Also, given the shade-tolerant nature of many native Central Hardwood Forest plant species, unless large monocultures of autumn olive were present, the impact would be less severe than if autumn olive were competing with only shade-intolerant species.

Potentially confounding the issue is the ability of autumn olive to fix nitrogen through a symbiotic relationship with the actinobacteria *Frankia* (Wang 2005). Schlesinger & Williams(1984) and Paschke et al (1989) studied how several nitrogen-fixing plant species interplanted with black walnut (*Juglans nigra*) affected the growth of black walnut. Schlesinger and Paschke both found that autumn olive planted with black walnut had an earlier, more consistent, and greater positive impact on black walnut diameter than other nitrogen-fixing plants. Schlesinger reported a diameter increase of 56-351% in black walnut across bottomland and upland sites starting as early as six years when interplanted with autumn olive. Other nitrogen-fixing plant species had a maximum 135% diameter increase in black walnut and had less consistent effects

compared to autumn olive. Autumn olive may also suppress weeds by limiting the number of plants in the understory with which larger trees must compete for resources (Paschke 1989). Several studies have found that limited light may reduce the benefits of higher nitrogen levels (Walters 1996, Finzi 2000, Walters 2000). Increased nitrogen levels affecting the average height of native plants only on southern edge aspects suggests that at northern, eastern, and western edge aspects, limited light may reduce the benefit of higher nitrogen levels.

Relationship between autumn olive and other exotic, invasive plant species

The increased density of total exotic, invasive species we observed co-occuring with increased density of autumn olive on southern forest-road edge aspects supports our hypothesis under objective 3. However, this relationship between total exotic, invasive species density and autumn olive density did not extend to northern, eastern, and western forest-road edge aspects. Regardless of aspect, autumn olive is present and disturbance is occurring along the forest-road edges. The disconnect between the success of autumn olive and other exotic, invasive species on northern, eastern, and western forest edges implies that other factors are clearly limiting the success of these other exotic, invasive plants. Again, south-facing forest-road edges are the only edge orientations where a significant relationship occurred, suggesting that light availability may be key for greater densities of exotic, invasive species.

Significant site characteristics

In relation to objective 4, investigation of site factors contributing to the success of autumn olive revealed seven variables linked to differences in height or abundance of autumn olive. The direction of the slope from plot center toward the forest interior and toward the forest edge affected the average height of autumn olive. Areas with a consistent downward slope from the road toward the forest interior had taller autumn olive. This taller average height on downward slopes could be a reaction to increased shading from the slope but was not measured in this study. As the level of shading increases or decreases, autumn olive could exhibit changes in growth rate. Greater shade could inhibit height growth in autumn olive, while moderate shade levels stimulate autumn olive resulting in greater resource allocation to height growth in an effort to attain more light. Grime and Jeffrey (1965) found that for some plant species, increased shading corresponded with greater vertical growth, which provided plants with greater sunlight. Walters et al (1993) found that shade intolerant *Betula* species were prone to increases in growth rate under low light conditions. Greater growth for these shade intolerant plants was achieved through greater resources allocated into leaf production and less into root production. An alternative theory is that a downward slope results in greater water and nutrient runoff from the road, promoting more rapid growth of autumn olive. Permeable roadways at CSSFWMA collect more water than paved roads, but runoff would contain higher calcium and lime as gravel is added yearly to the roadbed.

Slope toward the edge had an effect on the average height of autumn olive, and the density of 0.5-1m autumn olive. Slope type had an effect on the density of 0.5-1m

autumn olive. Road opening width affected the density of 2-3m tall autumn olive, and elevation affected the average autumn olive patch depth. As factors that benefit oak growth appear to differ from one stage of development to another (Chadwell and Buckley 2003), so to, it could be inferred that conditions required for autumn olive success change with stage of development. This portion of our study is mostly applicable for the construction of hypothesis for future research. The idea that factors affecting autumn olive might be uniquely to a specific life stage would ultimately be a starting point for the next step in research to characterize autumn olive and the sites that allow higher densities and greater heights of the exotic, invasive shrub.

Autumn olive presence or absence

In terms of the presence or absence of autumn olive, road type and percent road canopy closure both appear to be important factors in determining whether autumn olive will establish and proliferate successfully on a specific site. Although road traffic was not directly measured in this study, it appears that areas with less road traffic and fewer road maintenance activities harbor less autumn olive and, therefore, have a reduced capacity for invasion by autumn olive. Also, greater canopy closure over roads decreased the potential of encountering autumn olive along forest-road edges. Therefore, roads with large stretches with low canopy closure will likely have greater occurrence of autumn olive. Roads with less canopy cover will have greater penetration of light onto the forest-road edge, increasing alteration of microclimatic conditions from

those typical of forest interiors. These alterations in light regimes allow autumn olive a greater opportunity to become established and invade.

Conclusion

Overall, results for several different methods of analysis suggest that the depth to which autumn olive penetrates forest and the density of larger height class autumn olive plants differ by aspect. This difference by aspect results in the potential for autumn olive to establish, entrench, and emigrate into and from south, north, and west forest edges. As managers evaluate the likelihood of invasion through bird dispersal, south-facing forest-road edges should be monitored, as they tend to have more dense autumn olive in taller size classes, resulting in the production of large quantities of fruit and seed on these sites. Also, sites with downward slopes toward the forest interior, and wide road opening widths allow for increased density of larger autumn olive and must be watched.

It is planned to use the information gained in this study concerning those variables that best explained the abundance and growth of autumn olive along forest road edges to explore the development of a GIS-based risk map that managers could use to determine when and where autumn olive invasions are most likely to occur. Additional research utilizing similar methods to study the distribution and growth of other exotic, invasive species could be used to build more comprehensive risk maps, and is warranted.

In the future, further studies will need to be conducted to validate relationships between autumn olive and slope and autumn olive and opening width. Microclimate effects on the height, growth rate, and fruit production of autumn olive will also need to be investigated to determine how the invasive shrub is affected by alterations in light,

temperature, and moisture. Finally, changes in patterns across greater geographic locations would increase our ability to successfully predict future patterns of autumn olive spread.

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Appendix

Table A-1. *Equation for patch depth by slopes. The polynomial regression equation for the maximum patch depths of autumn olive plotted by slope toward the road and slope toward the interior forest. ^{2} represents that the component is raised to the power of 2.*

Edge Aspect	Intercept	Slope toward Road	Slope toward Interior^2
N	19.0347	-0.0938	-0.0079
E	6.1062	-0.0938	-0.0079
S	17.6986	-0.0938	-0.0079
W	12.0305	-0.0938	-0.0079

Table A-2. *Equation for 2-3m autumn olive density by opening width. The polynomial regression equation for the density of 2-3m height class autumn olive plotted by slope toward the road and slope toward the interior forest. Equations are divided by aspects due to differences based on forest-road edge aspect. ^{2} represents that the component is raised to the power of 2.*

Edge Aspect	Intercept	Opening Width^2
N	3.8786	-0.0093
E	3.0040	0.0025
S	2.6267	0.0071
W	3.2041	-0.0002

Table A-3. *Equation for average autumn olive height by slope. The polynomial regression equation for the average height of autumn olive plotted by linear and quadratic slope toward the interior components. ^{2} represents that the component is raised to the power of 2.*

Edge Aspect	Intercept	Slope toward Interior	Slope toward Interior^2
N	1.3060	-0.0031	0.0002
E	1.3060	-0.0084	0.0004
S	1.3060	-0.0229	0.0008
W	1.3060	-0.0004	0.0000

Table A-4. *Equation for 1-2m autumn olive density by slope and canopy closure. The polynomial regression equation for the density of 1-2m height class autumn olive plotted by linear and quadratic components of slope toward the interior and road canopy. ^{2} represents that the component is raised to the power of 2.*

Edge Aspect	Intercept	Slope toward Interior	Slope toward Interior^2	Road Canopy	Road Canopy^2
All	36.6011	0.1489	-0.0078	-0.9255	0.0070

Table A-5. *Equation for autumn olive density for combined height classes by slope and canopy closure. The polynomial regression equation for the density of all autumn olive height classes combined plotted by the quadratic component of slope toward the interior forest and the linear component of road canopy closure. ^{2} represents that the component is raised to the power of 2.*

Edge Aspect	Intercept	Slope toward Interior^2	Road Canopy
All	41.7160	-0.0134	-0.2605

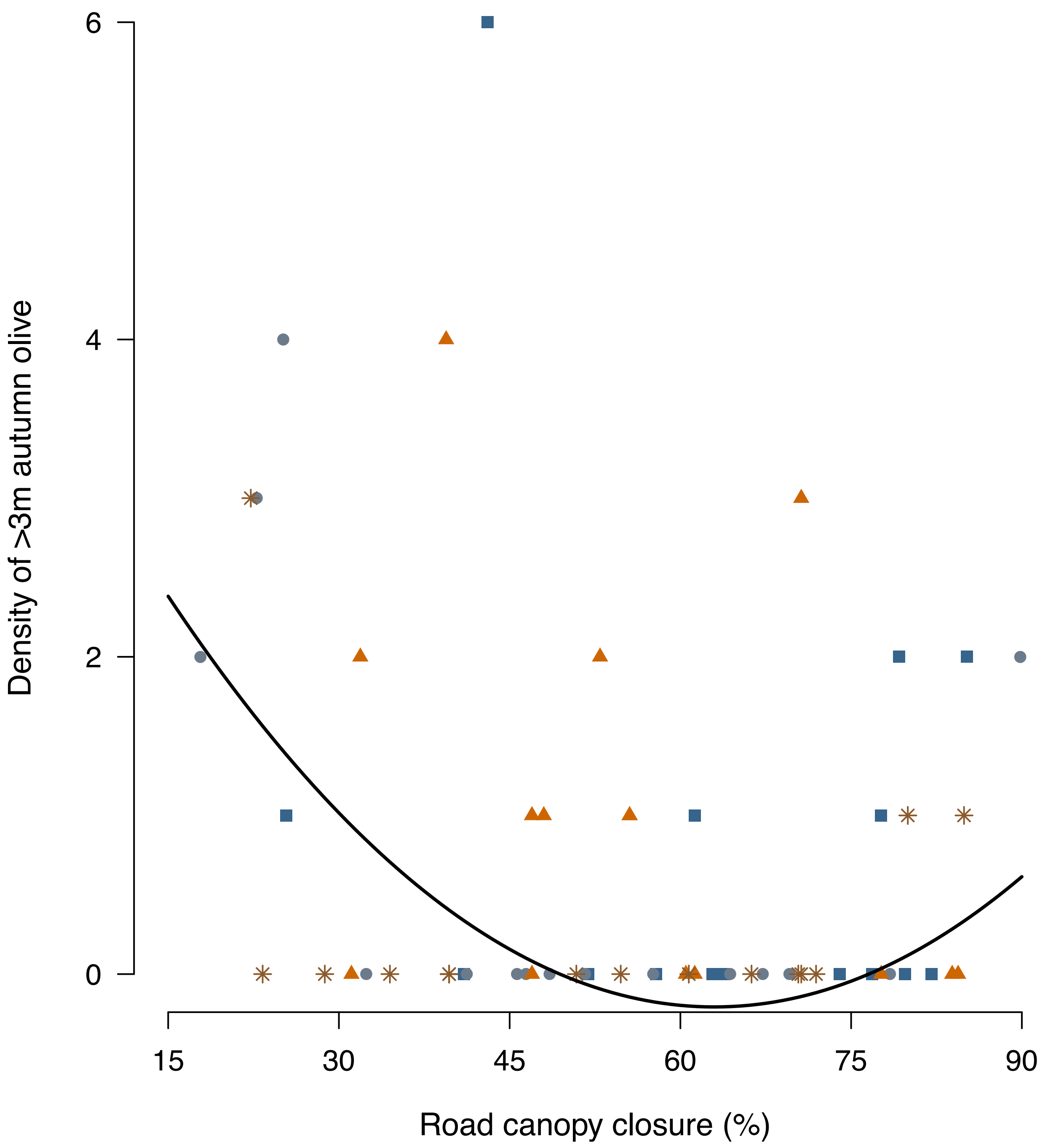

Figure A-1. *Scatterplot of the abundance of >3m autumn olive. Density of >3m autumn olive plotted against road canopy closure (%). Observations are divided by aspect: blue (■) represent north forest-road edge aspects, gray (●) east, orange (▲) south, and brown (✳) west.*

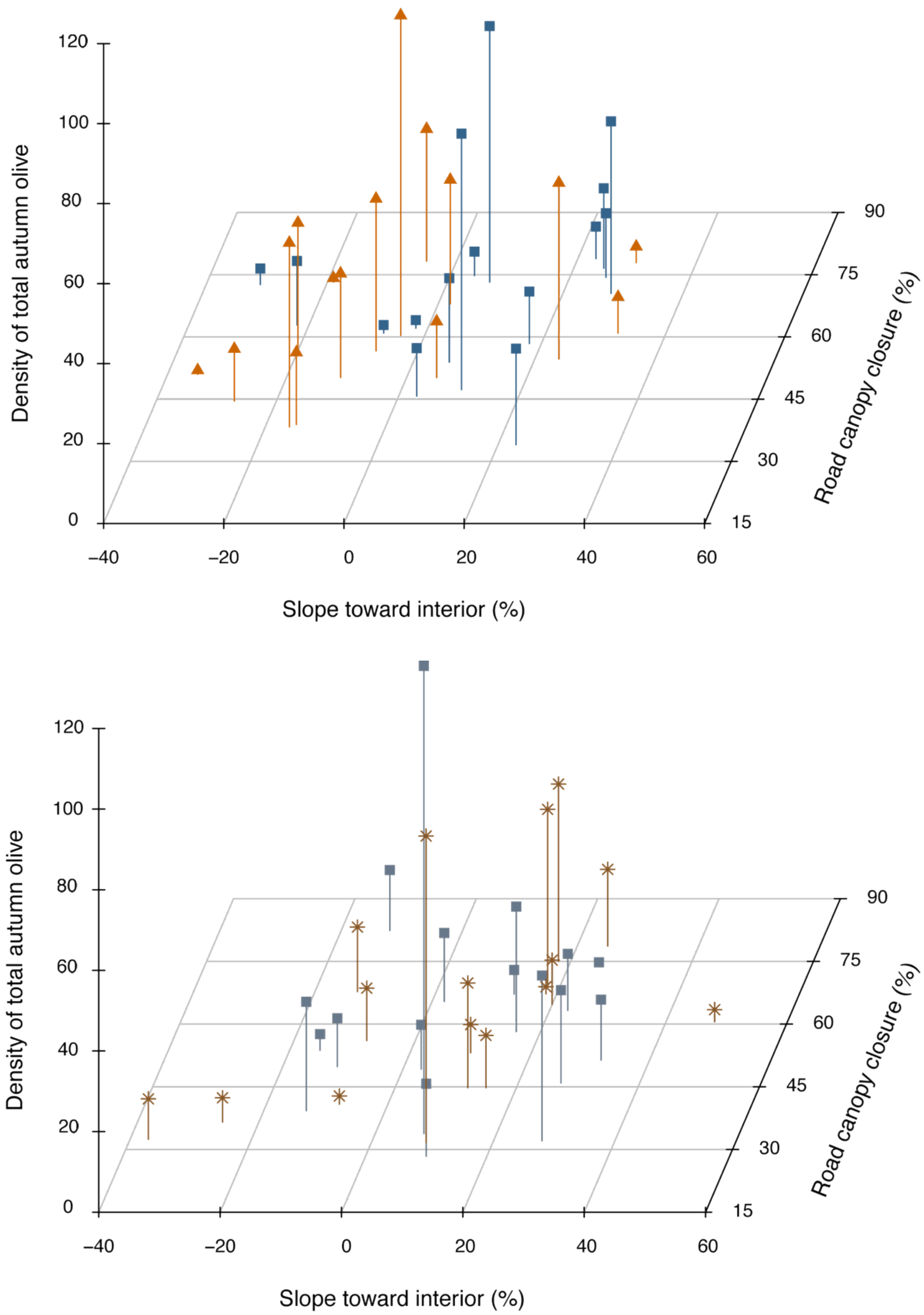

Figure A-2. *3D scatterplot of abundance of total autumn olive. Abundance of total autumn olive plotted by road canopy closure and slope toward interior forest. Observations are divided by aspect: blue (■) represent north forest-road edge aspects, gray (●) east, orange (▲) south, and brown (✳) west.*

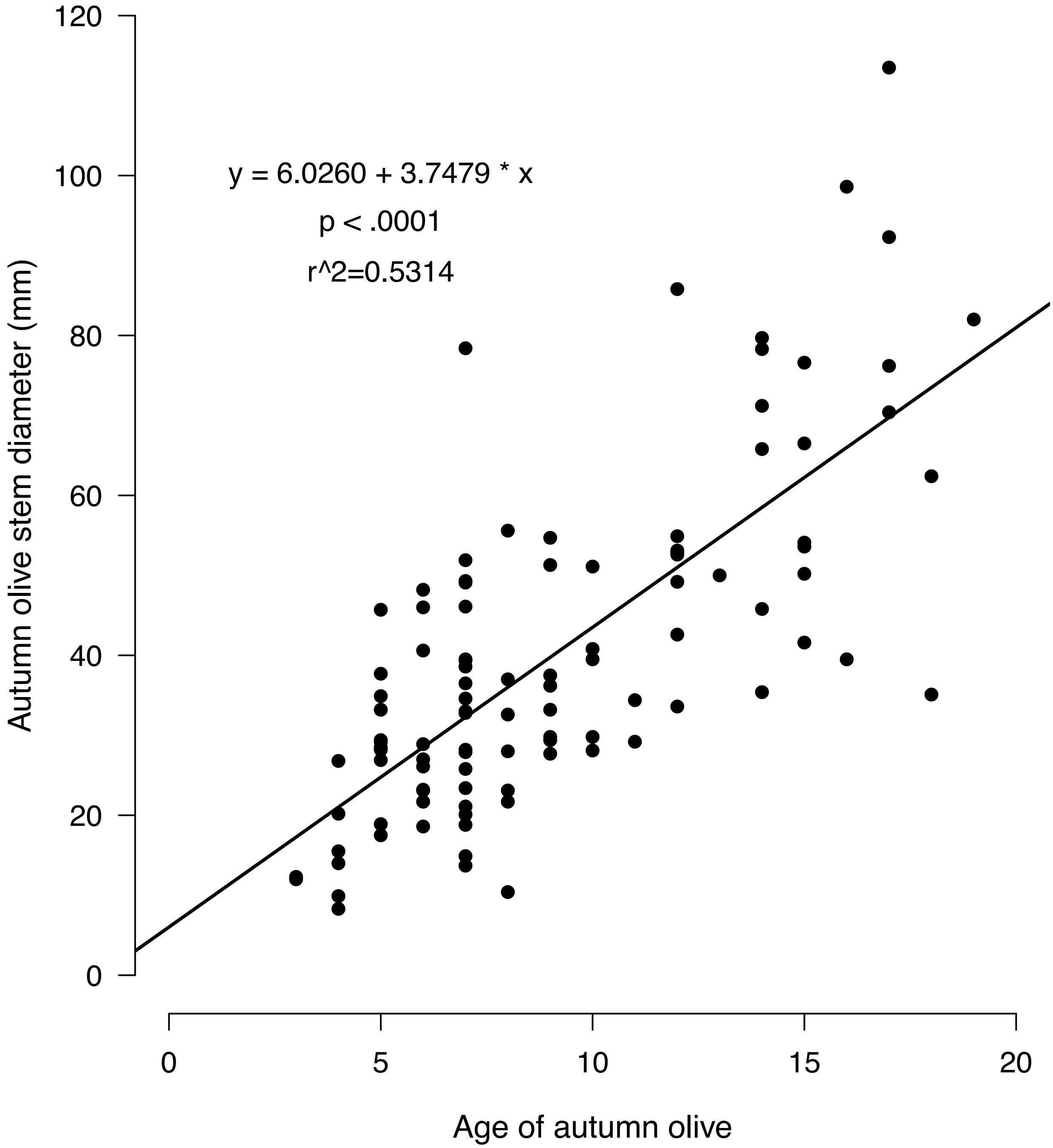

Figure A-3. *Diameter by age. Scatterplot of the diameter of autumn olive stems 6" above the ground plotted by the age of the plant with corresponding linear regression line. All autumn olive stems without divisions based on aspect or position. Linear regression equation, p-value and r^2 included.*

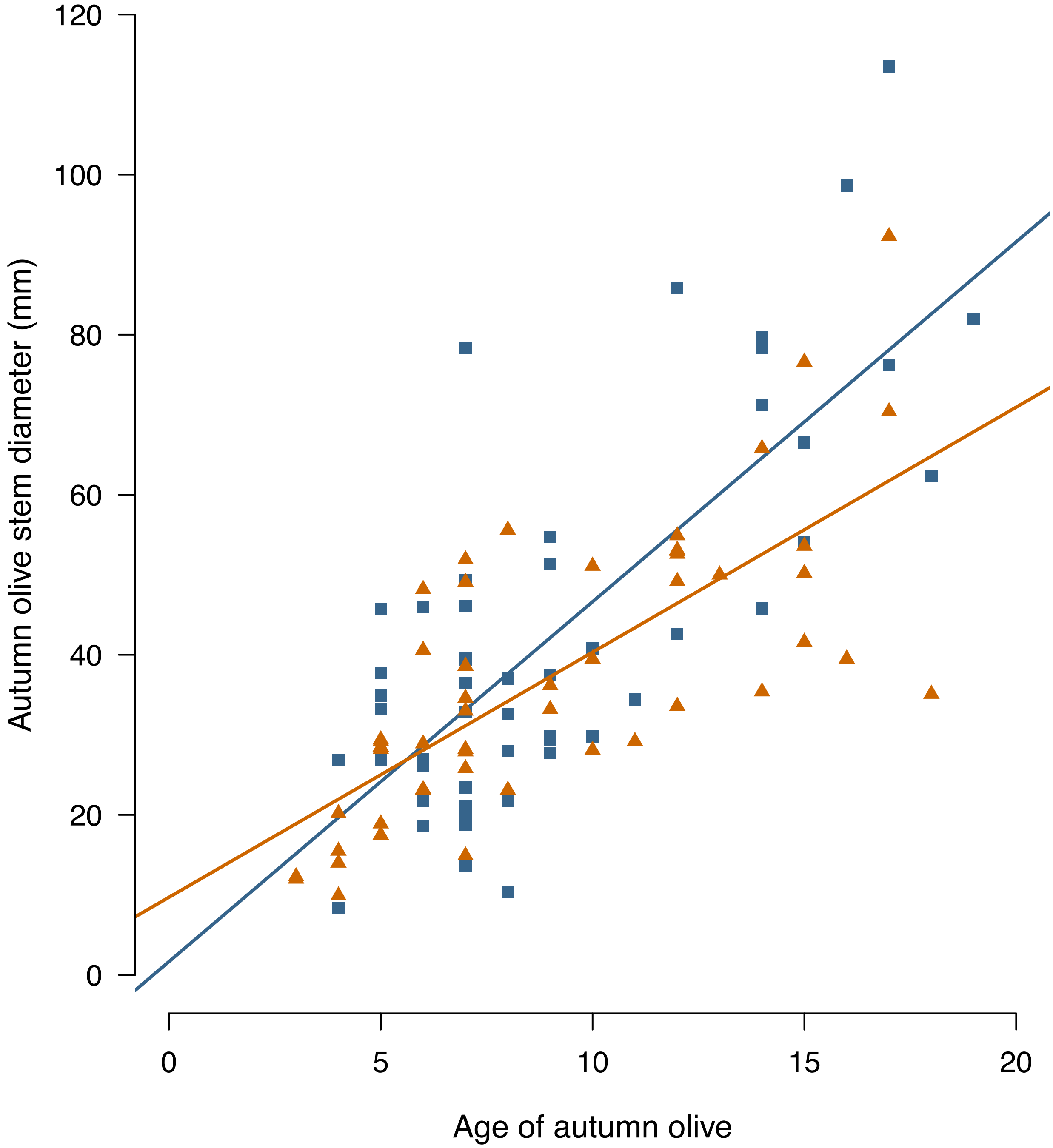

Figure A-4. *Diameter by age dependent on edge aspect. Scatterplot of the diameter of autumn olive stems 6" above the ground plotted by the age of the plant with corresponding linear regression line. Slopes differ. Blue (■) represent observations for northern aspects and orange (▲) southern aspects. Observations divided based on forest-road edge aspect.*

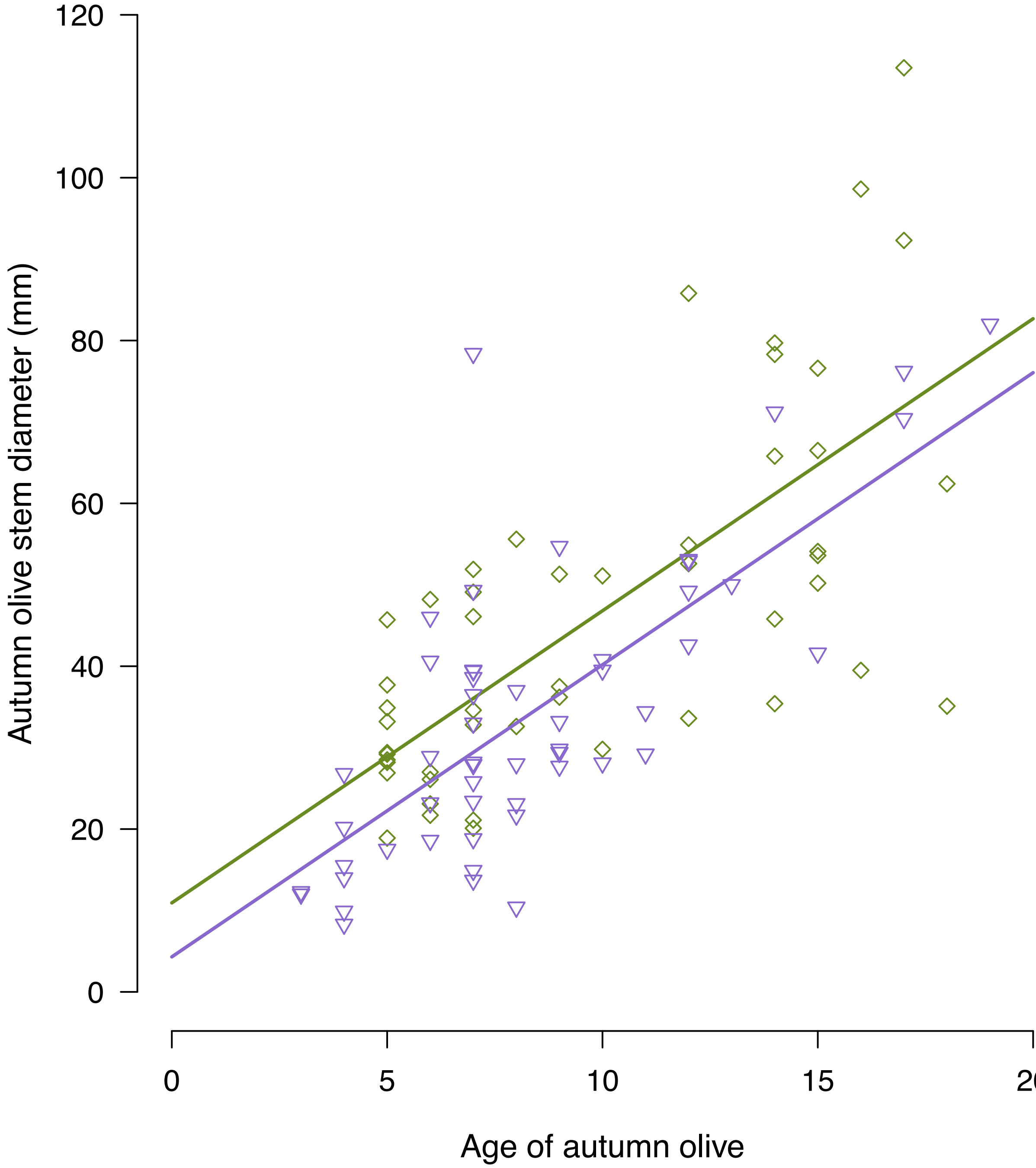

Figure A-5. *Diameter by age dependent on location relative to forest edge. Scatterplot of the diameter of autumn olive stems 6" above the ground plotted by the age of the plant with corresponding linear regression line. Slopes do not differ, intercepts do. Green (■) represent observations at 0m from the forest edge, purple (•) 10m toward the forest interior from the edge. Observations divided based on position relative to the forest edge.*

Table A-6. *Equation for diameter by age dependent on edge aspect. The linear regression equation for the diameter of autumn olive by age divided based on forest-road edge aspect.*

Edge Aspect	Intercept	Age
N	1.6679	4.4962
S	9.7062	3.0616

Table A-7. *Equation for diameter by age dependent on location relative to the forest edge. The linear regression equation for the diameter of autumn olive by age divided based on position 0m from the forest- edge or 10m toward the interior forest.*

Edge Position	Intercept	Age
0m	10.9343	3.5873
10m	4.3061	3.5873

Table A-8. *Equation for diameter by age dependent on edge aspect and location. The linear regression equation for the diameter of autumn olive by age divided based on the forest-road edge aspect and position 0m from the forest- edge or 10m toward the interior forest.*

Edge & Position	Intercept	Age
N - 0m	3.3237	4.6533
N - 10m	2.8540	4.0106
S - 0m	21.9230	2.2344
S - 10m	2.4378	3.5508

Table A-9. *Relationships between invasive species and total native and invasive species by average autumn olive height. Linear relationships between the abundance of exotic, invasive species and total species combined by the average height of autumn olive. Variables with significant relationships are italicized and bold. Comparisons completed for all measurements regardless of aspect and for average heights and densities based on aspect. R-square values present for all relationships with p-values indicating significance.*

Variables	All Aspects	North	East	South	West
Average height of exotic plants (all species)	ρ = 0.2098 R^2=0.0270	ρ = 0.7545 R^2=0.0078	ρ = 0.0764 R^2=0.2218	ρ = 0.6372 R^2=0.0176	ρ = 0.4270 R^2=0.0492
Density of all exotic, invasive plant species	ρ = 0.8537 R^2=0.0006	ρ = 0.8946 R^2=0.0014	***ρ = 0.0556*** ***R^2=0.2537***	ρ = 0.3796 R^2=0.0598	ρ = 0.4120 R^2=0.0524
Average height of all trees (native and invasive)	***ρ = 0.0336*** ***R^2=0.0755***	ρ = 0.5926 R^2=0.0226	ρ = 0.6909 R^2=0.0126	***ρ = 0.0204*** ***R^2=0.3491***	ρ = 0.9258 R^2=0.0007
Density of all trees (native and invasive)	ρ = 0.1777 R^2=0.0311	ρ = 0.3272 R^2=0.0738	ρ = 0.1820 R^2=0.1327	ρ = 0.6165 R^2=0.0198	ρ = 0.8193 R^2=0.0042
Average height of all plant species (native and invasive)	***ρ = 0.0309*** ***R^2=0.0778***	ρ = 0.7491 R^2=0.0081	ρ = 0.7008 R^2=0.0117	ρ = 0.0730 R^2=0.2264	ρ = 0.6653 R^2=0.0148
Density of all plant species (native and invasive)	ρ = 0.4347 R^2=0.0106	ρ = 0.4784 R^2=0.0394	ρ = 0.9596 R^2=0.0002	ρ = 0.3666 R^2=0.0631	ρ = 0.4982 R^2=0.0360

Table A-10. *Native species by density of autumn olive. Linear relationships between the density of autumn and native plant density and average height index. Variables with significant relationships are bold and italicized. Comparisons completed for all measurements regardless of aspect and for average heights and densities based on aspect. R-square values present for all relationships with p-values indicating significance.*

Variables	All Aspects	North	East	South	West
Average height of native trees	ρ = 0.5929 R^2=0.0050	ρ = 0.4499 R^2=0.0446	ρ = 0.5066 R^2=0.0346	ρ = 0.3510 R^2=0.0672	ρ = 0.7978 R^2=0.0052
Density of native trees	ρ = 0.9527 R^2=0.0001	ρ = 0.8502 R^2=0.0028	ρ = 0.9995 R^2=0.0000	ρ = 0.6728 R^2=0.0142	ρ = 0.3956 R^2=0.0561
Average height of all native plant species	ρ = 0.3269 R^2=0.0166	ρ = 0.1323 R^2=0.1656	ρ = 0.3184 R^2=0.0765	ρ = 0.3100 R^2=0.0791	ρ = 0.6258 R^2=0.0188
Density of all species of native trees	ρ = 0.7824 R^2=0.0013	ρ = 0.6780 R^2=0.0137	ρ = 07858 R^2=0.0059	ρ = 0.5975 R^2=0.0220	ρ = 0.4402 R^2=0.0465

Vita

Matthew R. Moore was born in Columbus, Ohio on March 21, 1984. In 1989 he began his schooling in the Tarrant County School System in Texas finishing elementary school in Cobb County, Georgia. Matthew graduated from Alan C. Pope High School in 2002 and continued his education at Berry College in Rome, Georgia. At Berry, he pursued a Bachelor of Science degree in Biology with a minor in Chemistry. He graduated in 2006.

After studying under Dr. Mary Ann Moran in the Marine Science Graduate Program at The University of Georgia for two years, Matt took a job with the Vermont Youth Conservation Corps training and supervising a trail maintenance crew of Vermont youths. Afterward, he spent a season restoring Mexican spotted owl habitat in the Fort Davis Mountains of west Texas. In fall of 2010 Matthew began his pursuit of a Master of Forestry degree from the University of Tennessee under Dr. David Buckley. He graduated with that Master of Forestry degree with a minor in Statistics in 2013.

Matthew is currently pursuing a career in native ecosystem conservation.