Celastrus orbiculatus AND ARCHITECTURAL DEGRADATION OF THE FOREST CANOPY AND THE REVIEW OF A RAPID ASSESSMENT PROTOCOL TO AID LAND MANAGEMENT

by

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ABSTRACT

Celastrus orbiculatus (oriental bittersweet) is a ubiquitous non-native liana (woody vine) species found on woodland edges, and in developing and established forested ecosystems of the North Eastern United States. Liana species and *Celastrus orbiculatus* in particular can have a devastating impact on forest succession and canopy development (Hegarty & Caballe, 1991). Lianas can also impact the carbon storage potential of a healthy forested ecosystem (van der Heijden et al., 2015).

In this liana tree-load interaction study, three tree species (*Liriodendron tulipifera, Prunus serotina, Fraxinus sp.*) were observed. Trees that fit five Vine Coverage Assessment (VCA) classes (*0 = no vines are impacting the crown, 1 = vine coverage is limited to the interior of the crown, 2 = up to 33% of the tree canopy is covered, 3 = 34% to 66% of the crown is covered, 4 = 67% to 100% of the crown is covered*) were used for data collection. For each tree, I examined the architectural degradation and estimated a Crown Biomass Reduction (CBR) from the live crown. The estimated CBR was subtracted from the total Above Ground woody Biomass (tAGwB), calculated from the measured diameter at breast height (dbh) of each tree (Jenkins 2004). A percentage of loss was assigned per tree and a calculated mean percentage loss assigned for each VCA class.

The mean percentage loss of tAGwB increased from 1.54%, for the control group (VCA 0); to 13.91% for the heaviest vine load (VCA 4). The mean loss of tAGwB of 13.91% (55.10 kg) which is 50% carbon (Birdsey, 1992) equals a reduction of sequestered carbon of 27.55 kg, per tree over its lifetime, at the highest vine load

(VCA 4). Based on atomic weight, this equates to a loss of potential atmospheric CO_2 reduction of 101.12 kg, per tree over its lifetime, at the highest vine load (VCA 4).

Additionally the rapid assessment protocol VCA, was a moderate to strong indicator of vine loading. It would be a useful tool for land managers, when the ultimate goal is reclamation of degraded forest communities, and maximizing the ecosystem services provided by healthy forested ecosystem including long term carbon sequestration.

Chapter 1

INTRODUCTION

In 1997, the Kyoto protocol was adopted indicating the concern over global warming and the need to limit greenhouse gasses, in particular carbon dioxide (Kyoto Protocol to the United Nations Framework on Climate Change). Although it was ratified in 2005, the United States is still one of the few countries yet to endorse the protocol. However, the United States has expressed concern over greenhouse gas reductions and carbon emissions as evidenced by congressional hearings (United States 110th Congress, 2010; Inslee & Shadegg, 2007); carbon trading and legislation such as The Energy Independence and Security Act of 2007 (United States 110th Congress, 2007); and regional action plans such as the Regional Greenhouse Gas Initiative (http://www.rggi.org). Considerable efforts are being made to quantify national (Smith et al., 2006; Zhu et al., 2010) and global carbon pools. Currently, the merchantability of carbon-offset credits has intensified this research.

The majority of carbon in the natural areas of the United States is stored within forested and wetland ecosystems (Zhu et al., 2010). The analysis of land use and land use change is instrumental in estimating carbon stock. Remote sensing techniques are used in the development of land use classification maps. The most common classification system is the Andersen Classification System (Andersen et al., 1976) used by the United States Geological Survey (USGS). Regional representative sampling of the major land cover classes are used to develop national carbon stock estimates. The Natural Resources Conservation Service maintains a Natural Resource

Inventory (NRI). Datasets for these inventories along with additional information on soil type are available through United States Department of Agriculture's Geospatial Gateway (http://www.datagateway.nrcs.usda.gov).

The sampling protocols follow the standards set forth by The Forest Health Monitoring (FHM) and Forest Inventory and Analysis (FIA) programs of the United States Forest Service (USFS). The current manual for plot design, data collection and national database standards can be downloaded at USFS website (http://www.fs.fed.us/rm/pubs/rmrs_gtr245.pdf). The North American Carbon Program (NACP) integrates the data from the United States FIA program and carbon stock estimates, data on ecosystem processes, and additional information on atmospheric CO_2, CH_4, and CO, with data from collaborating countries to further understand the carbon cycle and environmental fluxes (Hollinger, 2008).

I-Trees Eco (http://www.**itree**tools.org/**eco**/index.php) is a user-friendly forest ecosystem modeling program being used by regional and local government agencies to estimate the carbon storage and carbon source-sink dynamics, along with additional ecosystem services provided by individual trees and woodlands surrounding urban communities. The Urban Forest Effects (UFORE) model is the underlying program used to quantify ecosystem services based on forest structure (Nowak & Crane 2000). It provides one methodology for calculating carbon storage and annual atmospheric carbon dioxide reduction and carbon sequestration rates.

One factor limiting forest canopy regeneration in the northeast and other regions of the country is the proliferation of invasive plant species (Gordon, 1998). The Energy Security and Independence Act of 2007 discussed invasive plants and recommended using native species for reclamation and the sequestration of greenhouse gasses (United States 110th Congress, 2007). Many alien invasive species out-compete native plants in early successional woodlands. More insidious species are affecting later sere forests and extensive vine coverage may, "… arrest the normal succession more or less indefinitely" (Hegarty & Caballe, 1991). Vine species in particular may be having a substantial impact on the carbon sequestration potential of early- and mid-succession forests. There is little research that attempts to quantify the extent to which vine species may limit carbon storage in natural lands by degrading the woody biomass contained within the tree crown architecture of temperate forests.

The objective of this tree canopy - vine load interaction study is to determine if vine pressure from an alien invasive species, *Celastus orbiculatus* (Oriental Bittersweet) in a temperate early succession forest, reduces the biomass of the forest canopy significantly. A significant reduction in woody biomass has implications relating to long-term carbon fixation, atmospheric carbon dioxide reduction, along with additional ecosystem services provided by a healthy forest canopy. Additionally, a rapid assessment protocol was developed to estimate vine coverage in the field. A second objective of this research was to test the validity of this assessment and the parameters used.

Chapter 2

LITERATURE REVIEW

This section provides an overview of carbon storage estimation for individual tree components. A number of researchers, through destructive sampling, have developed the allometric equations currently used to develop national and international carbon storage budgets. Additionally, these equations provide the basis for forest ecosystem services modeling programs.

2.1 Carbon Allocation and Allometric Equations

Estimating the carbon stored within an individual tree species begins with the measurement of the diameter of the tree at breast height (dbh, 1.37m from ground level). Biomass is calculated using empirically derived regression equations based on tree allometry and the specific gravity of wood and bark. A number of researchers have developed these allometric equations (e.g. Perala & Alban, 1994; Young et al., 1980; Hahn, 1984). Ter-Mikaelian and Korzukin consolidated much of this research in 1997, presenting the individual component equations for 65 tree species found in North America (Ter-Mikaelian & Korzukin, 1997). The equation to calculate biomass is "$M = aD^b$" where M is the dry weight in kg, a and b are coefficients, and D is the dbh in cm. Individual above-ground components include, total above-ground biomass (AGB), stem wood, stem bark, branches, and foliage. Cairns et al. consolidated and refined, through statistical methods, the root to shoot ratios found in the literature developed by previous researchers (Cairns et al., 1997). The root to shoot ratio is used to estimate below ground biomass (BGB) from the calculated AGB. The regression model for below ground biomass is in the form; BGB = exp(-1.0587 + 0.8836 x ln *AGB* + 0.2840) (Cairns et al., 1997). This equation was developed for temperate forests only as this relationship is not consistent within tropical or boreal forests. Dry weight biomass is converted to a carbon (C) storage estimate by using published empirically derived carbon to wood content relationships. Although the estimates vary, .47 - .50 is most often cited as the C to dry weight biomass ratio. Dry weight biomass is approximately fifty percent carbon (Birdsey, 1992).

In 2004, Jenkins et al. published a *Comprehensive database of diameter-based biomass regressions for North American tree species*. This work consolidated the work of previous researchers. One important note regarding the use of empirically derived allometric regression equations in calculating biomass, is the need to review the range of tree diameters incorporated in their development. Jenkins et al. (2004) list the ranges of tree diameters sampled, along with the geographical region where the sampling occurred, which may also affect allometry.

2.2 USFS and Biomass Estimation

The USFS published a guide to forest carbon measurements in 2007 (Pearson et al., 2007). Above ground biomass equations and parameters were developed by Jenkins et al. (2004), and Brown et al. (1999). The parameters and allometric equations developed to calculate biomass are based on species classes. Jenkins et al. (2004) also published an extensive species-specific database of biomass regression equations for individual components of the tree (http://www.uvm.edu/~jcjenkin/?Page=biomassdatabase.html) and these equations are incorporated in USFS biomass calculations today (Heath et al., 2009; Woodall et al., 2011).

Biomass estimates calculated with dbh as the input parameter for each component using the Jenkins et al. (2004) species-specific biomass regression equations are based on tree allometry. The carbon content of individual tree components varies greatly. For example, the carbon to biomass ratio for *Betula papyrifera* wood is 0.49 and the bark ratio is 0.68 (Curtis, 2007). Curtis suggests since the mass ratio of bark to wood is less than 5%, the conversion factor of 0.49 for the entire tree should be used to convert the biomass estimate to carbon.

With urban trees in the United States estimated in 2001 to store 700 million tonnes of carbon valued at $20.17/tonne (Nowak & Crane, 2002), it is important to continually refine carbon storage estimates.

2.3 Atmospheric Reduction of Carbon Dioxide

Research concerning carbon source-sink dynamics is most often focused on understanding and quantifying emissions into the atmosphere and the reduction of atmospheric carbon dioxide in a mass balance approach. Growing trees remove atmospheric carbon dioxide, fixing carbon within their biomass through underlying physiological processes, and releasing oxygen. Alternately, the carbon in dead plant tissues is recycled within the ecosystem or is released as carbon dioxide as a byproduct of the biological processes of decomposition. Equating the mass of carbon contained within a tree to a reduction of atmospheric carbon dioxide is based on a ratio of the atomic weight of the elements. Carbon has an atomic mass of 12 while carbon dioxide has an atomic mass of 44, because the additional two oxygen atoms each have an atomic mass of 16. Multiplying the estimated mass of carbon sequestered within a tree (excluding the foliage component) by 3.67 (44:12) yields an estimate of the mass of carbon dioxide removed from the atmosphere, during its life span.

2.4 UFORE Model

The Urban Forest Effects (UFORE) model, the underlying model used for I-Trees Eco, was developed by researchers at the Forest Service, which at the time was a division of the United States Department of Agriculture (USDA), to help managers and researchers quantify urban forest structure and function (Nowak & Crane, 2000). There are four main modules (A-D) within the model. Most relevant to this research are module A, used to quantify forest structure, and module C, used to quantify carbon sequestration and annual reductions in atmospheric carbon dioxide. Module B estimates gas exchange and module D estimates fine particulate removal associated with the forest canopy. This information can be used to quantify ozone formation and the atmospheric pollutant reduction potential of the tree canopy.

The individual tree carbon storage calculations follow similar methodologies presented in 2.1 and 2.2, extrapolating carbon storage from a biomass estimation based on dbh. The UFORE model was developed using the species specific AGB equations found in the literature. When AGB estimations vary at the species level, a mean value was used. The ratio, BGB:AGB = 0.22, is used in the UFORE model, therefore, the AGB is multiplied by 0.22 to obtain BGB. The factor of 0.5 is used to convert dry weight biomass to an estimate of carbon storage.

Expansion factors found in the literature are used to adjust annual carbon sequestration rates for yearly dbh growth (Smith & Shifley, 1984; deVries, 1987; Nowak, 1994b). For trees in forest stands, an annual expansion factor of 0.38 cm yr^{-1} is used. For park settings and open grown trees, the expansion factors are 0.67 cm yr^{-1}

and 0.87 cm yr^{-1} respectively. These expansion factors are adjusted downward based on a percentage dieback observed in the tree crown. The I-Trees assessment "crown light exposure" is utilized to classify the tree into one of the three aforementioned categories. The expansion factors convert the dbh measurements at time of assessment (year x) to year x +1. Subtracting the carbon storage at year x from year x +1 yields an annual carbon fixation rate. This is converted to an estimate of the annual atmospheric carbon dioxide reduction for the area sampled.

In a follow-up paper, UFORE model developers incorporate tree decline and mortality into the model to assess carbon sequestration of urban trees in the United States (Nowak & Crane, 2002). Growth rate factors were adjusted by 0.76, 0.42, and 0.15 for "poor condition", "critical" and "dying", respectively. Annual mortality was estimated as 1.92% for trees 0-3 inches and 1.46% for trees > 3 inches in the good-excellent condition class, respectively. Annual mortality was estimated as 3.32% for trees in fair condition, 8.86% for trees in poor condition; 13.08% for trees in critical condition, 50% for dying trees, and 100% for dead trees (Nowak & Crane, 2002).

Vine assessments were attempted in the past, but were considered to be too cumbersome in the field (Personal communication, Nowak 2011). Currently, long-term field plots are used to assess urban trees throughout the Philadelphia region and New Castle County, Delaware. Field crews are rating the crown vine coverage on individual trees in sample plots on a scale of 0-4. The metrics for this rating are; 0 = no vines are impacting the crown, 1 = vine coverage is limited to the interior of the crown, 2 = the upward or outward growth of the tree is being distorted and up to 33% of the tree foliage is covered, 3 = up to 66% of the crown is covered, and often there is considerable crown damage or distortion, 4 = up to 100% of the crown is covered, and often there is severe crown damage and distortion. This assessment may offer further insight into current forest health and the impact of vine species.

2.5 USFS Tree Health Assessments

The Forest Inventory Analysis (FIA) is the nationwide monitoring program of the United States Forest Service (USFS). Phase 1 uses remote sensing applications to monitor US forest resources. Phase 2 consists of long-term field plots, one per every 6000 acres of forest, where forest type, site, and tree attributes are assessed. Phase 3 is the Forest Health Monitoring (FHM) program and uses smaller subplots and transects to collect more detailed information on tree heath, vegetation communities, forest floor components and soil characteristics. FIA and FHM surveys are conducted when the trees are in leaf. This study was conducted in winter in order to more accurately assess tree architecture; however, the field guides were consulted and a number of sampling protocols were used as a basis for this study.

2.5.1 Uncompacted Live Crown Ratio

The uncompacted live crown ratio is determined by dividing the live crown height by the total tree height. The base of the live crown is a horizontal line drawn below where the majority of the live branches begin. Lower branch loss or mortality is excluded from the live crown measurement. The crown silhouette is drawn connecting the branch tips, from the base of the live crown to the top of the highest point of the tree. The delineation of the live crown silhouette is the basis for further assessments within the FIA and FHM programs.

2.6 Component Ratio Method

Currently, the recommended protocol for calculating biomass and carbon storage is the Component Ratio Method (CRM) (Heath et al., 2009). The CRM incorporates a biomass expansion factor into the calculation. The volume of the merchantable stem (bole), defined for trees greater than 5” caliper as the stem and bark wood measured from 1’ above ground to a 4” diameter top, is calculated first. The volume measurement is converted to biomass based on the specific gravity of the wood and bark components. The CRM assumes the bole to biomass ratios for other individual components of the tree (branch wood, and leaf) follow the ratios as calculated by the equations defined by Jenkins et al. (2004).

Attempting to measure the caliper of a tree one foot above the ground in natural areas heavily degraded by invasive plants, including *Rosa multiflora,* can be difficult. Additionally, it can be difficult in the field to accurately identify and measure the location of the top of the merchantable stem, particularly in the tree crowns heavily invaded by *Celastrus orbiculatus.* Therefore, the CRM was not used for biomass and carbon storage estimation in this tree canopy– vine load interaction study.

2.6.1 Crown Dieback

The crown dieback rating begins with the estimation of the uncompacted live crown and crown silhouette and then deducts for recent branch mortality. Lower branch mortality is considered a natural occurrence in forest canopy trees, as sunlight becomes a limiting factor, and is excluded when estimating the live crown. Therefore, lower branch mortality is not considered in the dieback estimation. Dieback is a percentage-based deduction from the live crown silhouette. There are 21 classes beginning with zero and continuing in 5% increments. The FIA program allows for a tolerance of +/- two classes or 10% percent (20% bracket).

2.7 Vine Assessments

There is little information in the literature about lianas and established overstory tree canopy biomass allocations within temperate forests. Vines proliferate in disturbed ecosystems (Teramura et al., 1991), becoming a limiting factor on forest canopy development and altering forest succession (Hegarty & Cabelle, 1991). When vines overtop the tree canopy, they limit light resources available to developing and established trees (Ladwig & Meiners, 2009). The standard protocols for measuring vines to assess tree load include a percentage-based canopy coverage measurement, and a basal area measurement (Gerwing et al., 2006). These protocols correct inconsistencies in the location used when measuring the basal area of vines. A caliper measurement at "breast height" could be misleading in long-term field plots as vines can "slip" from the tree canopy over time (Gerwing et al., 2006). Since this study did not involve long-term field plots, vine diameters were measured at "breast height". This simplified the fieldwork in areas inundated with multiflora rose or honey-suckle. The calculation of the basal area of vines, although an important parameter, is not the focus of this study. In a 2009 vine study, in a comparable physiographic region, Ladwig and Meiners (2009) reported that "… only liana canopy cover was significantly related to tree growth. In addition to being the most useful measurement associated with decreased tree growth, liana canopy cover was by far the fastest sampling technique."

2.8 *Celastrus orbiculatus* (Oriental Bittersweet)

Celastrus orbiculatus (oriental bittersweet) was introduced as an ornamental in 1860 (Patterson, 1974). Its wide spread distribution was aided by arboreta and the nursery industry because of the ornamental value. The attractive fruit are abundant and persistent (Figure 5.5). They are prized in the landscape and for holiday decorations. Yellow capsules open to reveal red fruit. Seeds are spread by frugivory, often filling an open niche in rights-of-way and disturbed areas as well as undisturbed forests. Once present in an area, it easily spreads by root sprouts. It was reported as a weed in Delaware County, PA in 1916. Patterson's 1971 survey indicated the largest wild populations occurred in southeastern Pennsylvania and southwestern Connecticut. In 1971 it was being cultivated in Delaware but was not listed as a weed and no wild populations were reported (Patterson, 1974). It has since become a ubiquitous non-native vine species found on woodland edges, and in developing and established forested ecosystems of the Northeastern United States. Vine species and *C. orbiculatus* in particular can have a devastating impact on forest succession and canopy development (Hegarty & Caballe, 1991).

C. orbiculatus seeds germinate in the spring and early summer with relatively high temperatures of 25^{o} to 30^{o} C and in low light conditions (Patterson 1974). *C. orbiculatus* damages other plant material primarily by girdling and smothering, and secondarily by limiting water and other nutrients (Patterson, 1974). As an architectural parasite, it ascends to the canopy, twining dexterously with a shallow vine pitch, girdling and interrupting the downward flow of organic solutes within the phloem and causing abnormal wood development that can open up vectors for decay and wood borers (Lutz, 1943). Lutz reports that older trees can survive the constriction of the phloem by developing new conductive tissues or possibly by root grafting with other trees. However, the development of new conductive tissues may be too slow in younger trees causing the death of the tree (Lutz, 1943).

Bittersweet is often found on woodland edges. However, seedlings can also be found growing in the lowlight conditions in woodland interiors. Patterson (1974) reported rapid photosynthetic light acclimation in seedlings, allowing the plant to take immediate advantage of gaps in canopy coverage caused by storms or other natural or anthropogenic disturbance. Annual shoot growth can exceed 3 meters (Patterson 1974).

There is a native species *C. scandens* that is considered historical in Delaware not having been seen in 30 years. The two species can hybridize however pollen viability is low (Sarver et al., 2008). The ability of *C. orbiculatus* seedlings to tolerate shading gave it a competitive advantage over the native species (Leicht & Silander, 2006)

Chapter 3

MATERIALS AND METHODS

This section provides an overview of the methods utilized and the data collected from 150 trees (3 tree species, 5 vine load ratings, and 10 replicates). Data were collected during the winter, from January 15, 2013 to March 31, 2013. When a tree of the appropriate genus was located that conformed to the caliper or dbh (11 1/8" – 12 7/8") and Vine Coverage Assessment (VCA 0-4) parameters as defined by the experimental design, photographs of the bark and the crown were taken. A measurement of the dbh, VCA, and the tree height was recorded, and the individual stems of *C. orbiculatus* that impacted the tree crown were measured, recording the caliper "at breast height" to the nearest 1/8th inch. Every attempt was made to control the experiment by selecting trees impacted solely by *C. orbiculatus*. This proved to be very difficult in the field due to the abundance of *Vitis* sp. (fox grape). Some of the trees measured include a limited number of *Vitis* sp. vines. The same measurements were recorded for the *Vitis* sp.

A Crown Biomass Reduction (CBR) from the "live crown" was estimated from 0% to 100% (to the nearest 10%). Prior to attempting to estimate the CBR, the trees in the surrounding patch were visually examined for form, and the "live crown" of the tree being assessed was visually estimated. Winter (leaf-off) indications of crown dieback include bark loss, loss of fine branching structure and catastrophic branch loss.

In an attempt to sample trees across a wide variety of naturally regenerating forest communities, no more than three trees that met a specific caliper and VCA rating were recorded from an individual forest patch. Open grown and trees growing in hedgerows were not included, although these are often highly impacted by *C. orbiculatus.*

Large areas of the study site were visited during the collection of quantitative data. Photographs and notes were taken throughout, in an effort to better understand the distribution across forest age classes, habitat preferences, and morphological traits. These qualitative data are used in the discussion to offer insights to enhance best management practices used for limiting the impact of *C. orbiculatus* and to improve forest health.

3.1 Study Site

The White Clay Creek State Park is located in Northern New Castle County Delaware, in the Piedmont physiographic province. The original park, established in 1968, has grown to encompass nearly 3000 acres. It is a multi-use facility managed by Delaware State Parks, a division of the Delaware Department of Natural Resources and Environmental Control (DNREC). The park is part of the 107 square mile White Clay Creek Watershed that empties into the Christina River and is part of the greater Delaware River and Bay Watershed. The White Clay Creek, which runs through the park, is a nationally designated Wild and Scenic River (http://www.rivers.gov/rivers/) and is federally protected.

The mean annual temperature of Northern Delaware is 54 degrees with a mean annual precipitation rate of 45 inches. The region can experience weather extremes including coastal northeasters and tropical hurricanes, heavy winter snows, and severe thunderstorms (http://climate.udel.edu/delawares-climate). White Clay Creek State Park is located in the Piedmont physiographic region. The climax forest communities supported in this region of the Piedmont are mixed hardwood, with softwood forests becoming more common at higher elevations. The topography of the Piedmont creates varied microclimates and can support a wide range of plant communities, and exceptional biological diversity (Spira, 2011).

The forest canopy in the park, although highly fragmented, is in a period of recovery. Large areas of the park were released from agricultural land use and forest canopy regeneration is occurring on these sites. Statewide georeferenced orthophotos are composites from aerial photography taken during flights flown in 1937, 1968 and 2007. Based on the historical orthophotos (http://www.datamil.delaware.gov/) the age of the forested tracts can be divided between forests less than 45 years old, forests between 45 and 75 years old, and forests greater than 75 years old. Chris Bennett, a natural resource manager with DNREC, developed the forest age layer referenced in the field. Time series analysis allowed Bennett to classify the forest ages throughout the park. DNREC uses this information, along with botanical surveys, to focus their limited invasive plant removal and forest restoration resources. The majority of the restoration efforts within the park target the older than 75-year forest classification (personal communication, Chris Bennett and Rob Line, 2012).

3.2 Tree Species Sampled

Field assessments were completed during the "leaf off" period of winter January 15, 2013 – March 31, 2013. This allowed access to highly degraded areas of White Clay Creek State Park and facilitated an accurate assessment of the tree canopy, and live crown biomass. Three tree species were examined; *Liridendron tulipifera* (poplar, tulip poplar, LITU), *Prunus serotina* (cherry, black cherry, PRSE2), and *Fraxinus pennsylvanica* (green ash, FRPE). These species were chosen because they are readily identifiable in winter, and occur throughout the park in wide ranging cultural conditions and forest successional states.

It is important to note that ash trees can be difficult to identify to the species level, even for the trained dendrologist, based on winter characteristics (Taber, 2012). Therefore, for this project, *Fraxinus pennsylvanica* is actually *Fraxinus* sp. (Ash, FRAXI) Carbon calculations included in the final analysis used generalized biomass equations (mixed hardwood group).

Only trees in contiguous, naturally regenerating forest patches were considered for this study, eliminating "hedgerows" and regions of canopy closure developing over maintained areas. Heath and others (2011) defines forested patches as 36.6 meters wide (120'), and this metric was used for this project. However, trees were also considered in critical riparian forests. Riparian buffers are now a well-established best management practice and include a 60' wide forested zone (zone 2) (Welsch, 1991). It was important to include trees from these critical riparian forests along the White Clay Creek corridor, and forest patches were defined to ensure this occurred.

3.3 Measurements and Assessments

Vine load, as estimated by a Vine Coverage Assessment (VCA), was divided into four categories, and ten individual trees for each species were assessed for each load rating. As a control group, ten additional trees per species were measured that had no vine loading. Total trees measured was 150 (50 for each species included). Tree height was recorded using a digital hypsometer (Nikon 550). A photograph was taken of the bark and tree canopy for each tree used in the study. The caliper of each *C.*

orbiculatus vine "crossing breast height" was recorded. In order to control for tree age, the dbh of trees assessed was limited to a measurement 11 1/8" – 12 7/8". The dbh was measured to the nearest 1/8" using a calibrated circumference tape or caliper. In the field, a Crown Biomass Reduction (CBR) was estimated to the nearest 10%. Working from the vine caliper measurement, the total Vine Cross Sectional Area (VCSA) was calculated.

3.3.1 Crown Biomass Reduction (CBR)

A reduction to live crown biomass was estimated to the nearest 10%. The Forest Inventory Analysis (FIA) program incorporates a percentage-based crown dieback rating (http://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2006/p3_3-0_sec12_10_2005.pdf). The FIA percentage crown dieback metric is based on 5% increments. FIA protocols allow for a tolerance of plus or minus 2 categories (10%) or a 20% bracketing. FIA assessment is completed with trees in leaf. The following recommendations from FIA manuals were used to estimate live Crown Biomass Reduction (CBR): 1) review the form of the tree canopies of the surrounding individuals within the forest plot, 2) lower branch loss is not considered dieback. In the field, the "live crown of a healthy tree" was considered and then the reduction was estimated, based on catastrophic branch loss and textural variations or loss of fine branching structure (indicating dieback). Bark loss on main stems was a useful indicator of dieback as well. Binoculars were used to aid this assessment of canopy health and structure.

3.3.2 Vine Coverage Assessment (VCA)

To avoid the complexities of measuring vine coverage, or load, within the tree canopy, the same rapid assessment protocol used by the regional UFORE study was used where 0 = no vines are impacting the crown, 1 = vine coverage is limited to the interior of the crown, 2 = up to 33% of the tree canopy is covered and the upward or outward growth of the tree is often being distorted and, 3 = 34% to 66% of the crown is covered, and often there is considerable crown damage or distortion, 4 = 67% up to 100% of the crown is covered, and often there is severe crown damage and distortion. This VCA protocol, designed for volunteer applications corresponds to but simplifies vine crown coverage percentages used by Gerwing (2006) and Ladwig and Meiners (2009).

3.3.3 Vine Cross Sectional Area (VCSA)

Stem counts of *C. orbiculatus* vines ascending into the assessed trees, crossing the horizontal plane established at 1.37 meters above ground level (consistent with the dbh height), were completed. The caliper at "breast height" of individual vines was measured to the nearest 1/8" using a dial caliper. Vine Cross Sectional Area (VCSA) or the total area of all liana stems crossing at breast height was calculated and used for statistical analysis. The empirically-derived VCSA will be a metric to assess the validity of the VCA rating.

3.4 Biomass and Carbon Storage Equations

Dry weight biomass estimates were derived from dbh for the trees sampled. Biomass calculations follow the generalized equations presented by Jenkins et al. (2004). The regression equation for calculating total Above Ground Biomass (tAGB = *bm*) (kg) is in the form

$$bm = Exp(\beta 0 + \beta 1\, Ln(dbh))$$

Exp is the exponential function, and *Ln* is the natural logarithm. The *dbh* is the tree diameter at "breast height" in cm and $\beta 0$ and $\beta 1$ are parameters listed for the species group. Although there are species-specific equations for some of the tree components included, they were not available for all trees measured. The three tree genera included are all in the mixed hardwood group as defined by the generalized biomass equations. Therefore, the mixed hardwood dry weight biomass estimates were used. The estimated ratio of component biomass to total above ground biomass was derived from dbh, as presented by Jenkins et al. (2004). These ratios were used to partition total above ground biomass into the individual components, bole branch and leaf.

The leaf portion was removed from analysis, as this does not relate to long-term carbon sequestration. The estimate of total branch biomass was reduced by the percentage-based field observation CBR. Carbon content was assumed to be 50% of the estimated dry weight biomass (Birdsey, 1992).

3.5 Data Storage and Analysis

Field measurements were stored in an Excel spreadsheet (Microsoft Corporation, Redmond Wa.) and Vine Cross Sectional Area (VCSA) was calculated from individual vine caliper data. The spreadsheet was also used to calculate carbon storage estimates for tree components using the aforementioned equations. Initial summary statistics and data review was completed in an Excel spreadsheet (Microsoft Corporation, Redmond WA.). Data were transferred into Jump 10 (Statistical Analysis Software Institute Inc. Cary, NC.) for additional statistical analysis.

Chapter 4

RESULTS

4.1 Summary Statistics

4.1.1 Tree Height

The height of the *Liriodendron tulipifera* (Tulip Poplar) trees sampled ranged from 12.4 to 31.6 meters. The height of *Prunus serotina* (Cherry) and *Fraxinus sp.* (Ash) ranged from 7 to 26.4 meters and 10.4 to 26.8 meters, respectively. The mean tree height of individual trees in each of the Vine Coverage Assessment (VCA) classes was calculated (Table 4.1).

Table 4.1: Mean Height (m) of Trees Sampled for the Vine Coverage Assessment Classes. (1) - 0 = no vines are impacting the crown, 1 = vine coverage is limited to the interior of the crown, 2 = up to 33% of the tree canopy is covered and the upward or outward growth of the tree is often being distorted and, 3 = 34% to 66% of the crown is covered, and often there is considerable crown damage or distortion, 4 = 67% up to 100% of the crown is covered, and often there is severe crown damage and distortion.

VCA[1]	Tulip Poplar	Cherry	Ash
0	23.64	25.9	22.46
1	22.42	27.06	20.62
2	21.56	22.62	20.02
3	19.86	21.39	19.34
4	16.7	17.66	17.51

The VCA was plotted against tree height for the individual species measured (Figure 4.1). The VCA rating was most strongly correlated with a reduction in tree height for *Liriodendron tulipifera* with an R^2 of 0.50. VCA had a weak correlation to tree height in *Prunus serotina* (R^2 = 0.24). There was a moderately strong correlation between VCA and height for the *Fraxinus sp.* (R^2 = 0.41).

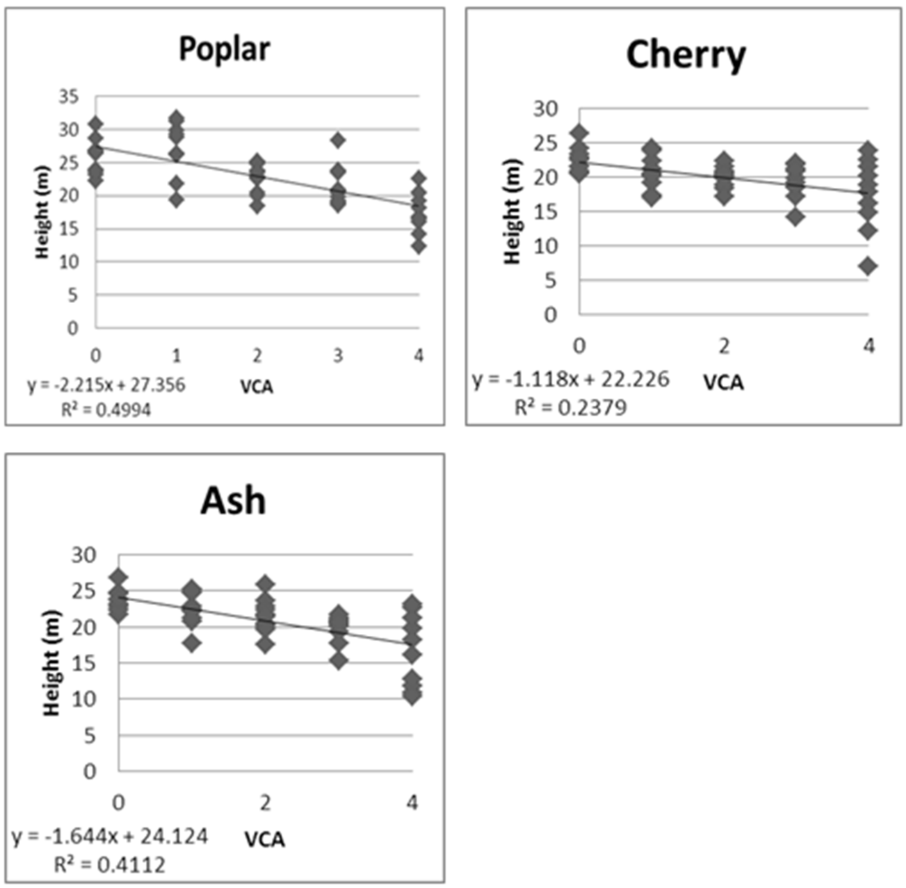


Figure 4.1 Height by Vine Coverage Assessment Class and Tree Species

The experimental design allowed for a range of tree calipers to be included in the sampling (11 1/8” – 12 7/8”). As the tree caliper could affect tree height, the next step was to test caliper as the independent variable. All tree species showed no, or weak correlation between caliper measurement and tree height. Cherry showed the strongest correlation between caliper and height with an R^2 of 0.27, and R^2 values of poplar and ash trees was 0.02 and 0.13 respectively.

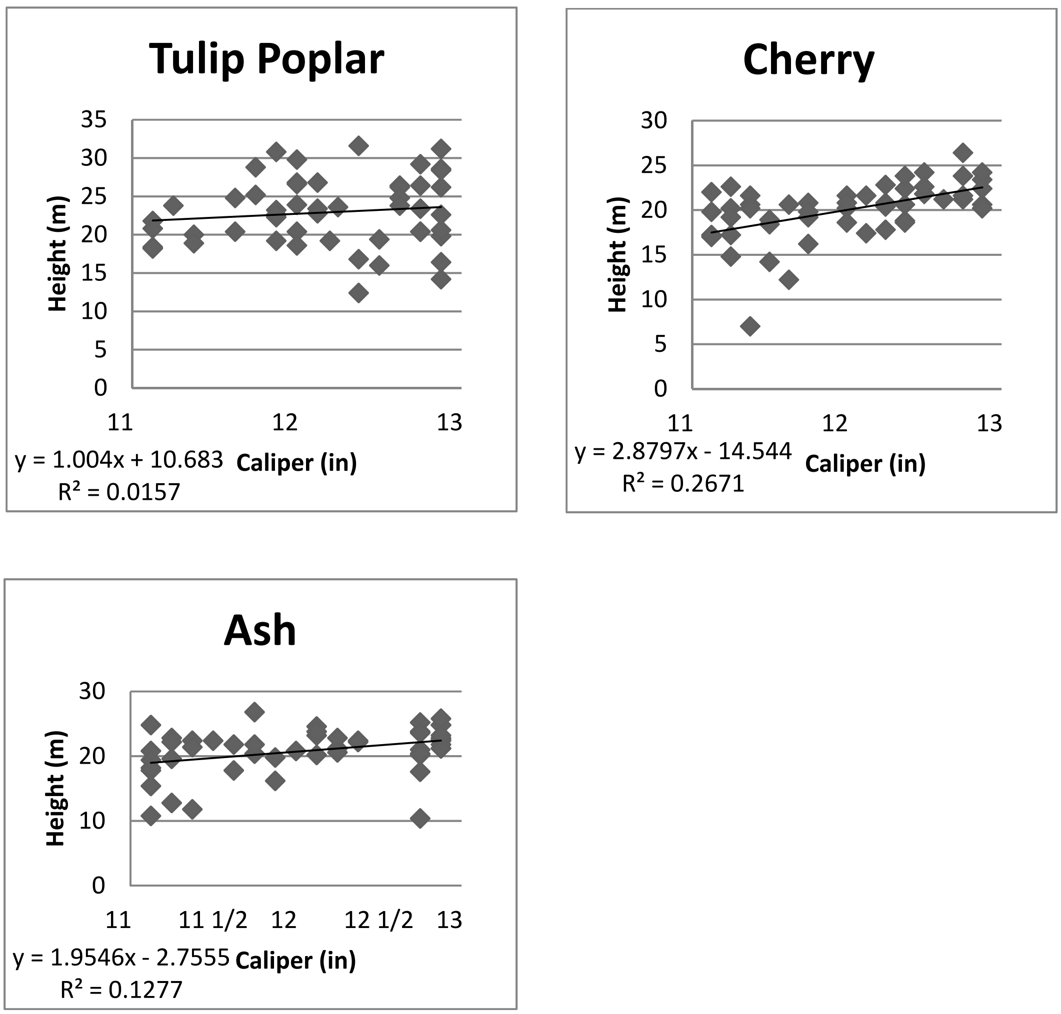


Figure 4.2 Measured Tree Height (m) and Caliper (in)

4.1.2 Measured Vine Cross Sectional Area (VCSA)

From the individual vine caliper measurements, the sum of the Vine Cross Sectional Area (VCSA) at "breast height" was calculated. This VCSA measurement was reviewed for its correlation to the VCA and its association with the crown biomass reductions estimated in the field.

As anticipated, the mean VCSA measurement for all trees increased (0.956 in^2 to 13.5342 in^2) when the vine load estimate increased, as shown in Table 4.2 the VCA class rating (1-4). The average VCSA was 0.9560 in^2, 3.1625 in^2, 8.9560 in^2 and 13.5342 in^2 for the VCA classes 1, 2, 3 and 4 respectively. VCA class 0 was not included in this chart because by definition this class had no vines on the tree.

Table 4.2: Mean Vine Cross Sectional Area (VCSA)(in^2) for VCA Classes and Tree Species

	VCA Class Ratings			
Tree species	1	2	3	4
Ash	0.9130	3.6546	9.8248	13.0057
Tulip Poplar	0.8664	3.1612	7.8613	12.4878
Cherry	1.0885	2.6716	9.1818	15.1091
All Trees	0.9560	3.1625	8.9560	13.5342

There was a strong association between the VCA field estimates for all trees and the measured VCSA, with an adjusted R^2 value of 0.67. A means test of the VCSA, considering all trees sampled, showed a significant difference at alpha 0.05 between all VCA classes, excepting the control group and VCA class rating 1. These results suggested the rapid assessment protocol VCA was a moderate to strong indicator of vine loading, as measured by the more intensive field measurement of the vine calipers and VCSA calculation.

4.1.3 Field Estimated Crown Biomass Reduction (CBR)

Estimating a reduction to the tree crown biomass is the most subjective of the field measurements incorporated in this study. Tree crown forms can vary widely. The species being assessed, the age of the forest, light exposure, competition and cultural conditions are just a few of the factors affecting tree form. FIA manuals were consulted to aid this assessment. It was important in the field to look at the form of other individual trees of the same species growing within the same forest conditions and microclimate.

A number of the trees included in the sampling showed lower branch loss that was being caused or accelerated by the girdling stress or weight of the *Celastrus orbiculatus* vine as it ascended into the tree crown. This was most often observed in *Liriodendron tulipifera,* presumably due to the wood strength of this species as compared to the other species being sampled. This observed lower branch loss was not included when considering a reduction to crown biomass, since lower branch loss is excluded when determining the "live crown". Biomass reduction estimates are from the "live crown" as defined in FIA manuals. The following figures are included to present a range of CBR estimates from the individual trees assessed. The figures include the three- or four-digit unique identifier assigned to each tree; the first digit is the genus (1-Liriodendron, 2-Prunus, 3-Fraxinus). The second digit is the assigned VCA (0-4). The third digit is the replicate (1-9), (tenth replicate represented as 9.1).

Figure 4.3 (118) shows a minimally invaded poplar (VCA 1), the single liana had not overtaken the crown. However, it was apparent that the lower branch loss was accelerated by the liana as it ascended into the crown. Since, the lower branch loss was not figured into the CBR (10%), the deduction was only for the branch loss that was high in the crown.

Figure 4.3	Tulip Poplar (118) CBR 10%

Figure 4.4	Tulip Poplar (142) CBR 40%

Figure 4.4 (142) is an example of a highly invaded tulip poplar (VCA 4). The crown biomass reduction of 40% was due to catastrophic loss of the central leader at the highest point of the crown. The CBR is also indicated by total height of 16 meters. The mean tree height of tulip poplar trees not impacted by lianas (VCA 0) was 23.64 meters. Figure 4.4 also shows a smaller caliper dead hardwood that was girdled by the oriental bittersweet. The developing hardwood was used by the liana as a scaffold during ascension to the crown of the poplar.

Figure 4.5 Tulip Polar (139.1) CBR 20%

Figure 4.5 (139.1) is a heavily invaded tulip poplar (VCA 3). Although the height recorded was 20.8 meters, below the mean of 23.64 meters (VCA 0), the crown biomass reduction estimate was only 20%. This was indicated by minor branch loss high in the crown

The highest mean CBR estimate for the control group (VCA-0) was 13% for *Prunus serotina*. The average CBR for the *Liriodendron tulipifera* and *Fraxinus* sp. was 3% for the control groups. The CBR estimate for VCA 1 was 0% for *Fraxinus* sp. and 2% and 3% for *Liriodendron tulipifera* and *Prunus serotina* respectively. The CBR estimate for VCA 2 was 11% for both *Liriodendron tulipifera* and *Prunus serotina* and 13% for *Fraxinus* sp. The CBR estimate for VCA 3 was 14%, 23%, and 25%, for *Liriodendron tulipifera*, *Prunus serotina* and *Fraxinus* sp., respectively. *Prunus serotina* had the highest average CBR at the highest vine load class (VCA-4) of 72%. The average CBR estimate with a VCA rating of 4 was 48% and 52% for *Fraxinus sp*. and *Liriodendron tulipifera*, respectively. Figure 4.6 shows the mean CBR assessment associated with the VCA classes for the species sampled.

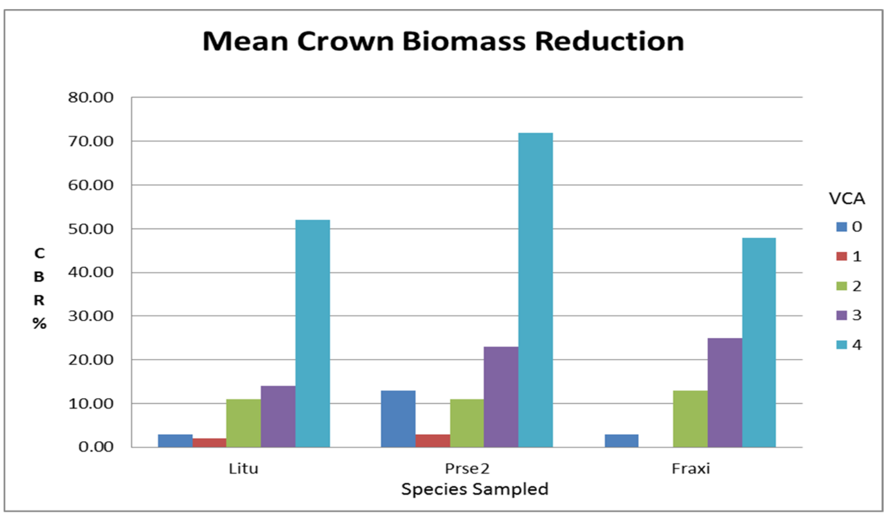
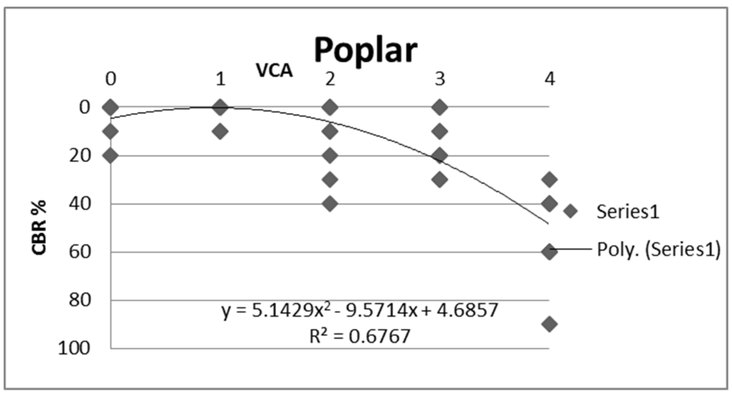
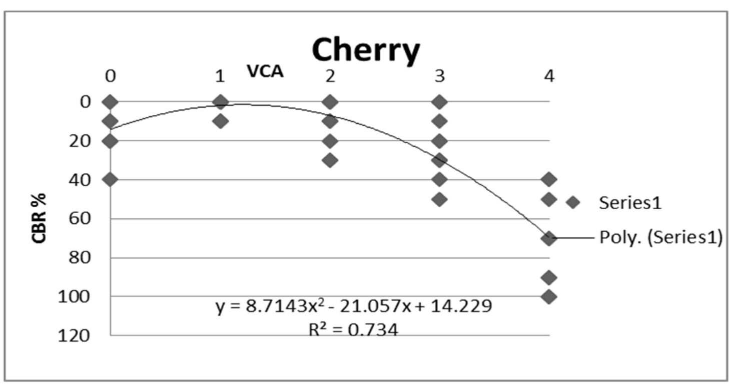


Figure 4.6 Mean field estimated Crown Biomass Reduction (CBR) for individual species and Vine Coverage Assessment (VCA) classes. (*Liriodendron tulipifera* = Litu, *Prunus serotina* = Prse2, *Fraxinus* sp. = Fraxi)

The Vine Coverage Assessment (VCA) showed a moderate to strong correlation to the live Crown Biomass Reduction (CBR) estimated in the field. *Lirodendron tulipifera* and *Prunus serotina* showed a strong correlation with a R^2 of 0.68 and 0.73, respectively. *Fraxinus sp.* was moderately correlated (R^2 .48). The estimated CBR data was widely distributed with associated vine load ratings as indicated by the VCA class. The association between VCA classes and CBR estimates, for all individuals sampled, was moderately strong ($R^2 = 0.61$). Figure 4.7 shows the distribution of the CBR data for the individual tree species sampled.





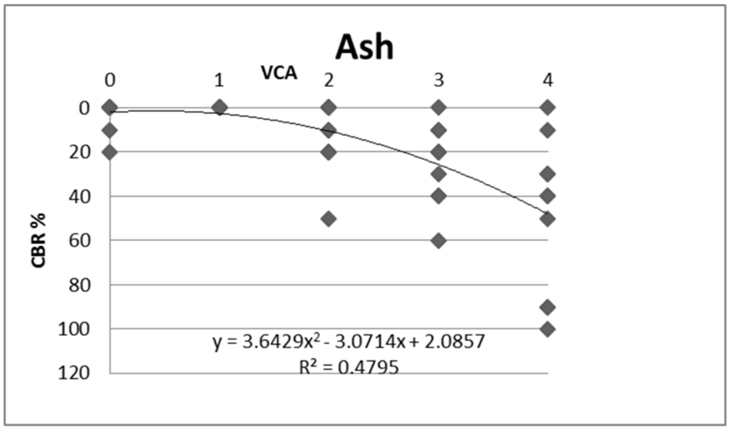
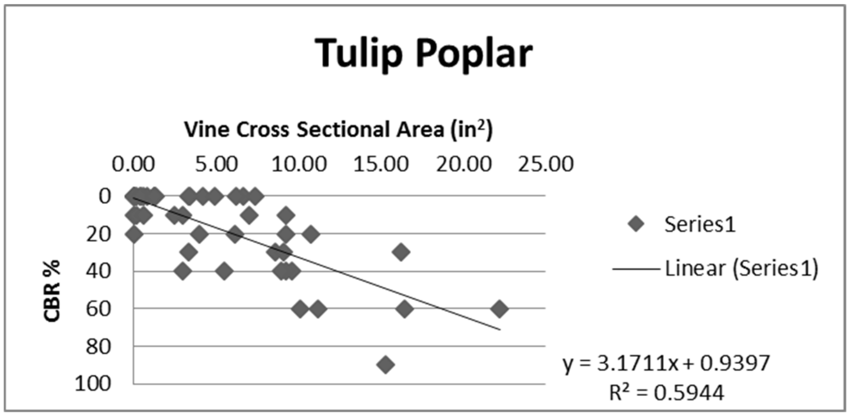
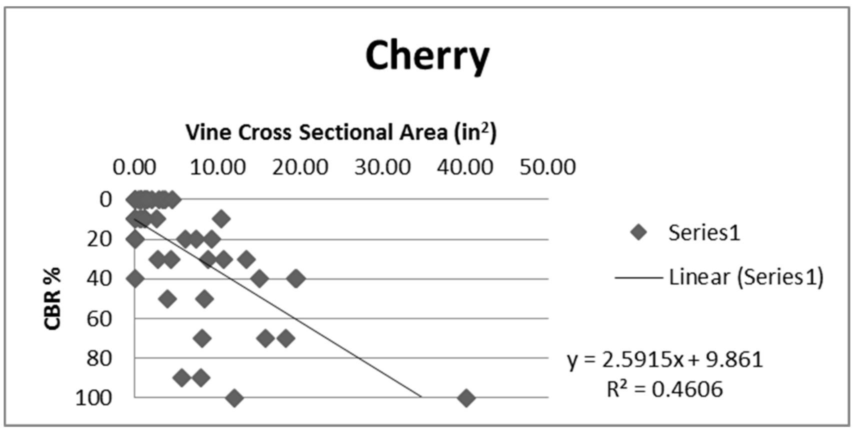


Figure 4.7 Distribution of Crown Biomass Reduction data for species sampled

4.1.4 Total Vine Cross Sectional Area (VCSA)

The total Vine Cross Sectional Area (VCSA), calculated from the most intensive field measurement of the individual liana stems, was compared to the CBR (Figure 4.8). This showed a moderate to strong correlation across all tree species. The weakest correlation was in the *Fraxinus sp*. data ($R^2 = 0.39$). *Lirodendron tulipifera* and *Prunus serotina* indicated a moderate to strong correlation with R^2 values of 0.59 and 0.46, respectively.





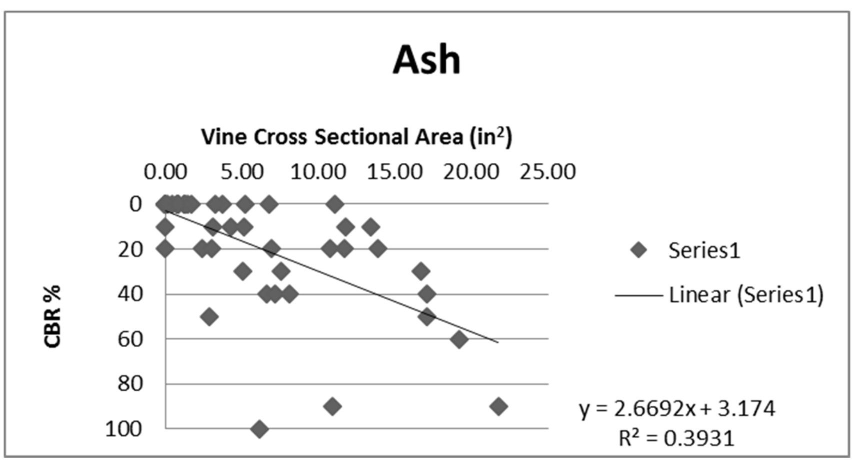


Figure 4.8 Vine Cross Sectional Area by Crown Biomass Reduction

4.2 Analysis of Variance and Means Tests

The measures of association between variables were tested with the statistical software package JMP 12.1 (SAS, Cary, NC). There were a number of issues considered during data analysis including; a large number of zeros in the CBR estimate, the CBR estimate was not normally distributed across VCA classes, there was an outlier in the control group (VCA = 0), and there were unequal variances within the data between the VCA classes.

Initial ANOVA (Analysis of Variance) and means testing was compared with more rigorous nonparametric tests. Nonparametric tests do not make as many assumptions about the distribution of the data, and are more appropriate when the outcome is an ordinal variable or rank, when there are outliers, and when the outcome has clear limits of detection.

4.2.1 Height and VCA:

Summary output from JMP indicated a significant difference (alpha 0.05), shown in Figure 4.9, in the mean height recorded for the total sample when the vine load, as measured by the VCA class, changed by a factor of 2 (ie: VCA 0 was different from VCA 2, VCA 1 was different from VCA 3, etc.). This also held true for *Liriodendron* and *Fraxinus* but not *Prunus.* There was a significant difference (alpha 0.05) in the mean tree height recorded for *Prunus* when the VCA class changed by a factor of 3.

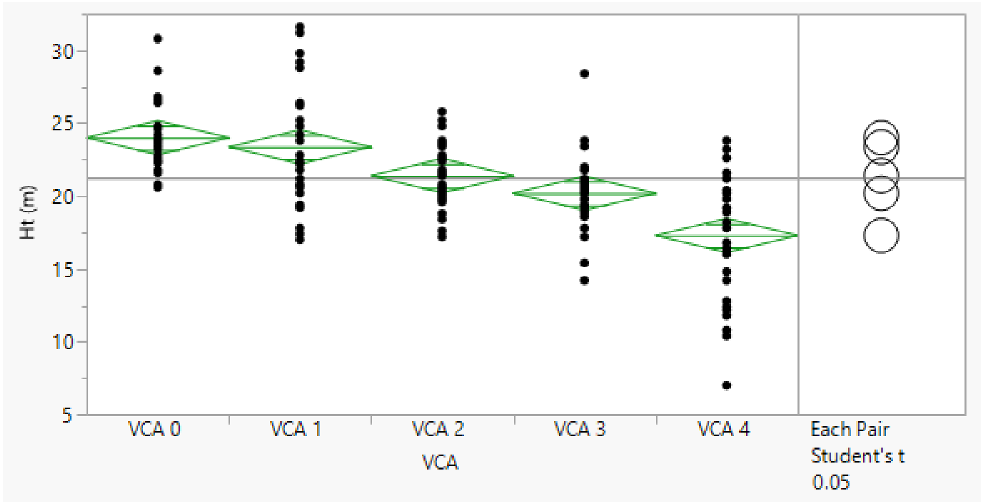


Figure 4.9 One way analysis of height by VCA (all trees assessed)

Table 4.3 Nonparametric means comparisons of tree height of VCA classes with control (VCA 0) using Steel Method

VCA Comparison	Score Mean Difference	Z score	p - Value
VCA 1 - VCA 0	-5.3333	-1.18346	0.5792
VCA 2 - VCA 0	-16.8000	-3.72842	0.0007
VCA 3 - VCA 0	-23.6333	-5.24443	<.0001
VCA 4 - VCA 0	-25.6000	-5.67892	<.0001

Nonparametric tests confirmed there were significant differences at alpha 0.05 between the mean height of the control group and VCA 2, VCA 3, and VCA 4 (Table 4.3).

An increase in vine coverage as estimated by the VCA was a limiting factor when considering tree height within the sample group. Refining the VCA to include greater detail would not be necessary from a management standpoint when estimating the impact of vine coverage on tree height as there was only a significant difference when the VCA class increased by a factor of two.

4.2.2 VCSA and VCA

The calculated VCSA_tot (Total Vine Cross Sectional Area), as the dependent variable, was compared to VCA (shown in Figure 4.10). VCA was a moderately strong indicator of vine loading (R square of 0.67) compared to the more intensive composite cross sectional area calculation (VCSA_tot).

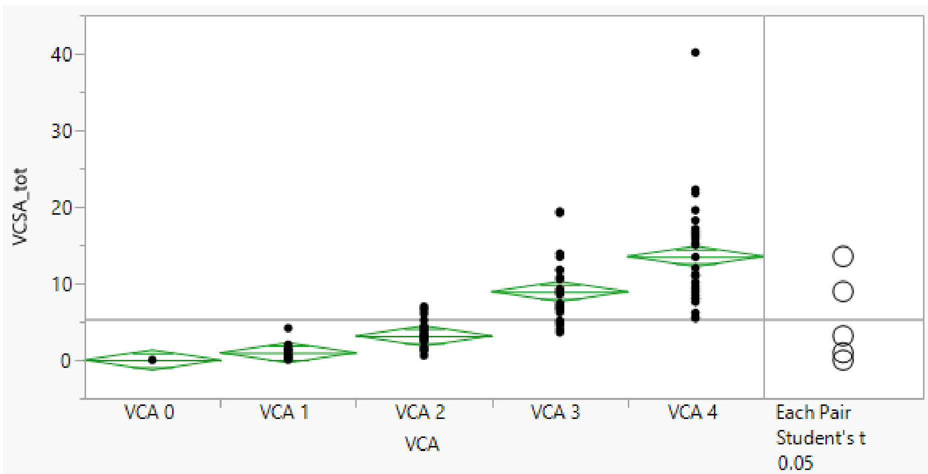


Figure 4.10 One way analysis of VCSA (in^2) by VCA (all trees assessed)

4.2.3 CBR and VCA

The field estimate of CBR, as the dependent variable, was compared to VCA (shown in Figure 4.11). There was a moderately strong correlation between the field estimated CBR and vine load as measured by VCA (R square = 0.61).

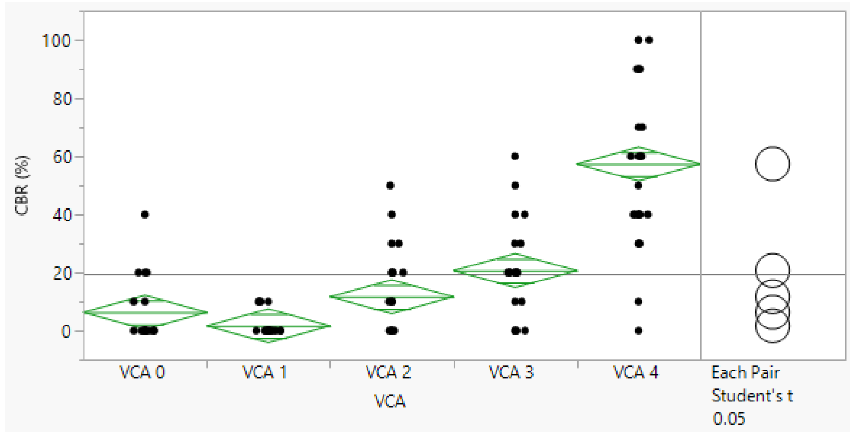


Figure 4.11 One way analysis of CBR by VCA (all trees assessed)

There was not a significant difference (alpha 0.05), in the field estimated CBR mean values, between the control group (VCA 0) and the minimally invaded class (VCA 1), and between the control group and VCA 2. There were significant differences between all other VCA classes. This suggests, as would be expected, there is a lag time before liana invasion causes a significant degradation of the tree crown biomass.

Table 4.4 Nonparametric means comparisons of CBR of VCA classes with the control group (VCA 0) using Steel Method

VCA Comparison	Score Mean Difference	Z score	p - Value
VCA 1 - VCA 0	-6.9667	-1.99358	0.1450
VCA 2 - VCA 0	6.8333	1.65766	0.2810
VCA 3 - VCA 0	16.5667	3.84750	0.0005
VCA 4 - VCA 0	27.5667	6.24923	<.0001

Nonparametric test confirmed there was a lag time before liana invasion caused a significant reduction in the tree crown biomass. There was not a significant difference (alpha 0.05) in the mean field estimated CBR for the control group and the sample means of VCA 1 and VCA 2. There was a significant difference (alpha 0.05) between the control group CBR mean and the CBR means of the more heavily invaded trees, as measured by the vine loads indicated by VCA 3 and VCA 4 (Table 4.4).

4.3 Biomass and Carbon Partitioning

4.3.1 Total Above Ground Biomass

Biomass calculations follow the generalized equations presented by Jenkins et al. (2004). The regression equation for calculating total Above Ground Biomass (tAGB = *bm*) (kg) is in the form

$$bm = Exp\left(\beta 0 + \beta 1 \, Ln(dbh)\right)$$

Exp is the exponential function, and *Ln* is the natural logarithm. The *dbh* is the tree diameter at "breast height" in cm and $\beta 0$ and $\beta 1$ are parameters listed for the species group. The three tree species sampled are all in the species group classified as "mixed hardwood". The parameters $\beta 0$ and $\beta 1$ listed for the mixed hardwood group are -2.4800 and 2.4835, respectively. As the experimental design controlled for tree diameter (dbh is 11 1/8" - 12 7/8") and all species sampled are in the same species group, it is a reasonable assumption to expect the mean total above ground biomass to approximate 405.98 kg (dry weight tAGB of a 12" caliper tree in the mixed hardwood species group). The mean tAGB values calculated from the field data are presented in Table 4.5

Table 4.5 Mean value of tAGB (kg) for the individual trees measured across species and VCA classes

	VCA classes				
Tree species	0	1	2	3	4
Ash	417	407	418	419	409
Poplar	419	439	389	428	445
Cherry	416	424	408	391	397

As expected, the values in Table 4.5 differ from the expected mean value due to the range of tree calipers included in the sampling group. The mean tAGB for the individual trees sampled was 415.12 kg.

4.3.2 Biomass Partitioning

Total above ground biomass can be partitioned into tree components using the ratio equations presented by Jenkins et al. (2004). The ratio equations are in the form

$$ratio = Exp\left(\propto 0 + \propto \frac{1}{dbh}\right)$$

Exp is the exponential function and *dbh* is the tree diameter at "breast height" in cm. Parameters ($\alpha 0 + \alpha 1$) are listed to calculate the ratio to partition total above ground biomass into individual components; foliage, stem (bole) wood, and stem (bole) bark. Branch biomass is calculated by the difference. Working from the same assumptions to estimate the mean values, the ratios were used to partition total aboveground biomass into the components for a twelve inch caliper tree. The total above ground biomass 405.98 kg, calculated for the 12" caliper example, is partitioned into component biomass; foliage 8.31 kg, stem bark 51.33, stem wood 250.10 kg, and branches 96.24 kg.

The mean biomass values for individual tree components calculated from the field data are presented in table 4.6. The total sample mean tAGB of 415.12 kg was partitioned into component biomass; foliage 8.48 kg, stem bark 52.52 kg, stem wood 256.23 kg, and branches 97.89 kg.

Table 4.6 Mean values of AGB for tree components for species and VCA class (*Liriodendron tulipifera* = Litu, *Prunus serotina* = Prse2, *Fraxinus* sp. = Fraxi)

VCA Class	Mean Foliage (kg)	Mean Stem bark (kg)	Mean stem wood (kg)	Mean branches (kg)
Litu	**8.65**	**53.67**	**262.13**	**99.61**
0	8.56	53.05	258.89	98.75
1	8.93	55.56	271.78	102.39
2	8.00	49.18	239.17	92.99
3	8.73	54.17	264.69	100.32
4	9.05	56.41	276.12	103.63
Prse2	**8.33**	**51.48**	**250.93**	**96.36**
0	8.50	52.63	256.82	98.08
1	8.65	53.65	262.05	99.57
2	8.35	51.57	251.37	96.49
3	8.03	49.38	240.19	93.25
4	8.14	50.16	244.20	94.43
Fraxi	**8.47**	**52.39**	**255.62**	**97.69**
0	8.52	52.76	257.44	98.27
1	8.34	51.53	251.23	96.40
2	8.54	52.91	258.21	98.48
3	8.56	53.08	259.14	98.67
4	8.36	51.70	252.08	96.63

4.3.3 Carbon Allocations and Atmospheric Reductions of CO_2

Working from the biomass estimates for the individual tree components, carbon can be estimated using the assumption that dry weight biomass is 50% carbon (Birdsey 1992). Using the 12" diameter tree example, carbon is apportioned in the above ground woody biomass as; bole (stem wood and bark) 150.72 kg C, and branches 48.12 kg C. Converting C to CO_2 using the conversion factor 3.67 C / CO_2 equates an atmospheric reduction of CO_2 to the individual tree components. Using the

12" diameter tree example, atmospheric CO_2 reduction is apportioned in the above ground woody biomass; bole 553.14 kg CO_2, and branches 176.60 kg CO_2. Calculations partitioning above ground woody biomass from the field data are presented in Table 4.7.

Table 4.7 Mean carbon and CO_2 reduction apportioned to tree components (*Liriodendron tulipifera* = Litu, *Prunus serotina* = Prse2, *Fraxinus* sp. = Fraxi)

VCA Class	Mean Bole (kg)	Mean Bole C (kg)	Mean Bole CO2 kg	Mean Branch C (kg)	Mean Branch CO2 kg
Litu	**315.81**	**157.90**	**579.50**	**49.81**	**182.79**
0.00	311.94	155.97	572.41	49.37	181.20
1.00	327.34	163.67	600.68	51.19	187.88
2.00	288.35	144.18	529.13	46.49	170.63
3.00	318.86	159.43	585.11	50.16	184.08
4.00	332.53	166.26	610.19	51.82	190.16
Prse2	**302.41**	**151.20**	**554.92**	**48.18**	**176.83**
0.00	309.45	154.73	567.85	49.04	179.98
1.00	315.71	157.85	579.32	49.78	182.70
2.00	302.94	151.47	555.90	48.25	177.06
3.00	289.57	144.79	531.36	46.63	171.12
4.00	294.36	147.18	540.15	47.21	173.28
Fraxi	**308.01**	**154.01**	**565.20**	**48.85**	**179.26**
0.00	310.20	155.10	569.22	49.13	180.32
1.00	302.76	151.38	555.56	48.20	176.89
2.00	311.11	155.56	570.89	49.24	180.72
3.00	312.22	156.11	572.92	49.33	181.06
4.00	303.78	151.89	557.43	48.32	177.32

The mean value of sequestered carbon apportioned to the bole and branches was 154.37 kg and 48.94 kg respectively. This equates to a mean reduction of atmospheric CO_2 of 566.54 kg apportioned to the bole and 176.93 kg to the branches for an individual tree sampled. The foliage component was removed from tAGB to calculate total Above Ground woody Biomass (tAGwB), as this study was focused on implications to long term carbon sequestration.

4.4 Biomass Reductions and CBR

The percentage based field estimate of Crown Biomass Reduction (CBR) was subtracted from the total Above Ground woody Biomass (tAGwB) apportioned to the branch estimate. Additionally, the estimate of C and CO_2 apportioned to the branches was reduced and a ratio of branch biomass loss to estimated total above ground woody biomass was calculated. The mean value of these calculations for individual species is presented in Table 4.8 and for the total sample in Table 4.9.

Table 4.8 Mean reduction of tAGwB, Carbon, CO_2, and percentage loss of tAGwB for species and VCA class (*Liriodendron tulipifera* = Litu, *Prunus serotina* = Prse2, *Fraxinus* sp. = Fraxi)

VCA classes	Mean CBR(%)	Mean reduc tAGwB (kg)	Mean reduc C (kg)	Mean reduc CO2 (kg)	Mean % Loss tAGwB
Litu	**16.40**	**16.33**	**8.17**	**29.97**	**3.94%**
0	3.00	2.95	1.48	5.41	0.72%
1	2.00	1.85	0.93	3.40	0.49%
2	11.00	9.75	4.88	17.90	2.72%
3	14.00	13.38	6.69	24.56	3.40%
4	52.00	53.71	26.86	98.57	12.39%
Prse2	**24.40**	**22.89**	**11.45**	**42.00**	**5.95%**
0	13.00	12.26	6.13	22.50	3.17%
1	3.00	3.16	1.58	5.80	0.71%
2	11.00	10.91	5.45	20.01	2.65%
3	23.00	21.16	10.58	38.82	5.63%
4	72.00	66.97	33.48	122.88	17.59%
Fraxi	**17.80**	**17.06**	**8.53**	**31.31**	**4.32%**
0	3.00	2.79	1.39	5.12	0.73%
1	0.00	0.00	0.00	0.00	0.00%
2	13.00	13.33	6.66	24.45	3.10%
3	25.00	24.56	12.28	45.07	6.04%
4	48.00	44.63	22.32	81.90	11.74%

Table 4.9 Mean reduction of tAGwB, Carbon, CO_2 and percentage loss of tAGwB VCA class (all species sampled)

VCA classes	Mean CBR(%)	Mean reduc tAGwB (kg)	Mean reduc C (kg)	Mean reduc CO2 (kg)	Mean % Loss tAGwB
0	6.33	6.00	3.00	11.01	1.54%
1	1.67	1.67	0.83	3.06	0.40%
2	11.67	11.33	5.66	20.79	2.82%
3	20.67	19.70	9.85	36.15	5.02%
4	57.33	55.10	27.55	101.12	13.91%

The mean percentage loss of tAGwB increased from 1.54%, for the control group (VCA 0), to 13.91% for the heaviest vine load (VCA 4). VCA classes 1, 2 and 3 showed a percentage loss of tAGwB of 0.40%, 2.82% and 5.02% respectively. The mean loss of tAGwB (13.91%) equated to a mean reduction of sequestered carbon of 27.55 kg at the highest vine load (VCA 4). This also equates to a mean loss of atmospheric CO_2 reduction of 101.12 kg at the highest vine load (VCA 4).

4.4.1 Means Test % Loss of Total Above Ground Woody Biomass (tAGwB)

There was a moderately strong correlation (R square 0.61) between the mean percentage loss of total Above Ground woody Biomass (tAGwB) and the vine load rating (VCA) (Figure 4.12).

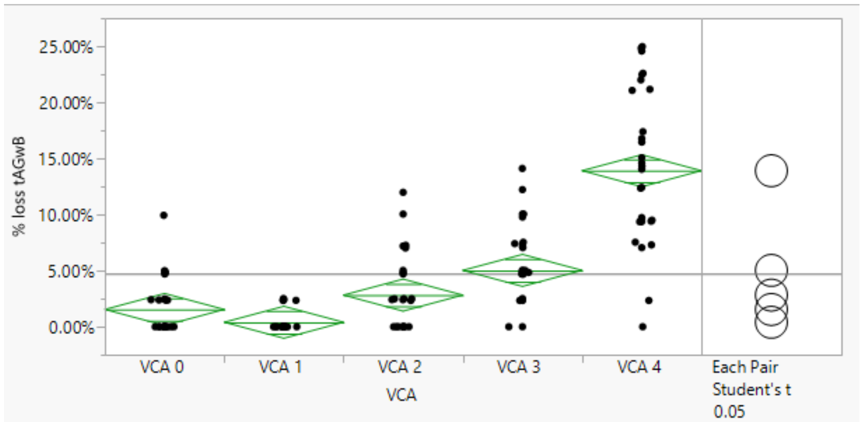


Figure 4.12 One way analysis of tAGwB by VCA (all trees sampled)

There was not a significant difference (alpha 0.05), in the mean percentage loss of tAGwB between the control group (VCA 0) and the minimally invaded class (VCA 1), and VCA 2. There were significant differences between all other VCA classes (Figure 4.12). As previously suggested, there is a lag time before liana invasion causes a significant degradation of the tree crown biomass.

Table 4.10 Nonparametric means comparisons of tAGWB of VCA classes with control group (VCA 0) using Steel Method

VCA Comparison	Score Mean Difference	Z score	p - Value
VCA 1 - VCA 0	-7.0333	-2.00415	0.1418
VCA 2 - VCA 0	7.1000	1.70955	0.2557
VCA 3 - VCA 0	16.6333	3.82998	0.0005
VCA 4 - VCA 0	27.1333	6.13189	<.0001

Nonparametric statistical analysis confirmed there was not a significant difference (alpha 0.05) in the mean percentage loss of tAGwB between the control group (VCA 0) and the minimally invaded class (VCA 1), and between the control group and VCA 2. The mean loss of tAGwB was significantly different from the control group, when the vine load increased to VCA 3 and VCA 4 (Table 4.10).

4.5 Review of Vine Coverage Assessment (VCA)

The rapid assessment protocol to estimate vine load, Vine Coverage Assessment (VCA), used in this study was developed to be simple, cost effective and user friendly. It could prove to be a useful tool for land managers and citizen science groups focused on forest restoration. Previous studies in a comparable physiographic region indicated that vine canopy coverage was the most closely associated with reduced tree growth and the measurement of the basal area of vines may not be necessary (Ladwig & Meiners, 2009).

The rapid assessment protocol VCA further simplified the previous vine coverage percentages, based on 10% increments. Generally, throughout this study, adding detail to the VCA would not have been necessary. Statistical analysis indicated there was not a significant difference in the impact on tree structure between adjacent VCA classes.

Table 4.11 Correlations between VCA and more intensive vine load measurements
*Sum Dia = Sum of field measured diameter of vines
*VCSA_C = Sum of vine cross sectional area of *Celastrus orbiculatus* calculated from diameter measurements
*VCSA_tot = Same as VCSA_C but adds any grape vines included in assessment

	VCA	Sum Dia	VCSA_C	VCSA_tot
VCA	1.0000	0.8191	0.7830	0.7905
Sum Dia	0.8191	1.0000	0.9421	0.9448
VCSA_C	0.7830	0.9421	1.0000	0.9989
VCSA_tot	0.7905	0.9448	0.9989	1.0000

There was a strong correlation (r = 0.7830 – 0.8191) between the rapid assessment protocol VCA and the other more labor-intensive vine load measurements as shown in Table 4.11. Chronbach's alpha showed a strong correlation and an overall strong measure of validity.

Statistical analysis shows there is a strong, but not perfect, correlation between the rapid assessment protocol VCA and the more labor-intensive field measurements used in vine studies. The rapid assessment protocol VCA would be a cost effective, user-friendly tool if the ultimate goal is forest restoration, or to manage forests to optimize ecosystem services, including maximizing carbon storage potential.

Chapter 5

DISCUSSION

This study was focused on a single point in time and asked the question whether *Celastrus orbiculatus* (oriental bittersweet), a non-native aggressive liana, is affecting the long-term carbon sequestration potential of temperate forests. Although there are many factors affecting forest health, oriental bittersweet can have a devastating impact on forest structure. Researchers have shown lianas, as an architectural parasite, impact the host plant by distorting or damaging the tree structure (Lutz, 1943; Ladwig & Mieners, 2009), severely limiting light resources available (Patterson, 1974; Ladwig & Mieners, 2009), and competing for water and nutrients (Shnitzer & Bongers, 2002). Host plants have decreased growth rates and increased mortality rates (Shnitzer et al., 2000). Lianas also have the potential to impact natural forest succession (Hegarty & Caballe, 1991).

5.1 Analysis of Rapid Assessment Protocol VCA

Gerwig et al. (2006) provides protocols that are appropriate for long-term field plots for liana studies. However, these protocols may be cumbersome and unnecessary for the land manager focused on forest restoration and maximizing the ecosystem services provided by healthy forest communities.

There was a strong association between the VCA estimates for all trees sampled and the measured total Vine Cross-Sectional Area (VCSA_tot), with an adjusted R^2 value of 0.67. The rapid assessment protocol VCA was a moderate to strong indicator of vine loading, as measured by the more intensive field measurement of the vine calipers and VCSA calculation. Therefore, the Vine Coverage Assessment

(VCA) is a simple and user-friendly alternative for use by the professional and non-professional.

There was a moderately strong correlation between the field estimated Crown Biomass Reduction (CBR) and vine load as measured by VCA (R square = 0.61). There was not a significant difference (alpha 0.05), in the field estimated CBR mean values, between the control group (VCA 0) and the minimally invaded class (VCA 1), and between the control group and VCA 2. There were significant differences between all other VCA classes. As expected, there was a lag before liana invasion causes significant degradation of the tree crown.

5.2 Estimated Reduction of Woody Biomass

The calculated total Above Ground woody Biomass (tAGwB) was reduced based on the tree canopy degradation, as indicated by the CBR.

There was not a significant difference (alpha 0.05), in the mean percentage loss of tAGwB between the control group (VCA 0) and the minimally invaded class (VCA 1), and between the control group and VCA 2. There were significant differences between all other VCA classes. This is another indication of the lag time before liana invasion causes a significant degradation of the tree crown biomass.

The mean percentage loss of tAGwB increased from 1.54%, for the control group (VCA 0); to 13.91% for the heaviest vine load (VCA 4). The mean loss of tAGwB (13.91%) equated to a mean reduction of sequestered carbon of 27.55 kg, per tree at the highest vine load (VCA 4). This also equates to a mean loss of atmospheric CO_2 reduction of 101.12 kg, per tree at the highest vine load (VCA 4). Further research would be required to estimate the impact *C. orbiculatus* truly has on carbon sequestration at the landscape scale, however this study suggests that the impact could be substantial.

It is difficult to assess the compensatory effects *C. orbiculatus* may have on the loss of woody biomass and carbon sequestration. To my knowledge there have been no allometric equations developed for this species, or generalized equations for use in temperate forests. There are generalized allometric equations for lianas that are specific to tropical forests (Schnitzer et al., 2006). Lianas, as an architectural parasite, need a relatively small amount of woody biomass for structural support and have low wood density with porous stems. Liana biomass growth in tropical forests has been estimated to compensate for 30% of the liana induced reductions in carbon storage caused by decreased tree growth (van der Heijden & Phillips, 2009).

The role lianas play in forest carbon dynamics has become a focus for researchers in tropical forests (van der Heidjen et al., 2013; Schnitzer et al., 2014; van der Heidjen et al., 2015). In a liana removal study, researchers found that lianas reduced net carbon uptake by ~ 76%. Reduction of tree growth was the primary factor. Another limiting factor for carbon storage was tree mortality as it was 4 times higher in the control plots (van der Heijden et al., 2015).

5.3 Temporal Considerations

The estimated reduction of crown biomass presented in this thesis does not fully consider the impact *C. orbiculatus* has on living, and future, development of healthy living woody biomass essential for long-term carbon sequestration. Often there was accelerated lower branch loss from canopy trees (Figure 4.3). Lianas are linked with reduced fecundity and tree growth (Schnitzer et al., 2000). It was common to see the destruction of developing hardwoods, resulting from girdling (Lutz, 1943) during liana ascension (Figures 5.1 and 5.2).

Figure 5.1 A small hardwood tree, utilized by *Celastrus orbiculatus* as a scaffold to access the forest canopy, which presumably succumbed to girdling stress.

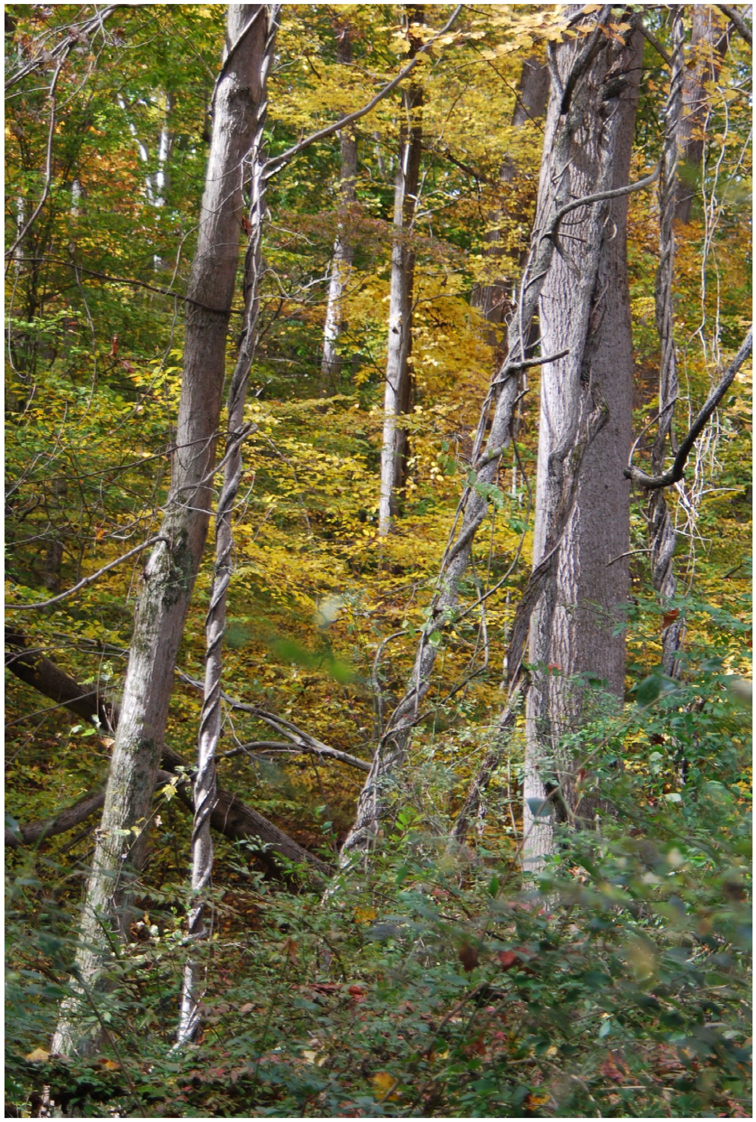


Figure 5.2 Moribund hardwood trees utilized by *Celastrus orbiculatus* as a vector to the canopy. Note the lack of lianas on the larger caliper trees.

Putz reported in 1995 that *Celastrus orbiculatus* did not directly climb trees greater than 15 cm dbh; however, biomechanical facilitation was common (Putz, 1995). This was observed throughout the park in my study. *C. orbiculatus* often utilizes existing *Vitis sp*. vines (Figure 5.3) to ascend directly into the canopy of large caliper trees.

Figure 5.3 *Celastrus orbiculatus* utilizing a grape vine to aid ascension to the canopy

It was also common to see the destruction of young trees by "smothering", the liana winning the competition for light water and nutrients, in fields, forest edges and gaps. Heavily invaded trees can be more susceptible to windthrow (Putz, 1984b).

Figure 5.4 A large *Celastrus orbiculatus* stem. The largest one measured was approximately 6.5 inches in diameter (at breast height).

5.4 Considerations for Land Managers

In 2017, the eradication of *Celastrus orbiculatus* from the temperate forests of North America is highly unlikely. This should not stop land managers from working to limit the impact of this insidious liana species on the ecosystem services and in particular the carbon storage potential of developing and existing hardwood forests. Although this presents a formidable challenge, it is likely to be easier now than in the future.

Land managers are focusing considerable resources toward restoration efforts throughout the White Clay Creek State Park (personal communication Rob Line, Chris Bennet, 2012). Managers are faced with a growing number of obstacles, existing and potential, threatening forest health including; aggressive non-native plants (multiflora rose, honeysuckle, porcelain berry, wavy leaf basket grass, Asiatic pear, mile-a-minute), insect invaders (Asian longhorn beetles, emerald ash borer, wooly adelgid), and animal pests (European earthworms, beaver).

There are a number of very important considerations when developing a plan to limit the of impact of oriental bittersweet in the White Clay Creek State Park and surrounding regions, as well as similar situations throughout the mid-Atlantic; The distribution has occurred over approximately the last 40 years (Figures 5.5 and 5.6).

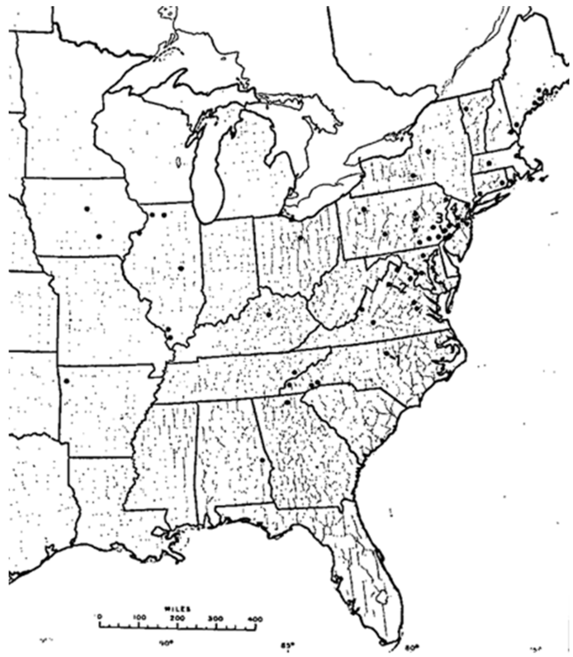


Figure 5.5 *Celastrus orbiculatus* distribution by county 1973 (Patterson)

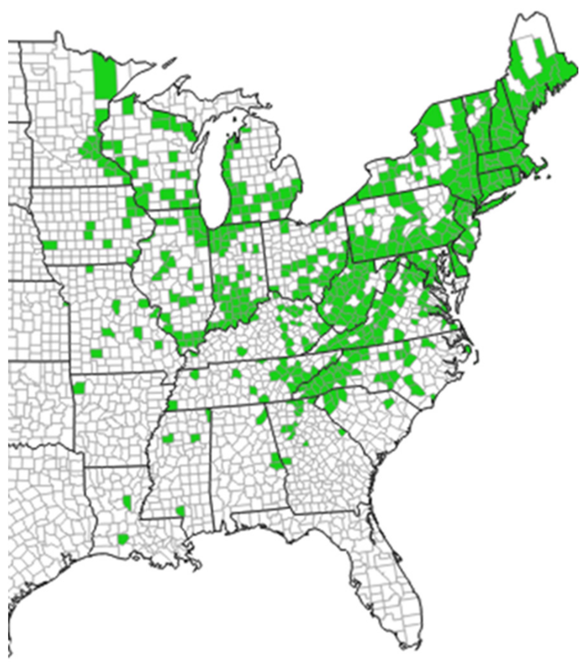


Figure 5.6 *Celastrus orbiculatus* distribution by county 2016 (EDDMaps)

Oriental bittersweet readily invades disturbed areas and grows rapidly on forest edges with full sun, especially southern and western edges (Lutz, 1943). Heavy fruit sets along with frugivory plays a major role in rapid and widespread distribution (Figure 5.7).

Figure 5.7 The heavy fruit set of a mature *Celastrus orbiculatus* showing the distinctive yellow capsule that has opened to reveal the red fruit. The showy, attractive fruiting vines were once prized in the landscape and often used in holiday decorations.

Oriental bittersweet can rapidly adapt to changing photosynthetic light. (Patterson 1974). Oriental bittersweet utilizes smaller diameter trees or existing vines to aid ascension into the canopy (Ladwig & Meiners, 2009; Putz, 1995).

Considering these factors, and from extensive field observations, it may be feasible to limit the distribution of oriental bittersweet from forest patches classified as over 75 years old. The age of these forests and well-established canopies act as a limiting factor to oriental bittersweet and other aggressive nonnative plants. Early Detection and Rapid Response (EDRR), the current strategies for invasives management, would be a very effective in these patches. Monitoring areas in full sun along edges, particularly southern and western, should be a high priority. State officials are focused on protecting these biologically diverse forest patches (personal communications, Rob Line and Chris Bennett, 2012). Gap management, as practiced by land managers of the Delaware Nature Society (personal communication, Jim White, 2012) should also be a priority.

The forest patches classified between the age of 45 and 75 years old present additional challenges. Most of these forest patches have well established canopies, limiting the aggressive growth of oriental bittersweet. However, through extensive field observations, it was readily apparent that oriental bittersweet had already invaded the interiors of many of these forest patches, although generally it was not well established or causing major damage within the forest canopy. The liana was most often utilizing the more established grape vine (Figure 5.3) or the developing secondary hardwood species as a scaffold to ascend into the canopy (Figures 5.4 & 5.6). Ladwig and Meiners (2009) reported *C. orbiculatus* was often found twining on small trees or existing lianas. This process appeared to be having a devastating effect on forest succession, as the developing hardwoods often succumbed to the girdling stress or were obviously moribund. These patches should be a high priority for land managers. Control efforts should pay large dividends in this age class, as this study suggests, due to the lag between initial invasion and large-scale canopy degradation.

Working to limit oriental bittersweet in forest patches classified as less than 45 years old presents many additional challenges. Mile-a-minute and porcelain berry, along with other invasives, can also have a devastating impact on developing forest cover. As with any other area, protecting existing canopy trees should be a high priority. Competition for light resources is one the most important factors on which land managers should focus. A well-established canopy can act as a limiting factor for most invasive species.

It is imperative to control *C. orbiculatus* in order to maximize the ecosystem services provided by healthy forested ecosystems, including the reduction of atmospheric carbon dioxide. Patterson's statement is still relevant today, "Control measures applied now while distribution is still limited, may prevent severe future problems" (Patterson, 1974). The county distribution maps shown in figures 5.5 and 5.6 indicate that *C. orbiculatus* has indeed spread well beyond its distribution in 1973, and it is likely to continue that spread, without a targeted management program.

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Appendix A

REMOTE SENSING

An Overview of the Principles for the Remote Sensing of Vegetation

Samuel F Berry

12/8/11

Introduction:

Remote sensing techniques and applications are widely used to study ecosystem processes, quantify existing land covers, detect forest and agricultural stressors, and assist in calculations of global national and regional carbon pools. Remote sensing techniques have advanced far from the first hand held camera operators surveying areas of interest from mountain peaks or hot air balloons and early aircraft. Currently, data is collected from modern aircraft and a multitude of satellites which follow diverse orbits or are held in fixed positions related to the earth (geostationary). Satellite orbits and information collected is dependent on the mission statements of the space programs and industry responsible for their operation. Information is being collected at varying spatial temporal and spectral resolutions, much of which is made publicly available through government web portals and private contractors. The data sets available are presented in a variety of formats. Radiometric data depending on the product offering may have been processed to remove atmospheric distortions caused by scattering or may have to be processed by the end user. Additionally, geometric corrections may be required. The products available include calculations for Leaf Area Index (LAI) Normalized Difference Vegetation Index (NDVI) Gross Primary Production (GPP) and Net Primary Production (NPP) that have been developed from the raw spectral reflectance information. The applicability of remote sensing and the appropriate imagery to be incorporated is contingent on the individual researcher and the scale of the project being considered along with the geographical area of interest.

Plant Biology and Physiology:

Leaf Biology

In order to utilize remotely sensed data for the stated applications and to better understand the products available it is best to first look closer at generalized plant biology, and plant physiology. A section of an individual leaf is comprised of an upper epidermis and a lower epidermis layer. The epidermis is covered by a thin cuticle layer that helps to limit water loss from the leaf. The epidermis layers are penetrated by the stoma which allow for gas exchange with the atmosphere. The stomata openings are surround by guard cells that govern opening size to allow for free gas exchange or to protect from water loss. The interior mesophyll can be divided into two distinct regions the palisade parenchyma and the spongy parenchyma. The vascular system is made up of xylem and phloem. The xylem delivers water and minerals to the plant taken from the ground and dies after a single season and preforms a secondary function of structural support. Tree rings are comprised of the xylem tissue. The phloem delivers the sugars produced during photosynthesis to the living tissues throughout the plant to fuel the metabolic processes. The “power plants” of plants are the chloroplasts. Photosynthetically reactive pigments including chlorophyll *a* and *b* and β carotene are found in the thykaloid membranes. Stacks of thykaloids make up the grana which are surrounded by fluid (stroma). The pigments contained within the chloroplasts absorb portions of the sun’s electromagnetic energy from the visible spectrum to drive the light dependent phase of photosynthesis, 70% – 90% of the blue and red portions are absorbed by the pigments. The chloroplast pigments are less absorptive in the green region and more green light is reflected, causing leaves to appear green.

Photosynthesis

Currently, there is a great deal of interest in greenhouse gas reduction in particular atmospheric carbon dioxide. Plants have the ability to remove atmospheric carbon dioxide through the process of photosynthesis and to store the accumulated carbon. Much of the long term carbon sequestration within a forest ecosystem occurs within the biomass of the larger trees. This carbon is incorporated into the plants supporting framework and significant biomass associated with the root structure. The carbon cycle is a dynamic and complex system within individual plants and the larger ecosystems. Considering photosynthesis, carbon dioxide enters the plant leaf through stomata openings where through a series of chemical reactions involving light energy and water delivered by the plants vascular system, glucose ($C_6H_{12}O_6$) is produced. This glucose is used to fuel cellular respiration, and to produce cellulose, starches and other organic compounds needed for plant development.

The chemical reactions in photosynthesis can be divided into light dependent reactions and light independent reactions. Light energy from the sun is used for photolysis of water. This reaction occurs within the thykaloid membrane of the grana contained within the chloroplasts of the leaf, the waste product produced is oxygen which is released into the atmosphere through the stomata. The resultant hydrogen ions, free electrons and energy released are used in the conversion of Nicotinamide Adenine Dinucleotide Phosphate ($NADP^+$) to Nicotinamide Adenine Dinucleotide

Phosphate-oxidase (NADPH) and in the transformation of Adenosine Diphosphate (ADP) and Phosphate (P) to Adenosine Triposphate (ATP). The light independent reaction occurs within the stroma of the chloroplast and is the process where carbon dioxide is then converted to glucose. The reactions incorporate the ATP as the energy source, NADPH as a source of hydrogen and a free electron, created in during the light phase. The reaction is initiated by the enzyme ribulose bisphosphate (RuBP) converting the carbon dioxide to glceraldehyde 3-Phosphate (C_3 Photosynthesis). This series of chemical reactions, initiated by RuBP, that take place to complete the conversion of carbon dioxide to glucose is referred to as the Calvin cycle. The Calvin cycle also yields $NADP^+$ + ADP + P and RuBP to be used in the next series of reactions.

In an effort to conserve water plants need to close their stomata at varied times during the diurnal cycle which in turn limits the available carbon dioxide for glucose production. Plants have developed different coping strategies and vary these processes. Some plants in response to the need to control transpiration, close their stomata at times during the day converting carbon dioxide to a four- carbon dicarboxylic acid oxaloacetate anion, (C_4 Photosynthesis) to be stored for use during the light phase of the reaction even if the stoma are closed. Desert plants use an alternate mechanism, only opening their stomata at night converting the carbon dioxide to a four-carbon acid malate (CAM photosynthesis), which is also used during the light phase of photosynthesis.

Plant Tissue Response to Incoming Electromagnetic Radiation

Satellite remote sensing applications for vegetation studies are dependent on a thorough understanding how solar radiation is absorbed or reflected from plant tissues. The portion of the visible electromagnetic spectrum that is absorbed for photosynthetic activities is primarily within the blue and red wavelengths with the green portion being reflected in the greatest percentage. Plant tissues are also highly reflective when considering the near infrared portion of the spectrum. The relationship between the strong absorption of red wavelengths and the strong reflectance of near-infrared wavelengths is used quite often in the field of remote sensing for vegetation for analysis. The reflectance comes primarily from the spongy mesophyll layer within the leaf structure. The properties of plant spectral response when examining middle-infrared wavelengths is dependent on the band widths being considered. Certain bands are influenced by atmospheric water absorption and absorption by plant tissue where alternate regions within the mid-infrared are more reflective. The importance of the spectral signatures of plant tissues will be considered in finer detail as specific vegetation indexes and plant stressors are reviewed.

Relative Water Content and Evapotranspiration:

Relative Water content

Relative water content is calculated by measuring the mass of a plant tissue sample and comparing it to a sample from a plant that is unstressed and water availability is not a problem. Relative water content = (fresh mass – dry mass) / (turgid mass – dry mass) and can be viewed as a measurement of leaf turgor pressure. A relative water content value of 1 is indicative of a plant with a readily available source of water. A great deal of scientific research is focused on the development of remote sensing protocols and applications that are able to estimate leaf water content within plants. Quantifying water stress in plants early is critical in all vegetation studies and is especially important in agricultural applications as water stress may lead to reduced crop yield.

Evapotranspiration

It is clear from the discussion of photosynthesis that plants have adapted their physiological processes to conserve water. Research scientists have worked to understand the ecosystem principles responsible for evaporation and plant transpiration. Core laws of physics are combined with empirically derived relationships to quantify the process of evapotranspiration. These relationships can be used to model ecosystem processes for use by water resource manager's, plant scientists, hydrologist and climatologists.

Evaporation is a diffusive processes following Fick's first law $E = K_e * v_a * (e_s - e_a)$ where E is evaporation and K_e is a coefficient quantifying the resistance of water to vertical transport. Wind speed is represented by v_a, e_s is saturated vapor pressure as determined by temperature and e_a is the existing vapor pressure considering relative humidity and air temperature. Fick's second law quantifies the time required for particles to travel a given distance across a known diffusion gradient. As the speed at which theses diffusive processes occur is related to wind speed eddies can influence convection and the vertical transport of water vapor. When looking at evaporation and transpiration at the canopy level the energy fluxes also needed to be considered. Penman described evaporation in terms of the relationships between mass transfer principles, air temperature, incoming solar radiation and vapor pressure differentials. Monteith built on the work of Penman and quantified evapotranspiration (ET). Incorporating empirically derived relationships between ET and latent heat of vaporization, atmospheric conductance, canopy conductance, the density of air, and the density of water. The resultant equation is referred to as the Penman-Monteith approach to quantifying ET, often used in computer modeling for hydrologic studies.

Remote Sensing Products:

Satellite Remote Sensing and Image Processing:

The United States and countries throughout the world along with private industry operate a wide variety of satellites. There is an incredible amount of information being collected at varied scales and resolutions. The most common form of vegetative analysis completed from the multispectral imagery is the calculations for leaf area index (LAI) and Net Primary Production (NPP) and the normalized difference vegetation index (NDVI). The principle behind calculating NDVI is that vegetation is highly absorptive in the red spectrum and highly reflective of the near infrared. Viewing NDVI can be used in the classification of imagery, analyzing changes in reflectance or “multitemporal image classification”. The satellites IKONOS and QuickBird capture imagery at very high radiometric resolutions, very detailed spatial resolutions and varied temporal scales. It is possible to classify plants to the genus or species level but the costs associated datasets is considerable and limit their widespread use. There is however a wide variety of information being collected that is made available without charge through geospatial web portals. The following chart summarizes the most common satellite remote sensors and indicates the spectral spatial and temporal resolutions made available from these sensors.

Table 1 main features of image products from the different sensors

Products (sensors)	Features	Vegetation mapping applications[a]
Landsat TM	Medium to coarse spatial resolution with multispectral data (120 m for thermal infrared band and 30 m for multispectral bands) from Landsat 4 and 5 (1982 to present). Each scene covers an area of 185 × 185 km. Temporal resolution is 16 days.	Regional scale mapping, usually capable of mapping vegetation at community level.
Landsat ETM+ (Landsat 7)	Medium to coarse spatial resolution with multispectral data (15 m for panchromatic band, 60 m for thermal infrared and 30 m for multispectral bands) (1999 to present). Each scene covers an area of 185 km × 185 km. Temporal resolution is 16 days.	Regional scale mapping, usually capable of mapping vegetation at community level or some dominant species can be possibly discriminated.
SPOT	A full range of medium spatial resolutions from 20 m down to 2.5 m, and SPOT VGT with coarse spatial resolution of 1 km. Each scene covers 60 × 60 km for HRV/HRVIR/HRG and 1000 × 1000 km (or 2000 × 2000 km) for VGT. SPOT 1, 2, 3, 4 and 5 were launched in the year of 1986, 1990, 1993, 1998 and 2002, respectively. SPOT 1 and 3 are not providing data now.	Regional scale usually capable of mapping vegetation at community level or species level or global/national/regional scale (from VGT) mapping land cover types (i.e. urban area, classes of vegetation, water area, etc.).
MODIS	Low spatial resolution (250–1000 m) and multispectral data from the Terra Satellite (2000 to present) and Aqua Satellite (2002 to present). Revisit interval is around 1–2 days. Suitable for vegetation mapping at a large scale. The swath is 2330 km (cross track) by 10 km (along track at nadir).	Mapping at global, continental or national scale. Suitable for mapping land cover types (i.e. urban area, classes of vegetation, water area, etc.).
AVHRR	1-km GSD with multispectral data from the NOAA satellite series (1980 to present). The approximate scene size is 2400 × 6400 km	Global, continental or national scale mapping. Suitable for mapping land cover types (i.e. urban area, classes of vegetation, water area, etc.).
IKONOS	It collects high-resolution imagery at 1 m (panchromatic) and 4 m (multispectral bands, including red, green, blue and near infrared) resolution. The revisit rate is 3–5 days (off-nadir). The single scene is 11 × 11 km.	Local to regional scale vegetation mapping at species or community level or can be used to validate other classification result.
QuickBird	High resolution (2.4–0.6 m) and panchromatic and multispectral imagery from a constellation of spacecraft. Single scene area is 16.5 × 16.5 km. Revisit frequency is around 1–3.5 days depending on latitude.	Local to regional scale vegetation mapping at species or community level or used to validate vegetation cover extracted from other images.
ASTER	Medium spatial resolution (15–90 m) image with 14 spectral bands from the Terra Satellite (2000 to present). Visible to near-infrared bands have a spatial resolution of 15 m, 30 m for short wave infrared bands and 90 m for thermal infrared bands.	Regional to national scale vegetation mapping at species or community level.
AVIRIS	Airborne sensor collecting images with 224 spectral bands from visible, near infrared to short wave infrared. Depending on the satellite platforms and latitude of data collected, the spatial resolution ranges from meters to dozens of meters and the swath ranges from several kilometers to dozens of kilometers.	At local to regional scale usually capable of mapping vegetation at community level or species level. As images are carried out as one-time operations, data are not readily available as it is obtained on an 'as needs' basis.
Hyperion	It collects hyperspectral image with 220 bands ranging from visible to short wave infrared. The spatial resolution is 30 m. Data available since 2003.	At regional scale capable of mapping vegetation at community level or species level.

[a] Many sensors provide imagery for producing VI (e.g. NDVI) that is calculated from the bands in the visible and near-infrared regions.

(XIE)

Reviewing data from remote sensing platforms the researcher needs to understand the factors that affect the power received by the sensors. Remotely sensing data may need to be corrected to account for geometric distortions caused by refraction, sensor position, and the instantaneous field of view recorded by the sensor. Radiometric errors caused by sensor failure and distortions caused the atmospheric scattering electromagnetic energy need to be accounted for. Rayleigh scattering is common in the upper atmosphere and is caused by very small particles in relation to wavelength. Shorter blue wavelengths are more susceptible to rayleigh scattering in the upper atmosphere, which is responsible for the blue color of the sky. As the sun sets in the evening the influence of rayleigh scattering on longer wavelengths, that have to travel further through the atmosphere to the viewer, is responsible for the varied colors including red that we perceive. Mie scattering is caused by particles that have a diameter equivalent to the wavelength being influenced. Non selective scattering is wavelength independent, caused by large particles lower in the atmosphere and is responsible for the haze we see directly or in remotely sensed imagery decreasing spatial details and contrast.

In addition to the effects of scattering some electromagnetic energy is attenuated as it travels through the atmosphere affecting the power received at the sensors. Gasses in the atmosphere including ozone, carbon dioxide and water vapor influence electromagnetic through absorption. Ozone in the upper atmosphere absorbs ultraviolet radiation, carbon dioxide and water vapor in the mid and lower atmosphere are responsible for the absorption of the mid and far infrared portions of the electromagnetic spectrum. There are regions within the electromagnetic wavelengths indicated and throughout the electromagnetic spectrum that are not as susceptible to attenuation. These spectral regions are important within the remote sensing field and are referred to as atmospheric windows.

When reviewing remotely sensed data collected by satellites or alternate sources the quality of the data and the way in which the raw data was processed and delivered is an important consideration. Sensor failures need to reviewed and the raw data received by the sensors may need to be corrected because of the radiometric distortions discussed. As previously mentioned, available data may have already been radiometrically corrected or the datasets need to be processed by the end user. Along with any geometric or radiometric corrections required it is important to consider the quality and accuracy of the data values. The data values of different band widths are often delivered in raster format. The radiometric resolution is determined by range of values being reported for individual wavelength bands (0-255 assuming 8 bit data). The qualities of the data sets are determined via a statistical analysis, including univariate and multivariate statistical methods or nonparametric analysis. Nonparametric analysis is used when the distribution of values may be skewed when reviewing histograms. Univariate statistics analyzes the variety and deviations within normally distributed date. Multivariate statics is used to compute the variance or covariance between 2 bands. The sample coefficient of determination or r^2 value is used in to quantify the range of values, when plotting 2 bands, which have a linear relationship.

There are a number of software packages available for working with remotely sensed datasets including ENVI and ERDAS imagine. The software programs contain a suite of tools designed for preprocessing. Geometric corrections are completed by "warping" an image so that it corresponds with known ground control points. Additionally, there are tools for image enhancement based on algorithms. A "floating" 3 cell by 3 cell grid run over the raster image and cell values are changed to reflect the cell values in the adjoining cells based on the algorithm being incorporated. These tools are used for spatial spectral and radiometric data enhancements. Tools are also available to merge data from two sources in order enhance the image quality of a lower resolution data set.

Remote Sensing for Ecosystem Studies and Vegetation Indexes:

Carbon Sequestration and Forest Monitoring

In 1997 the Kyoto protocol was adopted indicating the concern over global warming and the need to limit greenhouse gasses, in particular carbon dioxide. Although it was ratified in 2005 the United States is still one of the few countries yet to endorse it. The concern over greenhouse gas reductions and carbon emissions in the United States is evidenced by congressional hearings (S. Hrg. 111-652, S Hrg. 110-20), carbon trading legislation (American Clean Energy and Security Act) and regional action plans (Regional Greenhouse Gas Initiative). Considerable efforts are being made to quantify global carbon pools. Currently, the merchantability of carbon offset credits has intensified this research. Methodologies following protocols set forth by USFS Forest Inventory Analysis (FIA) or NRCS National Resource Inventory (NRI) have been developed to estimate carbon stocks at the national and regional level as well as the management level. Remotely sensed data including multispectral and hyperspectral satellite images are combined with in-situ measurements to analyze land use and land use change in an attempt to identify carbon pools and to assess the relative health of our remaining forested ecosystems.

Apparent from the world's oceans the greatest natural carbon sink is our forested ecosystems. The analysis of land use and land use change is instrumental in estimating carbon stock. Remote sensing techniques are critical in the development of land use classification maps. The most common classification system is the Andersen Classification used by the USGS. National carbon stock estimates are then developed from regional representative sampling of the major land cover classes. The Natural Resources Conservation Service maintains a Natural Resource Inventory-NRI). Datasets for theses inventories along with additional information on soil type is available through United States Department of Agriculture's Geospatial Gateway www.datagateway.nrcs.usda.gov. The sampling protocols follow the standards set forth by The Forest Health Monitoring (FHM) and Forest Inventory and Analysis (FIA) programs of the United States Forest Service (USFS).The current manual for plot design, data collection and national database standards can be downloaded at USFS website http://www.fs.fed.us/rm/pubs/rmrs_gtr245.pdf . The North American Carbon Program (NACP) combines the United States forest inventory and carbon stock estimates, data on ecosystem processes, along with additional information on atmospheric CO2, CH4, and CO, with data from collaborating countries to look to further understand the carbon cycle and environmental fluxes.

Leaf Area Index (LAI)and Normalized Difference Vegetation Index (NDVI)

The plant community or autotrophs from the ecologist perspective are the energy source directly or indirectly for all of the biological species comprising the higher trophic levels. The glucose produced during photosynthesis is utilized to fuel the production of plant tissues that are in turn consumed by heterotrophs which yield their energy to the predators of the food chain. As all of these ecological energy transfers begin within the chloroplasts contained within the leaves of plants the calculation of leaf area is important to environmental research and in the calculations to quantifying ecosystem productivity. Leaf area index can be defined by: one sided leaf surface area / ground surface area. The calculation of leaf area can be derived directly from destructive sampling, field deployed sensors measuring light attenuation through the canopy structure or indirectly incorporating empirically derived allometric equations relating LAI to plant biology. Calculating LAI from remote sensed data is dependent on the comparison of the power received at the sensors for various wavelengths and the spectral properties of leaf tissue. As from a previous discussion photosynthetic pigments absorb much of the incoming red wavelengths from the sun and a large portion of the infared light energy is reflected by leaf tissue. NDVI = (near infrared – red) / (near infrared + red) the values are determined by the power received at the remote sensor for the given bandwidths. Researchers have developed equations to quantify the relationship between the calculation of NDVI and estimated LAI for individual plant species and larger forest communities.

Remote Sensing for NPP

Ecologist and environmental scientist concerned with the ecosystem services provided by plant communities use the calculations of leaf area index and empirically derived relationships correlating LAI with larger plant communities to quantify ecosystem productivity. As stated in the introduction plants have the ability to sequester carbon through the process of photosynthesis. Photosynthetically Active Radiation (PAR) is in the spectral range of 400 –700 nm. *f*PAR is the fraction of PAR that is used by plants for their biological processes and for biomass production. Satellite remote sensing of PAR and *f*PAR is the first step in calculating Net Primary Production (NPP) and Gross Primary Production (GPP). Further calculations to interpret actual biomass production therefore carbon storage are completed using empirically derived relationships and allometric equations for individual forest types or larger biomes. The other most important remotely sensed data used in these calculations is the leaf area index. NASA operates the Earth Observation Satellite MODIS (Moderate Resolution Imaging Spectroradiometer) and makes available products derived from these calculations (MODIS17A3).

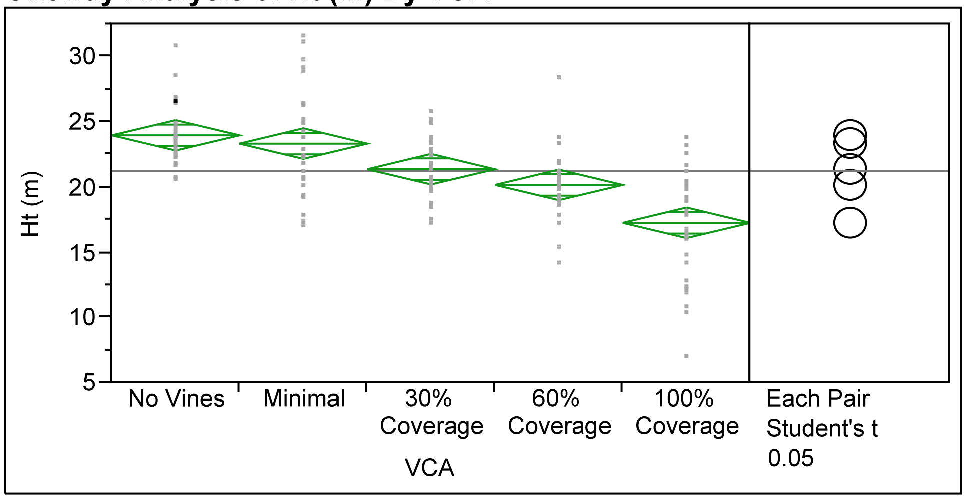
Conclusion:

All though this was only a brief overview of some of the most basic principles and techniques used in the field of remote sensing for vegetation studies, the application of these principles are wide ranging. A broader discussion of the research would confirm this, as the basic indexes presented and the spectral properties of vegetation are used by research scientists in multivariate applications. Agricultural specialists, foresters, ecologists, hydrologist and climate change researchers are among the scientists interested in these basic principles and in the refinement of vegetation indexes applicable to their research. The ecosystem services provided by plant communities are critical to the well-being of the entire global ecosystem and the study of the distribution and health of these communities will be an ongoing field of scientific study with remote sensing playing a critical role.

Appendix B

Statistical Summary Output (Jump)

Oneway Analysis of Ht (m) By VCA



Oneway Anova
Summary of Fit

Rsquare	0.361697
Adj Rsquare	0.344089
Root Mean Square Error	3.245924
Mean of Response	21.25067
Observations (or Sum Wgts)	150

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
VCA	4	865.6916	216.423	20.5412	<.0001*
Error	145	1527.7233	10.536		
C. Total	149	2393.4149			

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

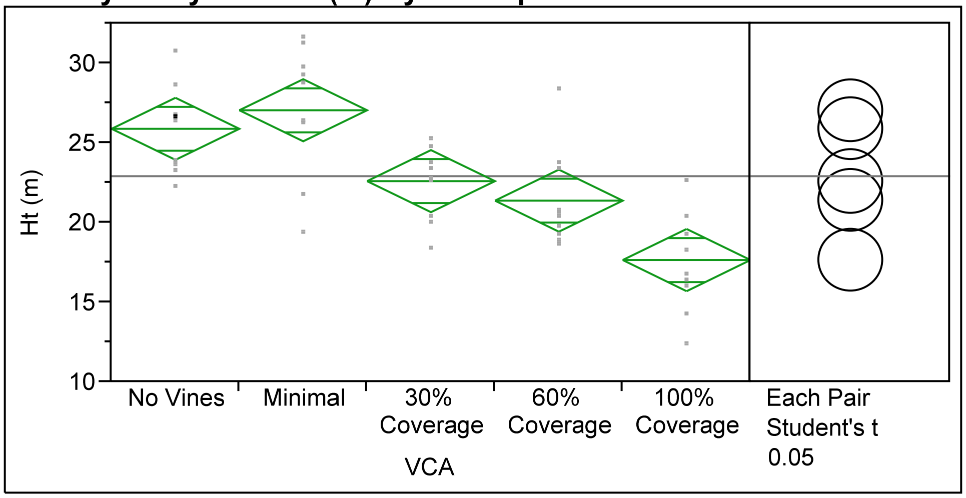
t	Alpha
1.97646	0.05

Connecting Letters Report

Level				Mean
No Vines	A			24.000000
Minimal	A			23.366667
30% Coverage		B		21.400000
60% Coverage		B		20.196667
100% Coverage			C	17.290000

Levels not connected by same letter are significantly different.

Oneway Analysis of Ht (m) By VCA Species=Litu



Oneway Anova
Summary of Fit

Rsquare	0.571262
Adj Rsquare	0.533152
Root Mean Square Error	3.059314
Mean of Response	22.926
Observations (or Sum Wgts)	50

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
VCA	4	561.18320	140.296	14.9898	<.0001*
Error	45	421.17300	9.359		
C. Total	49	982.35620			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
No Vines	10	25.9000	0.96744	23.951	27.849
Minimal	10	27.0600	0.96744	25.111	29.009
30% Coverage	10	22.6200	0.96744	20.671	24.569
60% Coverage	10	21.3900	0.96744	19.441	23.339
100% Coverage	10	17.6600	0.96744	15.711	19.609

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
2.01410	0.05

LSD Threshold Matrix

Abs(Dif)-LSD	**Minimal**	**No Vines**	**30% Coverage**	**60% Coverage**	**100% Coverage**
Minimal	-2.7556	-1.5956	1.6844	2.9144	6.6444
No Vines	-1.5956	-2.7556	0.5244	1.7544	5.4844
30% Coverage	1.6844	0.5244	-2.7556	-1.5256	2.2044
60% Coverage	2.9144	1.7544	-1.5256	-2.7556	0.9744
100% Coverage	6.6444	5.4844	2.2044	0.9744	-2.7556

Positive values show pairs of means that are significantly different.

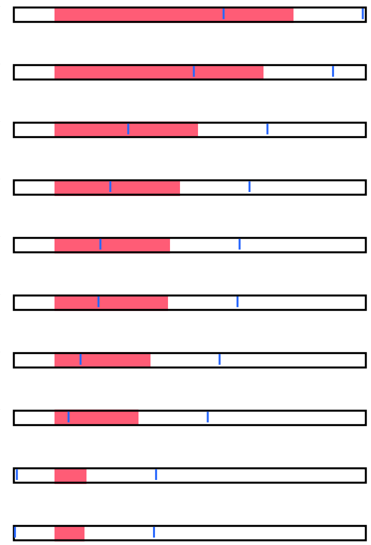
Connecting Letters Report

Level				**Mean**
Minimal	A			27.060000
No Vines	A			25.900000
30% Coverage		B		22.620000
60% Coverage		B		21.390000
100% Coverage			C	17.660000

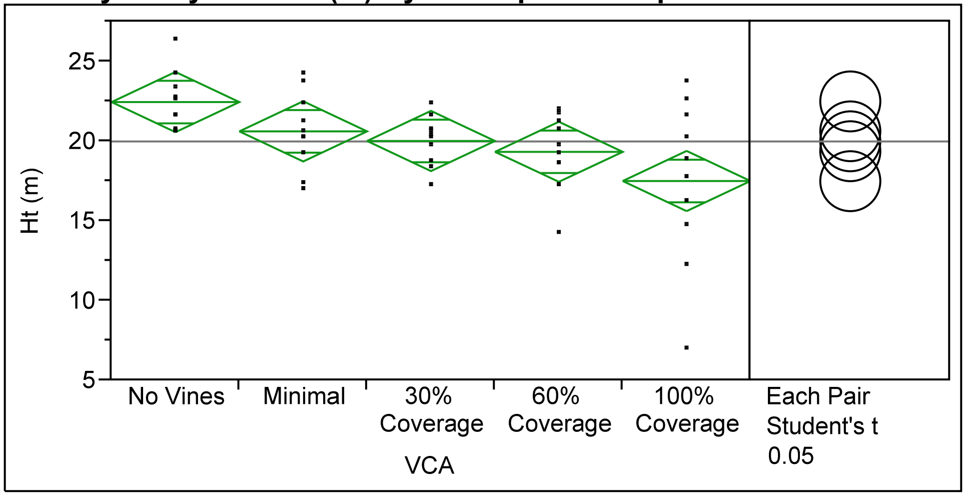
Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Minimal	100% Coverage	9.400000	1.368167	6.64437	12.15563	<.0001*
No Vines	100% Coverage	8.240000	1.368167	5.48437	10.99563	<.0001*
Minimal	60% Coverage	5.670000	1.368167	2.91437	8.42563	0.0001*
30% Coverage	100% Coverage	4.960000	1.368167	2.20437	7.71563	0.0007*
No Vines	60% Coverage	4.510000	1.368167	1.75437	7.26563	0.0019*
Minimal	30% Coverage	4.440000	1.368167	1.68437	7.19563	0.0022*
60% Coverage	100% Coverage	3.730000	1.368167	0.97437	6.48563	0.0091*
No Vines	30% Coverage	3.280000	1.368167	0.52437	6.03563	0.0207*
30% Coverage	60% Coverage	1.230000	1.368167	-1.52563	3.98563	0.3734
Minimal	No Vines	1.160000	1.368167	-1.59563	3.91563	0.4010



Oneway Analysis of Ht (m) By VCA Species=Prpe



Oneway Anova
Summary of Fit

Rsquare	0.248829
Adj Rsquare	0.182058
Root Mean Square Error	2.961265
Mean of Response	19.99
Observations (or Sum Wgts)	50

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
VCA	4	130.71600	32.6790	3.7266	0.0106*
Error	45	394.60900	8.7691		
C. Total	49	525.32500			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
No Vines	10	22.4600	0.93643	20.574	24.346
Minimal	10	20.6200	0.93643	18.734	22.506
30% Coverage	10	20.0200	0.93643	18.134	21.906
60% Coverage	10	19.3400	0.93643	17.454	21.226
100% Coverage	10	17.5100	0.93643	15.624	19.396

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
2.01410	0.05

LSD Threshold Matrix

Abs(Dif)-LSD	**No Vines**	**Minimal**	**30% Coverage**	**60% Coverage**	**100% Coverage**
No Vines	-2.6673	-0.8273	-0.2273	0.4527	2.2827
Minimal	-0.8273	-2.6673	-2.0673	-1.3873	0.4427
30% Coverage	-0.2273	-2.0673	-2.6673	-1.9873	-0.1573
60% Coverage	0.4527	-1.3873	-1.9873	-2.6673	-0.8373
100% Coverage	2.2827	0.4427	-0.1573	-0.8373	-2.6673

Positive values show pairs of means that are significantly different.

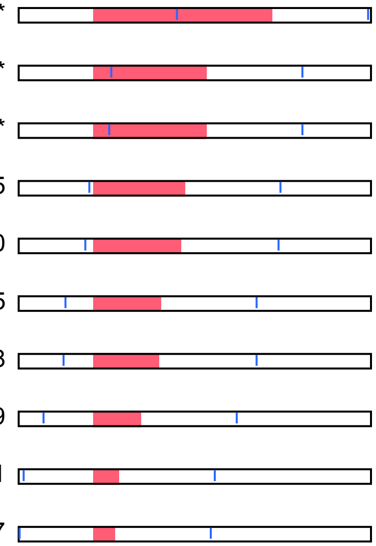
Connecting Letters Report

Level				**Mean**
No Vines	A			22.460000
Minimal	A	B		20.620000
30% Coverage	A	B	C	20.020000
60% Coverage		B	C	19.340000
100% Coverage			C	17.510000

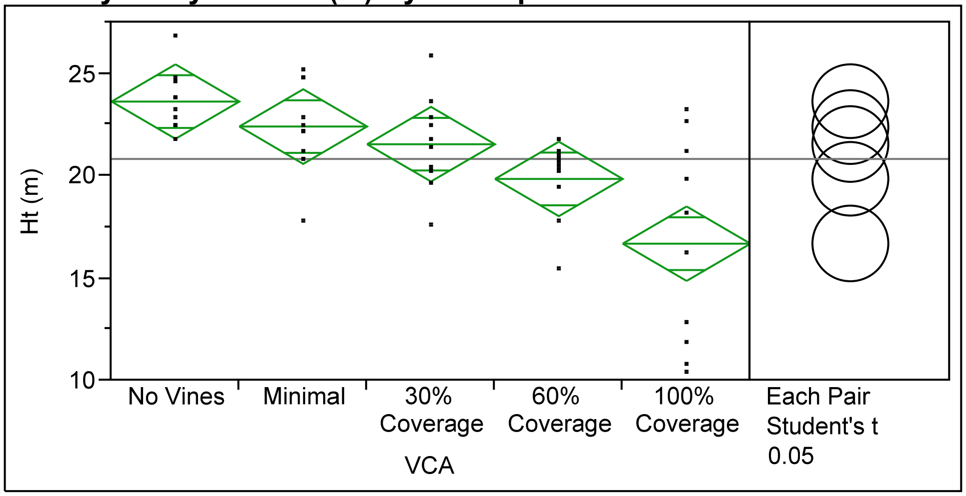
Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
No Vines	100% Coverage	4.950000	1.324318	2.28269	7.617313	0.0005*
No Vines	60% Coverage	3.120000	1.324318	0.45269	5.787313	0.0229*
Minimal	100% Coverage	3.110000	1.324318	0.44269	5.777313	0.0233*
30% Coverage	100% Coverage	2.510000	1.324318	-0.15731	5.177313	0.0645
No Vines	30% Coverage	2.440000	1.324318	-0.22731	5.107313	0.0720
No Vines	Minimal	1.840000	1.324318	-0.82731	4.507313	0.1715
60% Coverage	100% Coverage	1.830000	1.324318	-0.83731	4.497313	0.1738
Minimal	60% Coverage	1.280000	1.324318	-1.38731	3.947313	0.3389
30% Coverage	60% Coverage	0.680000	1.324318	-1.98731	3.347313	0.6101
Minimal	30% Coverage	0.600000	1.324318	-2.06731	3.267313	0.6527



Oneway Analysis of Ht (m) By VCA Species=Fr



Oneway Anova
Summary of Fit

Rsquare	0.440486
Adj Rsquare	0.390752
Root Mean Square Error	2.858858
Mean of Response	20.836
Observations (or Sum Wgts)	50

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
VCA	4	289.54720	72.3868	8.8567	<.0001*
Error	45	367.78800	8.1731		
C. Total	49	657.33520			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
No Vines	10	23.6400	0.90405	21.819	25.461
Minimal	10	22.4200	0.90405	20.599	24.241
30% Coverage	10	21.5600	0.90405	19.739	23.381
60% Coverage	10	19.8600	0.90405	18.039	21.681
100% Coverage	10	16.7000	0.90405	14.879	18.521

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for each pair using Student's t

Confidence Quantile

t	Alpha
2.01410	0.05

LSD Threshold Matrix

Abs(Dif)-LSD	No Vines	Minimal	30% Coverage	60% Coverage	100% Coverage
No Vines	-2.5751	-1.3551	-0.4951	1.2049	4.3649
Minimal	-1.3551	-2.5751	-1.7151	-0.0151	3.1449
30% Coverage	-0.4951	-1.7151	-2.5751	-0.8751	2.2849
60% Coverage	1.2049	-0.0151	-0.8751	-2.5751	0.5849
100% Coverage	4.3649	3.1449	2.2849	0.5849	-2.5751

Positive values show pairs of means that are significantly different.

Connecting Letters Report

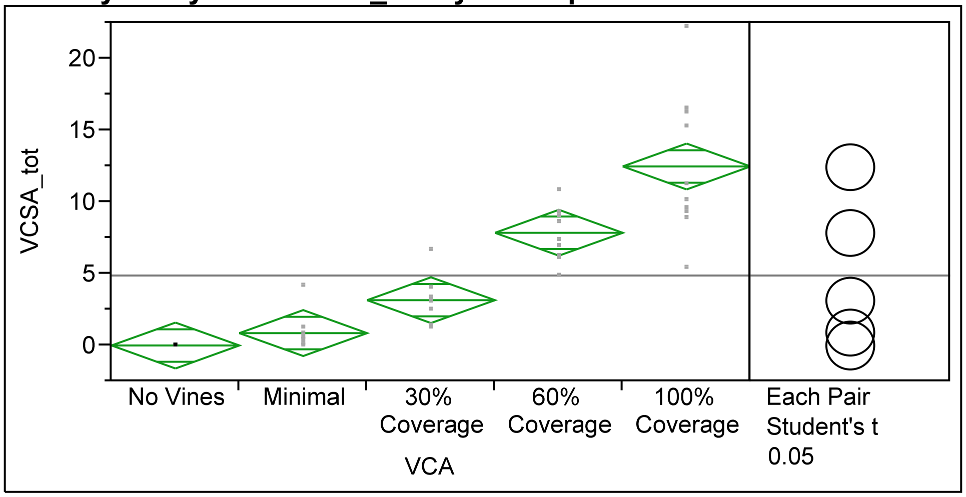
Level				Mean
No Vines	A			23.640000
Minimal	A	B		22.420000
30% Coverage	A	B		21.560000
60% Coverage		B		19.860000
100% Coverage			C	16.700000

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
No Vines	100% Coverage	6.940000	1.278520	4.36493	9.515071	<.0001*
Minimal	100% Coverage	5.720000	1.278520	3.14493	8.295071	<.0001*
30% Coverage	100% Coverage	4.860000	1.278520	2.28493	7.435071	0.0004*
No Vines	60% Coverage	3.780000	1.278520	1.20493	6.355071	0.0049*
60% Coverage	100% Coverage	3.160000	1.278520	0.58493	5.735071	0.0173*
Minimal	60% Coverage	2.560000	1.278520	-0.01507	5.135071	0.0513
No Vines	30% Coverage	2.080000	1.278520	-0.49507	4.655071	0.1107
30% Coverage	60% Coverage	1.700000	1.278520	-0.87507	4.275071	0.1903
No Vines	Minimal	1.220000	1.278520	-1.35507	3.795071	0.3451
Minimal	30% Coverage	0.860000	1.278520	-1.71507	3.435071	0.5046

Oneway Analysis of VCSA_tot By VCA Species=Litu



Oneway Anova
Summary of Fit

Rsquare	0.794346
Adj Rsquare	0.776066
Root Mean Square Error	2.511608
Mean of Response	4.875359
Observations (or Sum Wgts)	50

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
VCA	4	1096.4502	274.113	43.4535	<.0001*
Error	45	283.8679	6.308		
C. Total	49	1380.3182			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
No Vines	10	0.0000	0.79424	-1.60	1.600
Minimal	10	0.8664	0.79424	-0.73	2.466
30% Coverage	10	3.1612	0.79424	1.56	4.761
60% Coverage	10	7.8613	0.79424	6.26	9.461
100% Coverage	10	12.4878	0.79424	10.89	14.088

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
2.01410	0.05

LSD Threshold Matrix

Abs(Dif)-LSD	100% Coverage	60% Coverage	30% Coverage	Minimal	No Vines
100% Coverage	-2.262	2.364	7.064	9.359	10.226
60% Coverage	2.364	-2.262	2.438	4.733	5.599
30% Coverage	7.064	2.438	-2.262	0.033	0.899
Minimal	9.359	4.733	0.033	-2.262	-1.396
No Vines	10.226	5.599	0.899	-1.396	-2.262

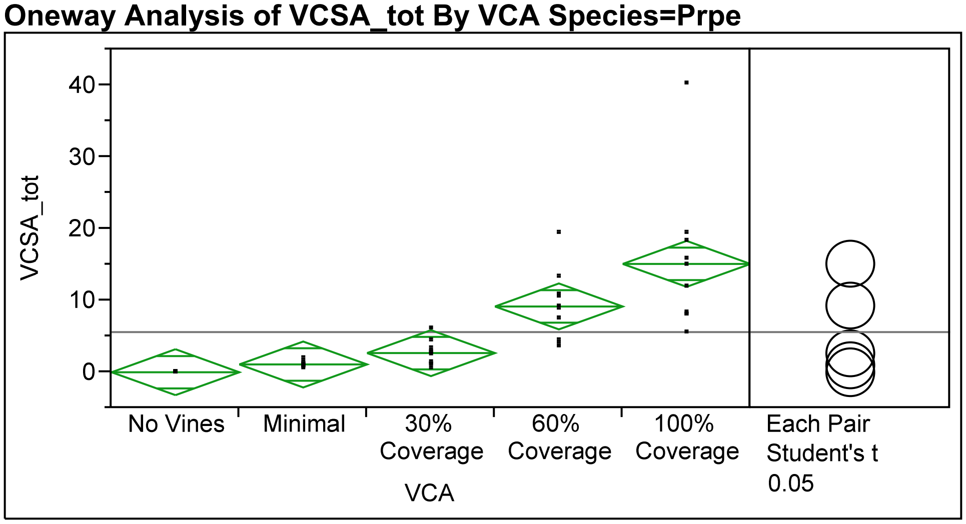
Positive values show pairs of means that are significantly different.

Connecting Letters Report

Level					Mean
100% Coverage	A				12.487831
60% Coverage		B			7.861345
30% Coverage			C		3.161228
Minimal				D	0.866392
No Vines				D	0.000000

Levels not connected by same letter are significantly different.

Oneway Analysis of VCSA_tot By VCA Species=Prpe



Oneway Anova
Summary of Fit

Rsquare	0.589819
Adj Rsquare	0.553359
Root Mean Square Error	5.027301
Mean of Response	5.610197
Observations (or Sum Wgts)	50

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
VCA	4	1635.4082	408.852	16.1769	<.0001*
Error	45	1137.3188	25.274		
C. Total	49	2772.7270			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
No Vines	10	0.0000	1.5898	-3.20	3.202
Minimal	10	1.0885	1.5898	-2.11	4.290
30% Coverage	10	2.6716	1.5898	-0.53	5.874
60% Coverage	10	9.1818	1.5898	5.98	12.384
100% Coverage	10	15.1091	1.5898	11.91	18.311

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
2.01410	0.05

LSD Threshold Matrix

Abs(Dif)-LSD	100% Coverage	60% Coverage	30% Coverage	Minimal	No Vines
100% Coverage	-4.528	1.399	7.909	9.492	10.581
60% Coverage	1.399	-4.528	1.982	3.565	4.654
30% Coverage	7.909	1.982	-4.528	-2.945	-1.857
Minimal	9.492	3.565	-2.945	-4.528	-3.440
No Vines	10.581	4.654	-1.857	-3.440	-4.528

Positive values show pairs of means that are significantly different.

Connecting Letters Report

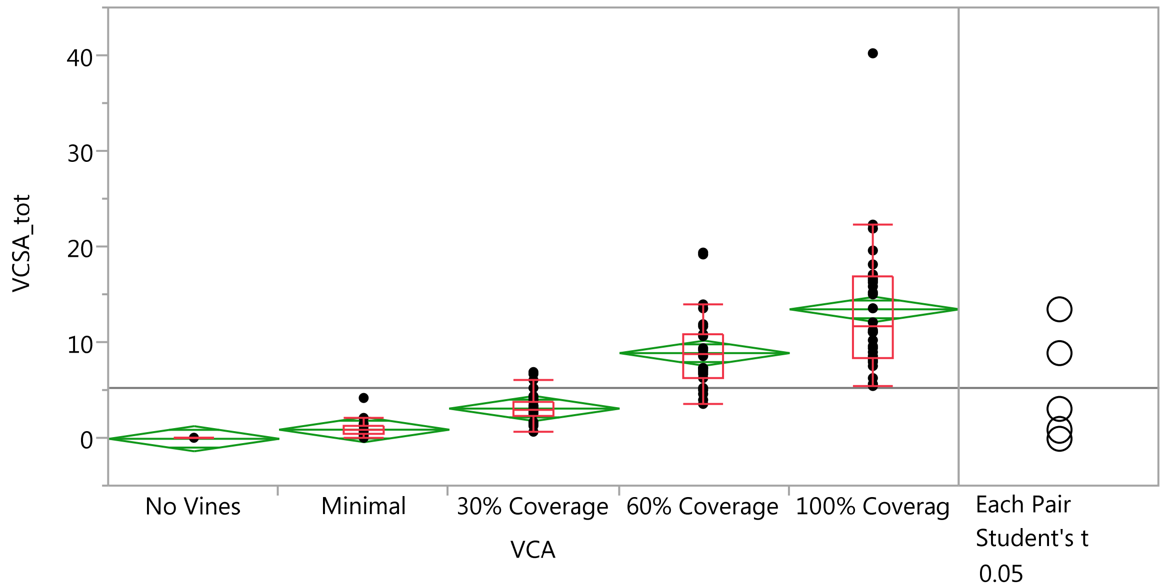
Level				Mean
100% Coverage	A			15.109097
60% Coverage		B		9.181795
30% Coverage			C	2.671581
Minimal			C	1.088513
No Vines			C	0.000000

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
100% Coverage	No Vines	15.10910	2.248277	10.5808	19.63736	<.0001*
100% Coverage	Minimal	14.02058	2.248277	9.4923	18.54885	<.0001*
100% Coverage	30% Coverage	12.43752	2.248277	7.9093	16.96578	<.0001*
60% Coverage	No Vines	9.18180	2.248277	4.6535	13.71006	0.0002*
60% Coverage	Minimal	8.09328	2.248277	3.5650	12.62155	0.0008*
60% Coverage	30% Coverage	6.51021	2.248277	1.9820	11.03848	0.0058*
100% Coverage	60% Coverage	5.92730	2.248277	1.3990	10.45556	0.0115*
30% Coverage	No Vines	2.67158	2.248277	-1.8567	7.19984	0.2410
30% Coverage	Minimal	1.58307	2.248277	-2.9452	6.11133	0.4850
Minimal	No Vines	1.08851	2.248277	-3.4397	5.61678	0.6306

Oneway Analysis of VCSA_tot By VCA



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
No Vines	0	0	0	0	0	0	0
Minimal	0.049087	0.19635	0.441786	0.822214	1.227185	1.484893	4.172428
30% Coverage	0.60132	1.227185	2.233476	3.012738	3.801204	5.999706	6.970409
60% Coverage	3.595651	4.599488	6.209554	8.688467	10.78388	13.85982	19.38952
100% Coverage	5.460972	6.30282	8.375535	11.60917	16.8247	21.56163	40.15348

Oneway Anova
Summary of Fit

Rsquare	0.674234
Adj Rsquare	0.665247
Root Mean Square Error	3.642107
Mean of Response	5.321727
Observations (or Sum Wgts)	150

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
VCA	4	3980.8735	995.218	75.0262	<.0001*
Error	145	1923.4171	13.265		
C. Total	149	5904.2905			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
No Vines	30	0.0000	0.66495	-1.31	1.314
Minimal	30	0.9560	0.66495	-0.36	2.270
30% Coverage	30	3.1625	0.66495	1.85	4.477
60% Coverage	30	8.9560	0.66495	7.64	10.270
100% Coverage	30	13.5342	0.66495	12.22	14.848

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
1.97646	0.05

LSD Threshold Matrix

Abs(Dif)-LSD

	100% Coverage	60% Coverage	30% Coverage	Minimal	No Vines
100% Coverage	-1.859	2.720	8.513	10.720	11.676
60% Coverage	2.720	-1.859	3.935	6.141	7.097
30% Coverage	8.513	3.935	-1.859	0.348	1.304
Minimal	10.720	6.141	0.348	-1.859	-0.903
No Vines	11.676	7.097	1.304	-0.903	-1.859

Positive values show pairs of means that are significantly different.

Connecting Letters Report

Level					Mean
100% Coverage	A				13.534210
60% Coverage		B			8.955993
30% Coverage			C		3.162455
Minimal				D	0.955977
No Vines				D	0.000000

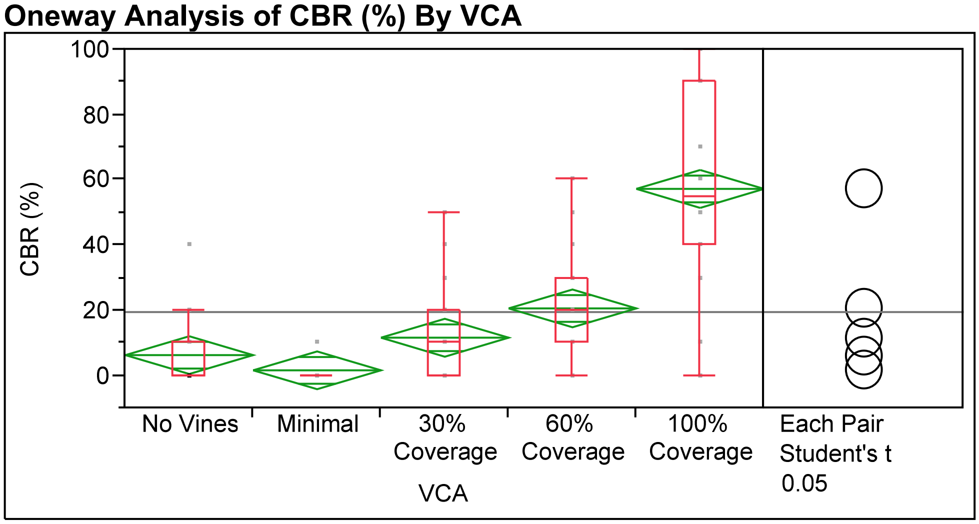
Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value	
100% Coverage	No Vines	13.53421	0.9403880	11.6756	15.39285	<.0001*	
100% Coverage	Minimal	12.57823	0.9403880	10.7196	14.43687	<.0001*	

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
100% Coverage	30% Coverage	10.37176	0.9403880	8.5131	12.23039	<.0001*
60% Coverage	No Vines	8.95599	0.9403880	7.0974	10.81463	<.0001*
60% Coverage	Minimal	8.00002	0.9403880	6.1414	9.85866	<.0001*
60% Coverage	30% Coverage	5.79354	0.9403880	3.9349	7.65218	<.0001*
100% Coverage	60% Coverage	4.57822	0.9403880	2.7196	6.43686	<.0001*
30% Coverage	No Vines	3.16245	0.9403880	1.3038	5.02109	0.0010*
30% Coverage	Minimal	2.20648	0.9403880	0.3478	4.06512	0.0203*
Minimal	No Vines	0.95598	0.9403880	-0.9027	2.81462	0.3110

Oneway Analysis of CBR (%) By VCA



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
No Vines	0	0	0	0	10	20	40
Minimal	0	0	0	0	0	10	10
30% Coverage	0	0	0	10	20	30	50
60% Coverage	0	0	10	20	30	40	60
100% Coverage	0	30	40	55	90	99	100

Oneway Anova
Summary of Fit

Rsquare	0.613636
Adj Rsquare	0.602978
Root Mean Square Error	16.0824
Mean of Response	19.53333
Observations (or Sum Wgts)	150

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
VCA	4	59564.000	14891.0	57.5734	<.0001*
Error	145	37503.333	258.6		
C. Total	149	97067.333			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
No Vines	30	6.3333	2.9362	0.53	12.137
Minimal	30	1.6667	2.9362	-4.14	7.470
30% Coverage	30	11.6667	2.9362	5.86	17.470
60% Coverage	30	20.6667	2.9362	14.86	26.470
100% Coverage	30	57.3333	2.9362	51.53	63.137

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
1.97646	0.05

LSD Threshold Matrix

Abs(Dif)-LSD	**100% Coverage**	**60% Coverage**	**30% Coverage**	**No Vines**	**Minimal**
100% Coverage	-8.207	28.460	37.460	42.793	47.460
60% Coverage	28.460	-8.207	0.793	6.126	10.793
30% Coverage	37.460	0.793	-8.207	-2.874	1.793
No Vines	42.793	6.126	-2.874	-8.207	-3.540
Minimal	47.460	10.793	1.793	-3.540	-8.207

Positive values show pairs of means that are significantly different.

Connecting Letters Report

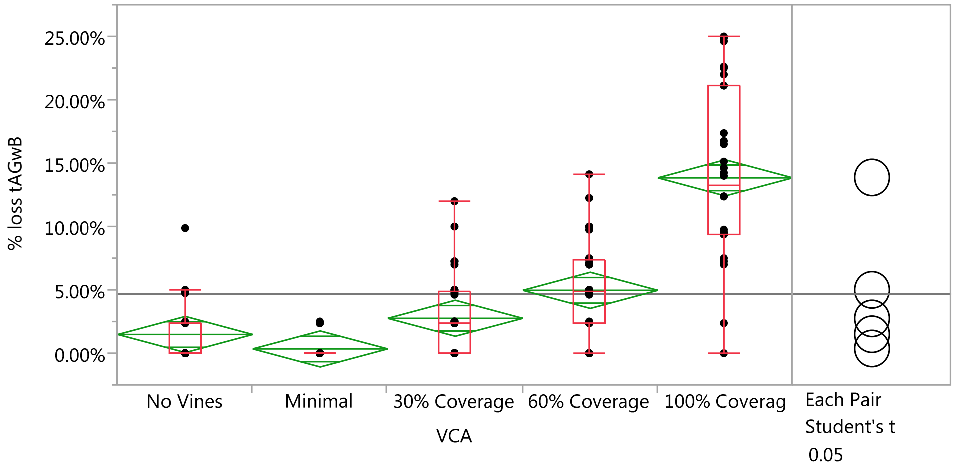
Level					**Mean**
100% Coverage	A				57.333333
60% Coverage		B			20.666667
30% Coverage			C		11.666667
No Vines			C	D	6.333333
Minimal				D	1.666667

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
100% Coverage	Minimal	55.66667	4.152459	47.4595	63.87383	<.0001*
100% Coverage	No Vines	51.00000	4.152459	42.7928	59.20717	<.0001*
100% Coverage	30% Coverage	45.66667	4.152459	37.4595	53.87383	<.0001*
100% Coverage	60% Coverage	36.66667	4.152459	28.4595	44.87383	<.0001*
60% Coverage	Minimal	19.00000	4.152459	10.7928	27.20717	<.0001*
60% Coverage	No Vines	14.33333	4.152459	6.1262	22.54050	0.0007*
30% Coverage	Minimal	10.00000	4.152459	1.7928	18.20717	0.0173*
60% Coverage	30% Coverage	9.00000	4.152459	0.7928	17.20717	0.0318*
30% Coverage	No Vines	5.33333	4.152459	-2.8738	13.54050	0.2011
No Vines	Minimal	4.66667	4.152459	-3.5405	12.87383	0.2629

Oneway Analysis of % loss tAGwB By VCA



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
No Vines	0	0	0	0	0.02427	0.049098	0.09934
Minimal	0	0	0	0	0	0.023815	0.025107
30% Coverage	0	0	0	0.023798	0.048539	0.072531	0.119819
60% Coverage	0	0	0.023408	0.049036	0.073819	0.100427	0.141091
100% Coverage	0	0.070788	0.093954	0.132312	0.210913	0.243762	0.249696

Oneway Anova
Summary of Fit

Rsquare	0.607889
Adj Rsquare	0.597072
Root Mean Square Error	0.039494
Mean of Response	0.047391
Observations (or Sum Wgts)	150

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
VCA	4	0.35062536	0.087656	56.1983	<.0001*
Error	145	0.22616644	0.001560		
C. Total	149	0.57679180			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
No Vines	30	0.015405	0.00721	0.0012	0.02966
Minimal	30	0.004003	0.00721	-0.0102	0.01825
30% Coverage	30	0.028228	0.00721	0.0140	0.04248
60% Coverage	30	0.050240	0.00721	0.0360	0.06449