Suitability of Pecan Shell Mulch for Weed Control and Rabbiteye Blueberry Establishment

by

Ashley A. Hoppers

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 7, 2017

Keywords: agricultural byproducts, *Carya illinoinensis*, production, root growth,
root system architecture, *Vaccinium virgatum*

Approved by

James D. Spiers, Chair, Associate Professor of Horticulture
J. Raymond Kessler, Professor of Horticulture
Amy N. Wright, Professor of Horticulture
Arlie A. Powell, Professor Emeritus of Horticulture

Abstract

Waste disposal for pecan (*Carya illinoinensis*) shells lack effectual, economic methodologies. If shell waste could be repurposed as a mulch, then pecan growers may have an opportunity to treat shell byproduct as a resource by supplying rabbiteye blueberry (*Vaccinium virgatum*) growers with an alternative to pine bark. Three studies were conducted to determine the effect of pecan shell mulch on weed control and rabbiteye blueberry establishment. In Feb. 2016, an on-farm planting of ‘Krewer’ rabbiteye blueberries was installed in Auburn, AL to determine the efficacy of seven treatments: “fresh” pecan shells, “aged” pecan shells, or pine bark mini-nuggets at 7.6 cm or 15.2 cm depths, and a no mulch (bare ground) treatment with no weed control except mowing. All mulch treatments had a lower weed density than no mulch, though, as the season progressed the 7.6 cm mulches resulted in higher weed density than the 15.2 cm mulches. From May–Aug. 2016, all mulches had higher soil moisture than no mulch; however, in Sept. 2016, 15.2 cm aged shells had a higher soil moisture than no mulch and 7.6 cm pine bark. Soil and soil-mulch interface temperatures were generally higher in the shell mulches than pine bark; however, plant size was only reduced in no mulch compared to 7.6 cm pine bark. Regarding weed control and transplant survival, pecan shells performed similarly to pine bark as a mulch during the first year of plant establishment.

Root growth of rabbiteye blueberry cultivars ‘Brightwell’ and ‘Premier’ was examined using the Horhizotron™, a technology that nondestructively measures horizontal root growth. The Horhizotron™ was constructed from eight panels of glass that fastened into an aluminum

base, forming four wedge-shaped quadrants around the original root ball. Each quadrant was filled with 10 cm of an amended 4:1 pine bark:sand (v/v) substrate. 7.6 cm of “fresh” pecan shells, “aged” pecan shells, pine bark mini nuggets, or an unamended 4:1 pine:sand substrate control was then randomly applied to each of the four quadrants. Root growth rates were determined weekly by measuring the length and depth of the five longest roots on either side of a quadrant. Horizontal root length (HRL) in ‘Premier’ showed that roots tended to initiate further from the original root ball into the quadrant profile in the control, pine bark, and aged shells than in the fresh shells. HRL in ‘Brightwell’ showed that roots in the control and pine bark grew further from the original root ball than in either shell mulch. In ‘Premier’ roots were more concentrated in the upper portions of the quadrant profile in the control than either fresh shells or pine bark, though aged shells were similar. Root depth in ‘Brightwell’ showed that roots in control and aged shells grew more in the upper portion of the quadrant profile than in pine bark and fresh shells. The location of root growth in the quadrant profiles was reflected in root dry weight (RDW). For both cultivars, RDW within the substrate layer was similar in all treatments, but mulch layer RDW varied. In ‘Premier’ mulch layer RDW was lower in pine bark than the remaining treatments; however, total RDW was similar across all treatments. In ‘Brightwell’ mulch RDW was lower in pine bark and fresh shells than in the aged shells, while control was similar to both shell mulches. Those differences impacted total RDW, as the quadrants that contained pine bark and fresh shells had a lower total RDW. These results indicated that as compared to pine bark, root growth in pecan shells was not hindered.

The third experiment was conducted to determine the level of weed control that could be obtained by using pecan shell mulch on crabgrass (*Digitaria sanguinalis*), common ragweed (*Ambrosia artemisiifolia*), or spotted spurge (*Euphorbia maculata*); three problematic weed

species in the southeastern United States Pine bark mulch was also included in the evaluation to provide a commercial standard for control. Results from the first experimental run showed that the weed germination by mulch depth interaction influenced weed counts of each weed species, and all mulch treatments, regardless of depth, resulted in complete control of each weed species. Data from the second and third experimental runs varied, and no distinctive trend in weed suppression was observed, though the smaller particle size of pecan shells may have been more favorable for weed seed germination for spotted spurge. Further evaluation of weed control of these weed species is recommended.

Acknowledgments

As I reflect on this research and the pivotal contributions made by others, I am profoundly humbled. I want to extend a personal thanks to my committee chair, Dr. James D. Spiers for investing in me and pushing me ever forward towards success. I am also grateful to Dr. Arlie A. Powell for his mentorship, Dr. J. Raymond Kessler for always making time to help me with statistics, and Dr. Amy N. Wright for her time and expertise. Mr. Dave Borden, thank you for donating the pecan shells used in these studies and for your confidence in this research. Mr. Frank Randle, thank you for giving this research a home, but also for your time, field work, and friendship; indeed, one never knows whose shoulders will be stood upon along the way. Amid the many peers that assisted me, Ashley Brantley, you were my lighthouse in the fog. Lastly, I want to acknowledge my husband. Chase, for every moment of despair you reassuringly held my hand, and for every victory your voice resonated above all others. No one achieves anything alone.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

°C	Degrees Celsius
AU	Auburn University
BMP	Best Management Practice
DAP	Days After Planting
g	Gram
h	hours
ha	Hectare
HRL	Horizontal Root Length
IPM	Integrated Pest Management
kg	Kilogram
L	Liters
m	meter
PSI	Plant Size Index
PYO	Pick-Your-Own
RD	Root Depth
RDW	Root Dry Weight
VPR	Visual Plant Rating
WDR	Weed Density Rating

CHAPTER I

Introduction

Of the blueberry species commercially grown in the southeastern United States, rabbiteye blueberry (*Vaccinium virgatum* [Aiton] syn. *V. ashei*) is the most widely cultivated. While the rabbiteye species is classified as a highbush blueberry type, it is distinguished from the highbush blueberry (*Vaccinium corymbosum* L.) by its notable tolerance of high temperatures and ability to withstand soils with depleted organic matter (Fonsah et at. 2008). Though robust, rabbiteye blueberries remain vulnerable to competition from weeds for water, nutrients, and spatial resources.

Numerous researchers have reported that mulched blueberries not only grow larger than blueberries grown without mulch, but they also produce higher yields (Buhler, 2002; Burkhard et al., 2009; Harkins et al., 2013; Krewer et al., 2009; Pritts and Kelly, 2001). Of the organic mulches available, blueberries responded well when acidic materials were used because they satisfied the blueberry's anatomy by sustaining acidic soil conditions while also serving as a durable weed barrier (Fonsah et al., 2008). Due to excellent weed control and increase in soil organic matter provided when decomposing, the use of pine bark mulch has become a standard cultural practice during land preparation for many rabbiteye blueberry producers in the southeastern United States (Fonsah et al., 2008).

Though desirable qualities have established pine bark mulch as a standard for blueberry production, it can be cost-prohibitive (Puls, 1989). Some producers opt to save money by foregoing mulch applications in favor of herbicides, but injury to non-target plants, resistant weed populations, inefficient BMP's, and environmental ramifications can be unintended consequences. In 2005, the total estimated first-year establishment and maintenance cost of growing rabbiteye blueberries in Georgia was $5022.04 per acre (Fonsah et al., 2008); of that total cost, milled pine bark accounted for $630.00 per acre. Therefore, this research sought to explore an alternative organic mulching option for blueberry growers.

Pecan (*Carya illinoinensis* [Wangenh.] K. Koch) shells are natural byproducts of the commercial pecan industry, and while they have occasionally been used in ornamental landscapes as a mulch, available data regarding the past and present waste disposal methodologies for pecan shells revealed that the industry byproduct lacks effectual and economic postharvest application (Anon., 1979; Bansode et al, 2004). In pecan producing states, shell waste may provide producers with an additional organic mulch option, as most of the available literature, albeit minimal, suggests it could be effective (Black et al., 1994; Mexel et al., 2003; Skelly, 2005; Stafne, 2009).

Though untested in this research, pecan shells have relatively high amounts of phenolic compounds (de la Rosa et al., 2011). Tomato plants grown in pecan shell-based container media were found to have a slightly chlorotic appearance and were stunted (Wang and Pokorny, 1989), which could have been caused by phytotoxic compounds present in the shells. Because those compounds could possibly lead to adverse effects, either early into plant establishment or develop late through long-term use, the first experiment in this research investigated the suitability of pecan shells as a mulch in a field trial to determine if first-year weed suppression and transplant survival was comparable to that obtained through pine bark.

Partly due to a shallow root system and the absence of root hairs (Himelrick et al., 1995), blueberry establishment can be challenging. Small, unestablished plants are particularly vulnerable to weed competition and require a moist, organic soil horizon for optimum root development (Braswell et al., 2015). Thus, the objective of the second experiment was to further evaluate pecan shells as a mulch by observing its effects on root growth and root system architecture following the transplanting of two popular commercial cultivars, *V. virgatum* 'Brightwell' and 'Premier.'

Lastly, the necessity to control weeds during orchard establishment and maintenance phases of production has motivated heavy reliance on pre-emergent and post-emergent herbicides, and hand weeding. The objective of the third experiment was to evaluate the effect of pecan shell mulch on weed control by examining the suppression of three problematic weed species that commonly occur in blueberry field production.

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CHAPTER II

Literature Review

Vaccinium

Hailing from the Ericaceae family, the blueberry, a perennial shrub cultivated for its marketable fruit, is a part of the North American *Vaccinium* section *Cyanococcus.* Included in this section are several blueberry species of significant economic and ecologic importance to the United States. Like many Ericaceous plants, blueberries are adapted to acidic soils, with a pH range of 4.5 to 5.5, and perform best when cultivated in well-drained soils with high organic matter content (Braswell et al., 2015). The blueberry species that are commercially valuable to the United States include the lowbush blueberry (*V. angustifolium* Aiton), northern highbush blueberry (*V. corymbosum* L.), rabbiteye blueberry (*V. virgatum* Aiton syn. *V. ashei* Reade), and the southern highbush blueberry (interspecific hybrids containing mostly *Vaccinium corymbosum* L.).

The cultivated selections of the lowbush are derived from a wild blueberry well-adapted to northern climates. Indigenous to the naturally acidic soils ranging from the southeastern foothills to the mid-coastal regions of Maine, the lowbush serves as an integral part of Maine's agricultural and economic prosperity (Hunt et al., 2010). Lowbush is found as far north as New Brunswick and throughout Nova Scotia (Trehane, 2004). The northern highbush blueberry is also adapted to cool climates, but this type is more erect than the lowbush. Not only is the northern highbush blueberry type the most prominently cultivated blueberry in temperate North America, but also throughout the world (Boches et al., 2006). Due to a relatively high winter chilling requirement, 650 to 900 hours, and lower heat tolerance (Himelrick et al., 2002), in North

America the northern highbush blueberry is most commonly found growing from North Carolina to Canada (Trehane, 2004). While, in general, the highbush cannot tolerate persistently warm climates, there have been reports that the northern highbush blueberry may be successfully established in some of the unconventionally cool sites in northern Alabama (Himelrick et al., 2002).

The rabbiteye blueberry is the predominant type of blueberry grown in Alabama. While the rabbiteye species is classified as a highbush type (Fonsah et al., 2008), its distinguishing tolerance of drought, heat stress, and disease sets it apart from the more winter-hardy highbush blueberry (Himelrick et al., 2002). Erect and long-lived, the bushy rabbiteye blueberry is native to southeast Alabama, southern Georgia, and northern Florida (Krewer and NeSmith, 2002), and requires less chilling, 350 to 650 hours, than either the lowbush or northern highbush types (Himelrick et al., 2002). Other important characteristics of the rabbiteye blueberry include its adaptability to upland mineral soils with minimal organic matter, and its tolerance for higher pH soil conditions than true highbush varieties (Puls, 1999).

The southern highbush blueberry is the result of interspecific hybridizations between two to three *Vaccinium* species (Lyrene, 2006). Southern highbush blueberry cultivars were developed largely from the genes of northern highbush cultivars combined with the native, low-chill southern species, *Vaccinium darrowii* Camp (also known as Darrow’s evergreen), and to a lesser extent rabbiteye types (Boches et al., 2006). Despite the rabbiteye blueberry being indigenous to the Deep South, because of the hybridization of *V. corymbosum*, *V. darrowii,* and *V. virgatum,* southern highbush cultivars ripen earlier and have lower chilling requirements than the rabbiteye blueberry. Most southern highbush cultivars require as little as 200 to 300 chill hours, which makes it possible for growers to capitalize on the early market and extend commercial blueberry operations as far south as central Florida (Himelrick et al., 2002). Despite the low-chill requirement and economic incentive for the higher price an early market fruit fetches, the rabbiteye blueberry remains the most significant and successfully cultivated blueberry type in the southeastern United States largely due to its vigor and robust characteristics (Himelrick et al., 2002; Fonsah et al., 2008; Puls, 1999).

Vaccinium virgatum

Since the first successful stand of rabbiteye blueberries was established over a century ago near Whitehouse, FL in 1887 (Krewer and NeSmith, 2002), the commercial culture of blueberries has prosperously expanded in production and profitability throughout Alabama and the southeastern United States. Having a place in fresh and processed sales on local and wholesale markets, the rabbiteye, northern highbush, and southern highbush blueberries are grown in Alabama; though rabbiteye cultivars had the greatest acreage, as its vigor, productiveness, and minimal cultural inputs provide incentive for commercial culture (Fonsah et al., 2008).

The rabbiteye blueberry tends to be more vigorous than other blueberry types, with some cultivars having the potential of reaching 6.1 m in height if left unpruned (Himelrick et al., 2002). In addition to stature, yields vary between the different blueberry types, though climatic and cultivar variations have been reported as more significant influences than genetic differences (Himelrick et al., 2002). The rabbiteye blueberry has been proven capable of producing high yields, with mature plantings having the potential to yield close to 11,200 kg/ha (10,000 lb/acre); however, commercial production levels tend to be significantly lower and average in the range of 5,600 to 9,000 kg/ha (5,000 to 8,000 lb/acre) (Fonsah et al., 2008; Himelrick et al., 2002). Rabbiteye fruit was characterized as sweet with an exceptional shelf life. Flavor persisted after peak ripeness, but berries were considered seedier with a tougher skin than highbush contemporaries (Fonsah et al., 2008; Himelrick et al., 2002). Rabbiteye fruit averaged 1.2–1.5 g per fruit, which is smaller than highbush (1.5–2.5 g). Despite the size differential, the fresh fruit quality of the rabbiteye was comparable to highbush types (Himelrick et al., 2002).

Aside from relatively high yields and drought resistance, growers laude rabbiteye blueberries for their longevity, as some fields were reported to remain productive for over 30 years (Fonsah et al., 2008). Additionally, the rabbiteye blueberry is adaptable to a wide variety of soil types. In general, blueberries grow best on light, sandy soils with ample soil organic matter; however, rabbiteye types were found to prosper in the nutrient-poor mineral soils found throughout the southeastern United States (Braswell, et al., 2015). Good rabbiteye blueberry production was been proven feasible in soils with a pH as high as 6.0, but nutritional problems, most commonly iron deficiency, may occur at this level (Puls, 1999).

Establishment and production considerations

While a blueberry planting is relatively expensive to establish, they are a lucrative commodity and are generally long-lived (Braswell et al., 2015; Fonsah et al., 2008; Puls, 1999). Among the factors that a grower must consider for orchard establishment, proper location is critical in determining success. Loose-textured soils like sands and loams high in organic matter are best suited for rabbiteye blueberry cultivation. Culture on newly cleared land in areas with large amounts of wood ash was not recommended, as those areas generally contain high amounts of ash, salts, and a higher pH (Braswell et al., 2015). Additionally, low-lying sites are not suitable for blueberry production. Cold air settles in depressed areas, such as a valley, and may result in cold injury. If frost damage occurs during bloom or early fruit set, crop yield may be reduced. Furthermore, soil is oftentimes poorly drained in such areas, and blueberries cannot tolerate persistently wet soils. Among the sites suitable for blueberry production, virgin soils that were not farmed are ideal, though pastureland with a pH below 5.5, and relatively low phosphorous accumulation is also acceptable (Braswell et al., 2015; Puls, 1999).

When production is attempted outside a 4.5–5.5 pH range, growth and development of blueberries in all life stages can be hindered. Nutritional problems, such as heavy metal toxicities of manganese and aluminum, generally occur when the soil pH level is maintained below 4.2. Other essential nutrients become unavailable at or below this pH, so in addition to heavy metal toxicity, the potential for nutrient deficiencies of calcium, magnesium, copper, boron, and molybdenum may also occur (Puls, 1999). Conversely, when grown at a pH higher than the recommended range, blueberries commonly exhibit iron deficiency that is observed as chlorosis in the new growth. If a high pH is sustained, stunting and death may occur. A site with an excessively low pH (< 4.2) can be amended with fine limestone approximately one year before planting to raise the pH. Similarly, higher pH (> 6.0) soils can be adjusted to a pH of 5.5 by incorporating finely ground elemental sulfur. Both amendments are slow-acting reactions, and should be soil incorporated approximately six months to one year before planting.

While southern highbush blueberries generally require more frequent fertilization than rabbiteye types, overall blueberries require less nutrients compared to other fruit crops. Over fertilization is deleterious to blueberry growth. The blueberry is a salt sensitive plant that has a predisposition for drought stress. Readily soluble fertilizers in excessive amounts can induce drought conditions, and result in either injury or death (Spiers, 1985). Thus, light doses or split applications of fertilizer should only be applied when the plants are not under drought stress. Other side effects include excessive vegetative growth, and a reduction in fruit quality (Krewer and NeSmith, 2006). Additionally, blueberries differ from most cultivated fruit species in their preference for nitrogen in the ammonium form over nitrate, so not only should the proper amount and placement of fertilizer be carefully monitored, but also the form of fertilizer. Due to the blueberry's sensitivity, slow-release forms of nitrogen either in an ammonium sulfate or sulfur-coated urea formulation is recommended.

As for pollination, partial to complete self-incompatibility is typical in most *Vaccinium* species (Chavez and Lyrene, 2009). Rabbiteye blueberry cultivars are either partially or completely self-incompatible, and require cross-pollination from a different cultivar with an overlapping bloom time for adequate bud, bloom, and fruit development (Himelrick et al., 2002). Pollination requirements for highbush blueberry types was more variable than for rabbiteye types, which is considerably less self-compatible than highbush blueberries (Garvey and Lyrene, 1987). Evidence indicated that the highbush blueberry can be self-compatible (Ehlenfeldt, 2001), partial to completely self-incompatible (Chavez and Lyrene, 2009), parthenocarpic (Ehlenfeldt and Vorsa, 2007), or yield early-maturing, large fruit from cross-pollination (Vander Kloet and Lyrene, 1987). Thus, pollination recommendations for commercial highbush blueberry plantings should be based on cultivar-specific requirements.

Due to the blueberry's bell-shaped flowers, pollen is frequently prevented from falling onto a receptive stigma, even in cultivars that are self-fertile, making adequate pollination difficult (Yarbrough, 2006). Additionally, blueberry pollen is sticky and heavy, making pollen transport via wind variable and unreliable. Hence, for a blueberry plant to set fruit, its flowers much be insect pollinated, which is predominantly done by bees (MacKenzie, 1997). Wild bees are often present in sufficient numbers to assure cross-pollination in small plantings, but honey bees should be provided for large plantings and in areas with sparse bee populations (Spiers, 1985). Depending on the cultivar, in addition to increased fruit set, cross-pollination may also result in increased berry size, seed content, and earlier ripening (MacKenzie, 1997).

Blueberry root growth and structure

A vigorous, unrestricted root system is essential for a plant's survival, yet when compared to the knowledge pertaining to the above-ground portion of the blueberry, relatively little is known about root system growth and development. Healthy root systems increase the surface area available for water and nutrient acquisition while also providing anchorage and storage (Jackson et al., 2005), thus understanding how a root system grows and develops can assist a grower in achieving production success. Factors such as temperature, season, and shoot growth have been found to influence root growth greatly in a number of fruit-bearing species (Abbot and Gough, 1987; Atkinson, 1973; Bhar et al., 1970); however, studies focused on the root growth of bush fruit and cultivated blueberry were relatively few (Gough, 1980; Patten et al., 1988; Spiers, 1998).

New roots allow a blueberry plant to amass water and nutrients, and exploit spatial resources in an orchard or container substrate, which is critical in transplant survival (Wright and Wright, 2004). Additionally, the duration of time between blueberry transplant and subsequent new root initiation directly influences the growth of a newly established planting. Blueberries have a fine, fibrous root system that is concentrated in the upper portions of the soil profile. Shallow rootedness can make young plants susceptible to drought, high soil temperatures, and weed competition during the summer growing season. The rabbiteye blueberry's root system was reported to penetrate more easily and deeply than the highbush (Himelrick et al., 2002), but root distribution is nonetheless shallow with roots rarely found growing deeper than 40 cm (16 in) (Sánchez and Demchak, 2003). The majority of roots develop within the top 20–30 cm (8–12 in) in the soil, of which approximately 90 % are located within the blueberry canopy's dripline. Thus, establishing a new planting in a site with heavy, compactible clay is not conducive to the natural blueberry root anatomy so is not advised.

In addition to a shallow, fibrous root system, blueberries are devoid of root hairs (Eck, 1988), which can make these plants more susceptible to drought and temperature extremes (Lyrene, 1997); however, when grown in soils with ample moisture (Spiers et al., 1985) and lower temperature in the summer (Spiers, 1995), mortality during establishment is reduced, and the productivity of a planting increased. Blueberries thrive in acidic soils, but nutrient availability at a highly acidic pH may be limited, making the acquisition of nutrients challenging. To compensate, like many Ericaceous plants, blueberries benefit from symbionts known as ericoid endomycorrhizal fungi (Sánchez and Demchak, 2003). The ericoid mycorrhizal-inhabited root is characterized by reduced vascular and cortical tissues, absence of root hairs, and the presence of swollen epidermal cells (Read, 1996). Often referred to as 'hair roots' (Read, 1996), the delicate symbiont-inhabited roots form a dense root system concentrated towards the surface of the soil profile.

When present, the fungi may influence total plant growth, as they facilitate the uptake of many soil nutrients, particularly nitrogen and phosphorous (Read, 1996). In exchange, the fungi use carbohydrates from the plant for nourishment. For the symbiosis to perform optimally, blueberries require a friable soil high in organic matter. These factors are important to consider when applying management practices that may impact blueberry growth and establishment, as research indicates that plants infected with mycorrhizae produce denser canopies, and have lower nitrogen requirements from added fertilizers (Yang et al., 2002). The amount of infected roots and the effect of the mycorrhizae are dependent on a range of factors, including, but not limited to soil type, pH, both quality and content of organic matter, and soil moisture (Yang et al., 2002). Additionally, Ericoid fungi survival was jeopardized in operations that frequently used inorganic fertilizers and cultivation (Sánchez and Demchak, 2003). Supplemental irrigation was recommended to maximize yields, as the shallow-rooted nature of the blueberry root system made it vulnerable to moisture fluctuations. Thus, intensive management practices (or the lack thereof) can compromise the symbionts ability to siphon water and nutrients, especially those that affect the soil chemically and physically.

Impact of weeds and herbicides in blueberry culture

Efforts to vanquish competing vegetation in agricultural systems have been a timeless battle. Despite the development of herbicides and integrated pest management (IPM) systems, weeds remain a persistent threat. One postulation for the seemingly immortal rendering of weed pressure on farming systems was offered by Buhler (2002), who asserted that the development of effective IPM programs for weeds has been relatively sluggish when compared to the development of other IPM disciplines. NeSmith and Krewer (1995) had similar observations concerning the expansion of the rabbiteye blueberry industry in the southeastern U.S, detailing that among the many uncertainties accompanying blueberry orchard establishment, one of the most detrimental was undesirable vegetation and its associated effects during the first few years of establishment. Nearly a decade later, a survey was conducted concerning commercial blueberry production in North America wherein respondents disclosed that weed problems were cited in nearly all production areas (Strik, 2006). Considering weeds are a major pest in many agricultural systems, growers should not rely on a single weed control tactic, but an integrated management program designed not only to eliminate existing populations, but also to reduce future weed germination for optimal control.

Proper weed management is critical for good production in many small fruit and berry crops (Krewer et al., 2009; Pritts and Kelly, 2001). Blueberry plants that are not fully established are most susceptible to weed competition for water, nutrients, sunlight, and spatial resources (NeSmith and Krewer, 1995), with weed control being most crucial and challenging during an orchard's first two years of establishment (Braswell et al., 2015). In addition to stunted growth and plant mortality, weeds decrease harvesting efficiency and interfere with general orchard maintenance. Weeds also have the potential to reduce an orchard's aesthetic appeal, which can be particularly damaging to Pick-Your-Own (PYO) operations that interact directly with clientele, and depend on positive consumer perceptions and experiences. In many commercial operations, growers use herbicides to manage vegetation in their cropping systems, with some of the more commonly used including, but not limited to simazine, sethoxydim, glyphosate, hexazinone, and terbacil (Burkhard et al., 2009). However, some herbicides, largely those that are non-selective, can cause non-target injury, and are restricted from use in certified organic production systems, making weed control in organic operations even more challenging.

Among the most prominently used herbicides is glyphosate, a nonselective, post-emergent herbicide that readily controls annual and perennial weeds. Aside from its trade name, Roundup®, glyphosate has many generic forms, all of which are downwardly mobile in the plant and use amino acid inhibition through targeting the *shikimic* acid pathway as their mode of action (Armstrong, 2014). Its use is limited to contact foliar application, as its formulation is inactive within the soil profile, instead depending on translocation via absorption through leafy or woody tissue to be effective. Accordingly, non-target injury is minimal if drift is avoided on above-ground tissues, particularly new growth. Fall applications require extreme care during application, because glyphosate can be taken up by the plant and stored within bark, stems, and roots over the course of dormancy, thus once the plant resumes growth in spring, injury in the form of stunting, and possible plant death may be observed (Longstroth, 2011).

Glyphosate is a relatively slow-acting material, and injury symptomology varies depending on the dose the plant receives. Especially bad cases involve extreme stunting of growing points (Longstroth, 2011). The symptomology ranges from the degree that there are only “tufts” of small leaves instead of new shoots, to milder cases that result in shoots with small, narrow leaves that appear willow-like in form. Shoots showing the full range of glyphosate injury have small tufts of foliage, stunted shoots with narrow leaves, excessive branching, as well as some normal-appearing shoots with narrow, willow-like leaves. Herbicide drift injury can be relatively easy to diagnose if there is only one branch affected on a bush or if surrounding bushes appear healthy. Depending on the extent of injury, blueberry canes may either recover and grow out of the symptoms or be irreversibly damaged and must be removed. Young plants are particularly vulnerable to injury and may not survive.

Aside from non-target plant injury, another potential consequence of chemical weed control is resistant species. While there are resistant weed species in other herbicide families, the extensive and repeated use of glyphosate products without the use of integrated weed management practices has increased the selection of resistant species. Though, the total number of glyphosate-resistant weed species is relatively low, the number of species is nonetheless increasing. A weed’s potential for developing glyphosate resistance is driven by weed biology, the intensity of glyphosate use, and the rate at which glyphosate is applied (Boerboom and Owen, 2006). Growers can address and avoid some of the negative effects glyphosate-resistant weed species have on their farming system by adopting Best Management Practices (BMP’s) that limit the use of glyphosate and products with a similar mode of action (MOA). Thus, by adding diversity to a weed control program, the probability of herbicide-resistance developing on a given operation may decrease. Application of the chemical at the right rate, stage of growth, and time of year may also increase the level of weed control.

As weed management continues to develop, there remains the overarching need to understand the essential elements of how the combination of production practices, soils, and environmental conditions coalesce to produce weed infestations in an agroecosystem. Two driving influences that impede the effectiveness of modern control practices include the development of herbicide-resistant weeds and the inherently complex nature of weed populations (Buhler, 2002). Though the adoption of herbicide-based weed management systems has allowed cropping systems to expand in number and size, heavy reliance on chemical control has created an environmental paradigm that favors the development of herbicide-resistance, population shifts, and off-site movement of herbicides (Buhler, 2002). Thus, it is evident that no one mode of weed control will consistently provide complete eradication due to the dynamic nature of weed populations. Control tactics should be viewed as a process that approaches weed control in a comprehensive fashion that is both economically and environmentally viable.

Alternative means of weed control

Many weeds are controlled with herbicides in commercial fruit production, but herbicide applications are sometimes not a viable option due to expense, plant sensitivity, pre-harvest intervals, or certified organic grower production standards (Bond and Grundy, 2001). Undesirable vegetation in blueberry orchards can be eliminated by mechanical means, such as tillage, but cultivation can damage the delicate, shallow root systems of blueberries when done too closely to the plant (Himelrick et al., 2002; Sánchez and Demchak, 2003). Cultivation may also present the grower with other types of challenges, including nitrate leaching and damage to soil structure, (Bond and Grundy, 2001). Perforated landscape fabric, or weed mat, was approved by the USDA for weed control in organic farming systems (Harkins et al. 2013), and was used with relative success in blueberry fields (Julian et al., 2012). Weed control was also accomplished by utilizing crop rotation, cover cropping, allelopathy, flame weeders, and biological control (Bond and Grundy, 2001). Aside from decreasing the instance of disease compared with overhead irrigation, the use of drip irrigation may also help reduce weed populations, as unlike overhead sprinkler systems, drip irrigation delivers water slowly in a small, fixed area over a plant's root system. This more precise application has the potential to decrease weed germination, which provides additional incentive for organic growers to choose drip irrigation in combination with weed mat for weed management (Harkins et al., 2013).

Another cultural weed control alternative shown to be effective is thickly applied organic mulches (Burkhard et al., 2009; Himelrick et al., 2002). A mulch constitutes any physical material applied to the soil surface that protects or improves the covered area, and is commonly used around plants with the intent of modifying the immediate soil environment to enhance growth (Black et al., 1994). With increasing interest in soil conservation and intensified efforts to exercise environmental stewardship, many growers are already employing BMPs that can reduce their operation's chemical footprints, (Merwin et al., 1995; Bond and Grundy, 2001), and because of these trends, a renewed interest in mulch, a cultural practice that was more heavily relied upon for weed management prior to the development of herbicides, is emerging.

For growers to consider mulch a worthwhile investment there are some stipulations that must be met, with some primary criteria being ease of acquisition, cost-efficiency, and consumer acceptance (Richardson et al., 2008). Mulching materials are derived from either organic or inorganic materials. Commonly used organic mulches include different types of bark, wood chips, pine needles, grass clippings, straw, sawdust, and other similar materials. Plant residues from preceding crops, like a “cover” or “smother” crop planted with the intention of serving as a weed suppressor, may also be used as mulch (Bond and Grundy, 2001). Some examples of inorganic mulches are polyethylene film, plastic mulches, gravel, or even recycled rubber products like old tires. Organic and inorganic waste products have been a point of interest in mulch research for many years. Products that would normally be sent to landfills, such as tires and has been evaluated; however, the effectiveness of tires as a weed barrier was lost after about two months (Calkins et al., 1996). Recycled waste products, such as tires and newspapers, while showing some effectiveness were not ideal means of control, and were generally limited in availability. They also had a relatively low level of consumer acceptance.

Among mulches with high consumer backing are tree-derived mulches, with some of the most popular being pine bark, cedar, cypress, and pine needles. Bark mulches are especially popular in homeowner and commercial markets, as in addition to their aesthetic appeal, tree-derived mulches have well-documented positive effects in weed suppression, with pine-bark being one of the most effective. Much of the weed suppression success of pine bark was attributed to its low fertility, large particle size, and hydrophobic properties (Richardson et al., 2008). In the eastern United States, pine bark is widely used in horticulture, and frequently accounts for 75-100% of a container’s volume in nursery and greenhouse substrates (Lu et al., 2006). Milled pine bark mulch also serves as a primary component in blueberry orchard establishment and maintenance (Fonsah et al., 2008).

Being a natural by-product of the forestry industry, bark is obtained when tree trunks are peeled. In the advent of bark utilization in the horticulture industry, the economic value of bark was considered far less than that of the timber itself, and was treated as an incommodious product that was often either given away free or at a negligible price. However, shortly after the economy began to recover after World War II, the forestry industry began to view bark as a marketable resource, and developed a profitable product line known as the "horticulture bark industry" (Lu et al. 2006). Since then, bark has been considered a valuable and consistently used resource in agriculture, though there is concern over the continued availability of bark for horticultural industries in the future (Jackson et al., 2005). Since the 1980s more than 95% of the United States' bark supply has been utilized, namely in the industrial fuel sector, which consumes approximately 83% of softwood bark, and 66-71% of hardwood bark (Lu et al., 2006). Meanwhile, the market's share for horticultural use (miscellaneous categorization) was estimated at about 15% of softwood and 30% of the hardwood bark supply (Lu et al., 2006). With increasing demand for bark as an energy source and a growing horticulture industry, the total amount and share of bark allocated to the horticulture market was estimated to decrease in coming years.

Organic mulches and pine bark in blueberry culture

Blueberry plants are shallow-rooted and perform best when planted in soils with high organic matter content. Many growers in the southeastern United States do not have these types of soils, and supplement their mineral soils with organic matter. One of the ways growers add organic matter is by mulching (Clark and Moore, 1991), which has been proven to reduce moisture stress in rabbiteye blueberry production (Spiers, 1986). In addition to organic matter supplementation, the use of mulches can also potentially reduce labor cost associated with hand-weeding, and lessen some of the negative environmental impacts associated with conventional chemical control tactics (Bond and Grundy, 2001). In many studies, the application of surface mulch has successfully improve production in blueberry systems via improved weed control, soil moisture, and plant growth (Burkhard et al., 2009; Clark and Moore, 1991; Fonsah et al., 2008; Krewer et al., 2009; and Spiers, 1986). Mulched plants have been found to grow larger and produce higher yields than plants grown without mulch by (NeSmith, 2003). Surface mulch also protects the soil from wind and water erosion, and has the potential to increase organic matter within the soil profile as it degrades over time, thereby improving structure and tilth (Black et al., 1994). Organic materials with high cellulose content and, thus a rapid decay rate, should be used with caution, because once nitrogen is applied, shrinkage may occur, which decreases aeration and can adversely affect root growth (Krewer and Ruter, 2009).

In the southeastern United States, mulching preference in blueberry production is primarily centered on pine bark products (Fonsah et al., 2008; Krewer and NeSmith, 2002), namely due to how well pine bark complements the blueberry's growth requirements; however, while milled pine bark shares many characteristics with what Krewer and Ruter (2009) characterize as "good blueberry soil," there are fundamental qualities that growers should understand for optimized production of blueberries. As a mulch, pine bark is attractive, durable, and long lasting in the landscape. Pine bark's longevity is largely due to lignin, an organic substance that is more resistant to decay than predominately cellulose-based mulches, like wheat straw, which is subject to accelerated rates of microbial decomposition when nitrogen is applied. Pine bark's relatively low rate of decomposition translates to an approximate loss of 2.5 cm per year in Georgia (Krewer and Ruter, 2009). Reapplication was recommended every 2 to 3 years, depending on the rate of decay and if plants have exposed roots (Himelrick et al., 2002). However, despite durability in the landscape, the limited nutrient-holding capacity of pine bark, combined with the frequent need to irrigate blueberries grown in pine bark beds, has had a significant effect on nutrient availability (Williamson and Miller, 2009). The impact on nutrition was most significant when a major portion of the root system was located within the pine bark layer rather than in the underlying soil.

Considering that weed emergence is generally inversely related to seed depth, the degree of weed control tends to increase with mulch depth. Thus, a particularly important consideration is the thickness of the mulch layer, as mulches inhibit weed growth by excluding light from the soil surface and serving as a physical barrier that hinders weed seedling emergence (Bond and Grundy, 2001). Though the recommended thickness of the mulch band in a blueberry orchard varies depending on species and region, most sources recommend a minimum of 8 cm (3 in). Braswell et al. (2015) recommended that mulch should be 10–15 cm (4–6 in) deep and cover at least a 1.2 m band centered on the plant row. Similarly, Himelrick et al. (2002) recommended an application of 8–15 cm (3–6 in).

Mulches also have the potential to influence root zone temperature. Two periods of accelerated root growth were observed for the highbush blueberry: the first being in early June, and the second in September (Abbott and Gough, 1987). During those periods of root growth, the soil temperatures were between 14 and 18 °C. Root growth declined when soil temperatures fell below or rose above that range. In a different study, soil temperatures were higher under polyfabric mulch than under pine bark mulch (Norden, 1989). Another important observation was the widespread development of shallow, blueberry feeder roots growing throughout the pine bark mulch and soil interface, reaffirming the blueberry’s propensity to develop a shallow root system. Pine bark mulch slowly adds organic matter to the soil interface as it degrades, creating a rich, moisture retentive layer hospitable to a blueberry’s shallow feeder roots (Clarke and Moore, 1991; Nesmith, 2003; Norden, 1989; Skroch, 1992), enhances beneficial microbial activity within the rhizosphere (Yang et al., 2002), and buffers soil temperature (Spiers, 1985).

Pine bark mulch limitations

Indeed, grower experience and research has proven that pine bark mulch can offer a number of benefits to blueberry production, but it has also shown that there are limitations and potentially negative impacts associated with its utilization. Primary issues include cost (Fonsah et al., 2008; Fonsah et al., 2013), contamination with lime rock and weed seeds, excessively high levels of manganese, piles that have undergone anaerobic respiration, moldy bark, and storage pile fires (Krewer and Ruter, 2009). A fairly common and significant problem for blueberry growers is using pine bark contaminated with lime rock that is frequently used at saw mills. As when pine bark is collected, it is possible that some of the lime will be scooped up and mixed with the pine bark, thus contaminating the bark by raising the pH outside of the desired range for blueberry culture. On occasion, Georgia growers have reported that pine bark mulch is contaminated by soils containing weed seeds; however, lime rock contamination continues to be a more persistent and significant issue in Georgia (Krewer and Ruter, 2009).

Anaerobic respiration may also occur if mycelia is allowed to develop below the pile surface, generally 61–76 cm, and create a “cap” that excludes oxygen (Bilderback, 2000), which is more apt to occur in piles that are stacked above 2.4 m and those that are chronically waterlogged. Plant injury may occur when harmful byproducts, such as phenolic and alkaloid compounds, and acetic acid are produced by this process. Another detrimental effect caused by anaerobic respiration is a severe pH drop that may be as low as 2.0, which has the potential to flush nutrients from the pine bark, causing potential for yet another instance of toxicity (Bilderback, 2000). Conversely, if pine bark is stored in piles that are excessively dry, water-repellant mycelia may begin to develop. Once spread into a mulch layer in the field, the mycelia have the potential to grow rapidly (Krewer and Ruter, 2009). Benefiting from the irrigation intended for newly installed plants, this mold prevents irrigation water from infiltrating through the mulch into the root zone of young plants. Consequently, newly set plants may dry out and die (Krewer and Ruter, 2009). Wetting bark before storing is the best way to avoid this type of fungal issue.

Growers have also reported experiences with high manganese levels accumulating in blueberry plants (Krewer and Ruter, 2009), causing leaves to turn red or yellow and abscise. This problem may occur in farming systems that use pine products as a mulch or soil amendment because pine bark contains manganese that along with iron is more readily available at a lower pH. To avoid high manganese accumulation in plants, growers should monitor manganese levels using tissue analysis, and refrain from using manganese-containing fertilizers and fungicides if manganese levels are excessively high (Krewer and Ruter, 2009). Another issue is fires in pine bark storage piles. This can be a problem when stockpiling finely milled pine bark above 2.4 m, and if temperatures reach over 66 °C (Krewer and Ruter, 2009).

While pine bark serves as an ideal mulch for blueberry production and has historically been readily available to producers, a historical and projected analysis of pine bark supply to the horticulture sector projected decline in availability to and a subsequent rise in price (Lu et al., 2006). Aside from supply, generally the cost of pine bark makes it economic only for growers that have the capital for its continued use, which tends to be in high-value cropping systems or crops, like blueberries, that will benefit from its presence for multiple years. Additionally, the limited nutrient-holding capacity of pine bark, combined with the frequent need to irrigate blueberries grown in pine bark beds, has had a significant effect on nutrient availability (Williamson and Miller, 2009). The impact on nutrition has been most significant when a major portion of the root system is located within the pine bark layer rather than in the underlying soil.

Consequently, developing alternative mulches is paramount for the continued sustainability of the blueberry industry that heavily relies on pine bark (Fonsah et al., 2007; Fonsah et al., 2008; Krewer and Ruter, 2009; NeSmith, 2003).

Pecan production

The economic significance of *Carya illinoinensis* (Wangenh.) C. Koch (pecan) is credited to the edible nuts that the species produces. The pecan is considered one of the most preferred nuts and is an economically important commercial crop in the United States. Pecans contain a high percentage of unsaturated fatty acids, vitamins and minerals (de la Rosa et al., 2011), and are popular in both fresh and processed markets. The pecan’s native range predominantly occupies the southeastern portion of the United States, beginning in Georgia, extending as far west as Texas, and down to northern Mexico, with the species’ northern distribution thinning near Missouri and Indiana (Sparks, 2005). The variance in climate and topography throughout the pecan’s indigenous zone is vast. Because the species is well-adapted to varying climates, it has been a top-performing commercial commodity throughout these zones. Native stands of pecan were found as far north as Iowa (Reid and Hunt, 2000); however, the majority of commercial pecan operations occupy the southeastern sector of the United States, wherein approximately 93% of the country’s total commercial pecan harvest is produced using improved pecan production (National Agricultural Statistics Service, 1999).

The types of pecans found in the United States can be characterized as native or seedling, and improved. Native pecans were developed under natural conditions and seedling pecans were produced from seed (Herrera, 2000). Improved pecans have been developed through selective breeding and grafting to be higher yielding with nuts that have a greater percentage of nut meat. Differences in quality, nut meat percentage, and yield between native and improved pecans has consistently resulted in improved pecans fetching a higher price than the price for native pecans (Herrera, 2000). Regardless of pecan type, when pecan nuts are processed, the nut meat is extracted and the pericarp residues are cast aside. Depending on the cultivar and fruit quality, the shelling process reduces a pecan’s weight by approximately 50–65 %, and its volume is reduced approximately by half. Consequently, shell residue accounts for a considerable amount of the pecan industry’s waste, and because there is currently no established market for these shells, the industry is left in a quandary regarding effective shell disposal methods (Stafne et al., 2009).

The largest utilized pecan crop in the United States was produced in 1981 with an in-shell weight of approximately 154 million kg (340 million lb) (Herrera, 2000). The USDA Noncitrus Fruits and Nuts 2015 Summary reported the utilized pecan production in 2015 was estimated at 115 million kg (254 million lb) (National Agricultural Statistics Service, 2016). From the 2015 utilized harvest, approximately 102 million kg (225 million lb) was derived from improved pecan production that accounted for 89% of the total. While there was a 4% decrease in yield from 2014, the value of the 2015 utilized pecan crop increased 8% to $560 million. Improved production increased 8% from 2014 to a value of $521 million. The price per pound for all pecans, at $2.20, was $0.24 higher than the price per pound received in 2014. The value of the industry is increasing.

Out of the 115 million kg (254 million lb) of utilized pecans in 2015, approximately 96 million kg (212 million lb) were sold shelled, and approximately 19 million kg (42 million lb) were sold in-shell. The nut meat obtained from the 96 million kg (212 million kg) of nuts sold shelled was an estimated 69 million kg (87 million lb) that translated into about 40% nut meat and 60% shell waste. Thus, the utilized pecan harvest of 2015 supplied the United States. with an estimated 57 million kg (125 million lb) of pecan shell byproduct. While the percentage of nut meat produced in 2013 and 2014 was higher than that obtained in 2015, the resulting shell waste for those years was nonetheless significant, 50 million kg (110 million lb) in 2013, and 49 million kg (108 million lb) in 2014, respectively. Combining the past 3 years of utilized pecans sold shelled, approximately 134 million kg (296 million lb) of the harvest was nut meat, and 156 million kg (343 million lb) of the harvest was shell waste.

The value of total utilized pecan production from 2013 to 2015 was an estimated $1.5 billion. The top five states, in order of native pecan production in 2015, were Oklahoma, Texas, Louisiana, Georgia, and Missouri. The top five states, in order of improved pecan production in 2015, were Georgia, New Mexico, Texas, Arizona, and California. When total pecan production is included, Georgia has been the leading producer in the United States for the past 3 years. In 2015, Georgia produced 42 million kg (93 million lb) of pecans, which was valued at $200 million and accounted for approximately 36% of the total utilized production in the United States.

Pecan shell disposal and current utilization

While the value of the pecan industry can be measured from a nut production standpoint, other, less established benefits of the industry exist. The market value of pecan shell waste as a value-added product is difficult to quantify, thus potential income that could be achieved through shell waste sales should be considered incommensurable at this time (Mexal et al., 2003). One illustration that appraised the income that could be derived from the marketing of pecan shells projected that an orchard has the potential to produce 635 kg (1,400 lb) of shells from 1400 kg (3,100 lb) of pecans, which translates to about 27 million kg (59 million lb) of shells per year (Mexel et al., 2003). In 1999, the New Mexico/West Texas pecan industries produced approximately 32 million kg (70 million lb) of in-shell pecans, and at an average shell-out percentage of 55%. It was conjectured that 14 million kg (31 million lb) of shell waste was produced. Thus, based on the production model, the New Mexico/West Texas pecan production region has the potential to yield 14 to 27 million kg (31 to 59 million lb) of shells each growing season.

If the residual shell biomass was marketed as a biofuel for a small power plant, Mexal et al. (2003) conjectured that the value of the shells would be about $20/ton, which could add $280,000 to $520,000 to a grower's annual income. Alternatively, like pine bark in the timber industry, shell waste has the potential to be marketed as a mulch or substrate to the horticulture sector, which has the potential to fetch a higher price than when sourced as a biofuel. Mexal et al. (2003) estimated that if a grower charged $50 m^3 for pecan shell mulch, then, assuming 500 kg/m^3 (1,000 lbs/yd^3), the sales could add $1.4 to $2.6 million to a grower's income. Lastly, the trend in increased production due to the relatively young age of many pecan trees indicates that production volume, and thus shell waste, will continue to increase.

In the 1970s shell waste was predominantly discarded in vacant fields, with dump sites commonly occupying an area of 6 ha (15 acre) and piled 2.4 m (8 ft) high (Anon., 1979). Thirty years later, current pecan shell disposal is not dissimilar from the past, as shells are generally piled either near shelling facilities, or discarded in landfills at the expense of the producers (Stafne et al., 2009). Additionally, approximately 2.7 million kg (6 million lb) of pecan shell waste is annually produced in Louisiana, and while there were instances of them being used as a mulch in ornamental landscapes, shell waste largely remains an untapped byproduct creating a significant waste disposal issue for the state (Bansode et al., 2004).

In Alabama, Catherine Browne, Auburn University Research Assistant IV and Executive Secretary for the Alabama Pecan Growers Association, attested that most Alabama growers do not shell their own pecans (Browne, personal communication). Rather, growers generally sell their harvest to a buyer or an accumulator, who in turn may either crack and shell the pecans or sell to a different party that will crack and shell for them. Shell waste is usually not utilized and is considered a waste byproduct; however, there are some shellers, like Bobby Drinkard at Whaley Pecan Company, Inc., Troy, AL who have found alternative markets for their shells. Drinkard said that while the market for alternative uses varies with changes in economic conditions, there are opportunities for the postharvest marketing of his shells. In one instance, there was a particle board supplier that approached him about buying his production for particle board (oriented strand board). He also has sold to a cement manufacturer for use as boiler fuel, and regularly makes sales to a Certified Public Accountant that uses his shell waste in combination with poultry litter to create a compost.

Dr. Lenny Wells, an Associate Professor and Extension Horticulture Specialist for pecans at the University of Georgia, said that the majority of pecan growers in Georgia deal with shelling the same way as Alabama growers (Wells, personal communication). The bulk of a grower's harvest is sold in-shell to accumulators, most of which ship them directly to China in-shell. Though, like in Alabama, there are some larger growers, like the Merrit Pecan Company in Weston, GA, that may shell and process some of their harvest on their own. Merrit has also been known to utilize some of his shell waste as a mulch around newly planted pecan trees. Dr. Larry Stein, Associate Department Head and Extension Specialist in pecan, fruit, and vegetable production at Texas A&M University, confirmed that the disposal process described in Alabama and Georgia is the same for most of Texas (Stein, personal communication).

Despite the occasional instances of alternative uses, the predominant accounts of waste disposal difficulties demonstrate that the current approach to pecan shell disposal is not dissimilar from the methods that were used in the past. Nearly 90% of pecans grown in the United States are shelled prior to retail, and considering that all remaining pecans will ultimately be shelled, it can be estimated that approximately 50% of a given state's pecan harvest will ultimately become unrecycled waste (Thompson and Grauke, 2003). Thus, disposal of the resulting waste from the shelling process is of major economic importance. Despite this waste management conundrum, little advancement has been made regarding the development of alternative approaches to pecan shell disposal and postharvest marketing. If this biomass could be repurposed in the horticultural sector either as a mulch or substrate amendment, it is possible that pecan shell waste could generate a new market for pecan producers much like pine bark did for the forestry industry in the 1970s. Most of the available literature, albeit minimal, suggests shells could be an effective organic mulch and weed barrier in production systems (Black et al., 1994; Skelly, 2005; Stafne et al., 2009).

Pecan shells as mulch

Ideal mulches are sourced from materials that are abundant, self-sustaining, and efficient in weed suppression. This category includes commercial standards like pine bark, but it may also encompass new, innovative materials. The growing concern regarding pine bark's supply, consistency, and price in the southeastern United States. has encouraged the search for alternative mulches that can be used in production systems (Jackson et al., 2005). If mulches comparable to milled pine bark became available, then blueberry growers may be provided with an alternative option that could decrease costs for weed control. Some of the current applications for pecan shells include mulching, imitation fire logs, glue and soap abrasives, and activated carbon resource (Littlefield et al., 2011). Biomass feedstock that could be converted into energy, fuels, and chemicals is another possible value-added use for pecan shells (Bansode et al., 2004;

Littlefield et al., 2011). Alternative approaches to pecan shell disposal and utilization should be investigated, as pecan shell waste could possibly be harnessed as a valuable renewable resource rather than a costly disposal problem.

In many regions, commercial blueberry production has undergone improvements that have benefited growers. In the southern regions of the United States, the release of improved southern highbush and rabbiteye blueberry cultivars has allowed Florida, Georgia, and North Carolina growers to target the lucrative production window for early markets, net higher yields, and produce fruit of higher quality (Strik, 2006). Yields were enhanced by high density plantings of southern highbush blueberry in pine bark beds, raised beds with irrigation for rabbiteye blueberry plantings in Georgia, and harvest efficiency improved using machine harvesting and pruning technologies. Improved post-harvest handling of fruit has also benefited many southeastern growers over the past decade (Strik, 2006).

Accordingly, southeastern blueberry production has dramatically increased within the past decade. The southeastern blueberry industry has grown to approximately 9,300 ha (23,000 acres) with an estimated market value of $72.8 million (Braswell et al., 2015). As of 2014, Georgia was the leading southeastern blueberry-producing state with over 6,475 ha (16,000 acres) (National Agricultural Statistics Service, 2014). All the southeastern states have increased production in a similar fashion within the last 10 years; however, a primary limiting factor for the sustainability and further expansion of the blueberry industry within the Southeast is the cost of establishment, of which milled pine bark is a substantial component (Fonsah et al., 2007; Fonsah et al., 2008, Puls, 1999). All of these states have prominent pecan industries that produce pecan shells as a waste product. The Oklahoma pecan industry depends primarily on native pecan production, and alternate-bearing tendencies often result in variable annual yields (Wood et al., 2003). Because pecan shell mulch is generated regardless of kernel quality, it has been conjectured that pecan shell waste could potentially provide Oklahoma pecan producers with an additional source of income during alternative bearing years (Wood et al., 2003).

Generally, pine bark has a pH between 4.0 and 5.0, which makes it a well-suited mulch in blueberry production (Krewer and Ruter, 2006). The pecan shell has been described as having an acidic nature due to the presence of phenolic and carboxylic groups (Hernández-Montoya et al., 2011). The acidic composition of pecan shells was also observed in a study that sought to determine the effect of pecan shell mulch on peach (*Prunus persica* L. Batsch) trees (Stafne et al., 2009). Throughout the study the soil pH decreased in the pecan shell mulch treatments. The decrease in pH indicated that pecan shell mulch could possibly maintain the acidic growth requirements of blueberries, as well as other fruit species that require an acidic substrate. Pecan shell mulch may also reduce or eliminate any need to add sulfur to maintain a pH favorable for blueberry production (Stafne et al., 2009).

In addition to an acidic pH, the main elements found in pecan shells were oxygen, carbon, magnesium, potassium, and calcium (Hernández-Montoya et al., 2011). During degradation pecan shell mulch may release these nutrients into the soil profile, which would not only improve soil organic matter content but also provide nutrients favorable for blueberry growth and development. A foliar analysis conducted by Stafne et al. (2009) revealed that pecan shell mulch treatments increased nitrogen, potassium, and zinc content in the foliage during the study’s first year.

Primary factors that influence the desirability of a mulch as a food source for decomposer organisms are carbon and energy sources, nutrient content, and chemicals that may either inhibit or stimulate decomposer activity (Duryea el al., 1999). Pine bark has a low carbohydrate food quality, high lignin concentration, and a low respiration rate, indicating that pine bark decays slowly (Duryea et al., 1999). While the decay rate of pecan shells in a production system, as compared with milled pine bark, is unclear, the principle constituents of the pecan shell are lignin, and acidic phenolic and carboxylic groups (Hernández-Montoya et al., 2011). Thus, pecan shells may not only have a naturally acidic pH, but also decompose more slowly than other organic mulches high in carbohydrates and cellulose. Depending on how quickly pecan shells decompose in the landscape, it may result in reduced costs associated with re-application, but may pose different challenges in the landscape, such as decreased weed suppression and water holding capacity when compared to the alternatives. Stafne et al. (2009) observed that after 1 year, the 5.1 cm (2 in) pecan shell treatment had greater weed density than the 10.2 and 15.2 cm (4 or 6 in) treatments. The increase in weeds was attributed to the breakdown of the pecan mulch at the lowest depth, indicating a thin mulch layer would require reapplication at least every other year to maintain effective weed control. Conversely, the main drawback from the 15.2 (6 in) treatment was soil waterlogging and subsequent tree death, though it was conjectured that tree mortality was likely due to the peach's intolerance of chronically wet soils, and the deep mulch layer coupled with the record rainfall received during the 2007 season.

Shell waste disposal was reported as an issue in other tree nut crops. Applying hazelnut (*Corylus avellana* L.) husk mulch at either low or high residue levels lead to a significant decrease in weed density compared to bare ground (Mennan and Ngouajio, 2012). While the overall results of the study showed that a hazelnut husk mulch helped reduce weed density, in order to maintain a higher level of weed control, it was recommended that mulch be combined with additional weed management practices. There has also been a report of repurposing macadamia (*Macadamia integrifolia* Maiden & Betche) shell waste back into the orchard in the form of husk compost (Porter et al., 2005). The husk compost improved soil health by increasing microbial activity, water holding capacity, pH, soil carbon, and nitrogen content.

Research has been conducted investigating the use of alternative organic materials in horticulture production systems by monitoring above-ground growth responses, but there is also a need to evaluate how these materials impact root growth. Determining the effects of pecan shell mulch on weed management, soil properties, water retention, plant establishment, and root system architecture has provided implications for its suitability within blueberry production systems. If pecan shells could be successfully marketed to the blueberry industry as a viable organic mulch, then growers may be provided with an alternative, acidifying, organic mulch that could have a significant impact on the sustainability of the industry. Likewise, developing a value-added market for an industry byproduct would supply pecan growers with an additional revenue stream that could help offset profit loss during alternate bearing years. Hence, the sustainability of both of these prominent industries would be improved.

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CHAPTER III

The Effects of Pecan Shell Mulch Age and Depth on Weed Control and Rabbiteye Blueberry Establishment

Introduction

Growing concern for pine bark supply, consistency, and price in the southeastern United States has encouraged the search for alternative mulches that can be used in horticulture. Analysis of the historical and projected supply of pine bark to the horticulture sector showed that the market share for horticultural usage is in decline, indicating that demand for alternatives will be pursued in the future (Lu et al., 2006). Other issues with pine bark mulch include cost (Fonsah et al., 2008; Fonsah et al., 2013), contamination with lime rock and weed seeds, excessively high levels of manganese, piles that have undergone anaerobic respiration, moldy bark, and storage pile fires (Krewer and Ruter, 2009). In Florida, limited nutrient-holding capacity of pine bark combined with the frequent need to irrigate blueberries grown in pine bark beds have had a significant effect on nutrient availability (Williamson and Miller, 2009). The impact on nutrition was most significant when a major portion of the root system was located within the pine bark layer rather than in the underlying soil. Developing alternative mulches may contribute to safeguarding the continued sustainability of the blueberry industry, which heavily relies on pine bark (Fonsah et al., 2007; Fonsah et al., 2008; Krewer and Ruter, 2009; NeSmith, 2003).

Throughout the southeastern United States, pecan (*Carya illinoinensis* (Wangenh.) C. Koch) pericarp or shells, are an abundant and widespread byproduct of the commercial pecan industry. If an alternative use for this waste product could be developed, then pecan shells may be given a new purpose as a value-added product for the pecan industry. Since approximately 90% of pecans grown in the United States are generally shelled prior to retail, then considering that all remaining pecans will ultimately be shelled, it can be estimated that approximately 50% of a given pecan-producing state's harvest will ultimately become unrecycled waste each year (Thompson and Grauke, 2003). If this biomass could be repurposed in the horticultural sector either as a mulch (Stafne et al., 2009) or substrate amendment (Wang and Pokorny, 1989), then it is possible that pecan shell waste could generate a new market for pecan producers much like pine bark did for the forestry industry in the 1970s (Lu et al., 2006).

The market value of pecan shell waste as a value-added product is difficult to quantify, thus potential income that could be achieved through shell waste sales should be considered incommensurable (Mexel et al. 2003). Some of the current applications for pecan shells include mulching, imitation fire logs, glue and soap abrasives, and as an activated carbon resource (Littlefield et al., 2011). Biomass feedstock that could be converted into energy, fuels, or chemicals is another possible value-added use for pecan shells (Bansode et al., 2004; Littlefield et al., 2011).

Like pine bark in the timber industry, shell waste has the potential to be marketed as a mulch or substrate to the horticulture sector, which generally fetches a higher price than when sourced as a biofuel (Mexel et al., 2003). Value-added shell sales could be particularly valuable to a pecan grower during alternate bearing years. For example, the commercial Oklahoma pecan industry depends primarily on native pecan production, and the alternate-bearing tendencies of seedling pecans versus cultivated varieties often results in variable annual yields (Wood et al., 2003). Because pecan shell mulch is generated regardless of kernel quality, one may conjecture that pecan shell waste could potentially provide pecan producers with an additional source of income during alternative bearing years.

Reallocating shell waste into a farming system as a mulch has also been explored in other tree nut crops. Porter et al. (2005) repurposed macadamia (*Macadamia integrifolia* Maiden & Betche) shell waste back into the orchard in the form of husk compost. Husk compost improved soil health by increasing microbial activity, organic matter content, water-holding capacity, and pH. Similarly, applying hazelnut (*Corylus avellana* L.) husk mulch at either low or high residue levels led to a decrease in weed density compared to bare ground orchard floors (Mennan and Ngouajio, 2012). While the overall results of the study showed that hazelnut husk mulch reduced weed density, the authors recommended that surface mulch be accompanied by additional weed management practices. Mulches are an effective weed management strategy, but an integrated control program is generally needed for effective and persisting weed control.

Pine bark is the standard mulch recommendation in the southeastern United States commercial blueberry industry; however, due to the fluctuating supply and demand, there is a need to investigate alternative materials that may deliver comparable weed control and plant performance in a field production context. If the horticulture industry could find an alternative, renewable mulch through the utilization of pecan shell byproduct, then not only would the commercial pecan industry be given an opportunity to market a waste product as a value-added resource, but blueberry growers would be given an alternative organic mulching option. In sandy soils, most blueberry roots establish within the mulch and soil interface, where the decomposed mulch meets with the surface of the native soil. This soil type is like that of many blueberry operations across Alabama and Georgia that are located within the upper and lower Coastal Plains where sand-based soil types abound.

The objective of this experiment was to compare the effects of fresh and aged pecan shell mulches to the industry standard, milled pine bark, on weed control, growth, and establishment of ‘Krewer’ rabbiteye blueberry (*Vaccinium virgatum* [Aiton] syn. *V. ashei*) orchard planted on a sandy mineral soil in the upper Coastal Plains of Lee County in Auburn, AL.

Materials and Methods

Site Description

In Feb. 2016, an on-farm planting of ‘Krewer’ rabbiteye blueberries was installed at Randle Farms in Auburn, AL (lat. 32° 31’ N; long. -85° 26’ W USDA hardiness zone 8a). The predominant soil type was Cowarts loamy sand with 6% to 10% slopes and more than 2 m (80 in) to the nearest restrictive feature. The soil had a pH of 5.7 (Auburn University Soil, Forage, and Water Testing Laboratory, Auburn, AL). Rabbiteye blueberries have been grown on the site since the early 1970s.

Site preparation

The pH of the soil was lowered from 5.7 to 5.1 with a soil-incorporated elemental sulfur application (Auburn University Soil, Forage, and Water Testing Laboratory). Weeds were controlled with glyphosate (Razor®Pro; Nufarm Americas Inc., Alsip, IL) and sethoxydim (Poast®; BASF Corporation, Florham Park, NJ). Plant rows were 33.5 m long and 3.7 m apart, and ran east to west. Soil was pre-plant amended with peat moss and aged pine bark, per the production standards recommended by the Alabama Cooperative Extension Service (Himelrick et al., 2002). One-year-old 2.84 L (1 trade gal) ‘Krewer’ and ‘Titan’ rabbiteye blueberry plants (Cornelius Farms, Manor, GA) were used.

Treatment Design

The treatments in each block were three mulches (fresh pecan shells, aged pecan shells, and pine bark mini-nuggets) applied at two mulch depths (7.6 and 15.2 cm [3 and 6 in]), and a no mulch control for a total of 28 experimental units. Each experimental unit had two sub-plots (two

‘Krewer’ plants), and was separated on either side by a ‘Titan’ guard plant. Data were collected for each ‘Krewer’ plant, whereas ‘Titan’ plants served as a buffer between treatments.

Treatment Application

Two different ages of pecan shell waste were evaluated: fresh pecan shells that were less than one-year-old (2015 harvest season), and aged pecan shells that were over one-year-old (2014 harvest season) (Whaley Pecan Company Inc., Troy, AL). The shells were milled, finely textured, and mostly free of residual nut meat. Pine bark mini-nuggets (West Fraser Mills, Opelika, AL) were also selected for a standard cultural practice.

The fresh and aged pecan shell mulches were oven-baked at the Auburn University Paterson Horticulture Greenhouse Complex for 14 days at 105 °C. The fresh and aged pecan shells were then sieved through a series of wire screens [4.75, 2.00, and 1.40 mm (0.19, 0.08, 0.06 in) screens] to determine particle size distribution ratios. The pine bark mulch was likewise oven-baked, and sieved through a series of wire screens [24.5, 12.7, and 6.35 mm (1, 0.5, and 0.25 in) screens] to determine particle size distribution. Particles retained on each sieve were weighed and percentage (by weight) was calculated.

On 1 Mar. 2016, prior to treatment application, all ‘Krewer’ and ‘Titan’ blueberries were measured and headed back to a 30.5 cm (12 in) height (measured from the crown to the main shoot) to establish a uniform initial plant size. Cane counts for each plant were recorded, and counted again after the growing season in Oct. 2016. Mulch treatments were implemented on 4 Mar. 2016. To ensure accurate broadcasting of each mulch treatment, two wooden frames were constructed. For the 7.6 cm (3 in) treatments, a wooden frame with dimensions of 4.57 m × 1.52 m × 7.6 cm (15 ft × 5 ft × 3 in) was used, and for the 15.2 cm (6 in) treatments, a frame with dimensions of 4.57 m × 1.52 m × 15.2 cm (15 ft × 5 ft × 6 in) was used. Each block had a

WatchDog® A-series data logger (Model A150, Spectrum Technologies, Inc., Aurora, IL, USA) installed to measure air temperature.

Data Collection

Plants were drip-irrigated as needed, with the objective of applying 2.5 to 5 cm (1 to 2 in) of water per week (Himelrick et al., 2002; Braswell et al., 2015). Soil moisture content (SMC) was monitored every 7 days on the east and west side of each 'Krewer' blueberry's critical root zone with a ML2X ThetaProbe Soil Moisture Sensor (Delta-T Devices Ltd., Burwell, Cambridge, England) at a depth of 7.6 cm. Before SMC measurement, mulch treatments were gently moved away from the soil surface. From May to Sept. 2016, leaf chlorophyll content were nondestructively measured weekly using a Minolta Chlorophyll Meter Spad-502 (Minolta, Tokyo, Japan). The most recently mature leaves from the middle portion of a shoot were measured. Plant growth was recorded monthly throughout the growing season by generating a plant size index (PSI), which was determined by measuring plant height from the crown to the top of the main shoot, and by taking cross sectional diameters parallel and perpendicular to the row ([height + widest width + width perpendicular to widest width]/3). Foliar samples were collected from each treatment (replications combined) in mid-July. and analyzed by Brookside Laboratories, Inc., New Bremen, OH for nutrient content.

Weed density ratings (WDR) were conducted at treatment application, 4 Mar. 2016, and were continued monthly to Sept. 2016. Each no mulch treatment was mowed after rating. Ratings were based on subjective, visual observations on a 1 to 5 scale that approximated weed coverage within each mulch treatment's subplot area, where 1 = no weeds, 2 = 1% to 24% weed coverage, 3 = 25% to 49% weed coverage, 4 = 50% to 74% weed coverage, and 5 = 75% to 100% weed coverage (Figure 3.1). Because each blueberry was planted with a spacing of 1.52 m with a 1.52 m mulch band (5 ft × 5 ft), each blueberry occupied an area of 2.3 m^2 (25 ft^2). A 0.76 m × 0.76 m (2.5 ft × 2.5 ft) frame with four equal quadrants was constructed to assist with the accuracy of the ratings. The total area the frame occupied was 0.58 m^2 (6.25 ft^2). The frame was used four times (103, 136, 164, 206 DAP [days after planting]) to measure weed density around each 'Krewer' plant (each time the frame was placed in a different quadrat around the plant) until the entire 2.3 m^2 (25 ft^2) area each plant occupied was measured, averaged, and recorded. Once the WDR was recorded for both 'Krewer' plants within each treatment, the ratings were averaged to determine the total weed density for each subplot.

Monthly temperatures were measured from July to September using a Digi-Sense® Type K thermocouple thermometer (Oakton Instruments, Vernon Hills, IL) inserted at the soil-mulch interface where the mulch layer met with the soil surface, and at a 15.2 cm depth below the soil surface. Soil-mulch interface temperature readings were not applicable no mulch plots. Two temperatures were taken for each treatment, and measured within the dripline for each 'Krewer' plant. A visual plant rating (VPR) scale was developed to gauge phytotoxicity and plant health. The rating scale was numbered 1 to 5 with 1 = a plant near death, 2 = a general lack of vigor, 3 = a plant of average vigor, 4 = a plant showing good vigor, and 5 = extremely healthy and vigorous (Figure 3.2). Ratings conducted by two researchers were taken May through Sept. 2016, along with the PSI and WDR.

Statistical Analysis

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). The experimental design was a generalized randomized complete block with four blocks and repeated measures over time. The treatment design was a 2-way factorial of mulch treatment and data recording date. Where residual plots and a significant

COVTEST statement with the HOMOGENEITY option indicated heterogeneous variance among treatments, a RANDOM statement with the GROUP option was used to correct heterogeneity. Differences among mulch treatments for plant size index, soil temperature at 6-inch depth, soil-mulch interface temperature, soil moisture, and SPAD were determined using the simulated method. Comparisons between groups of mulch treatments were estimated. Cane counts were analyzed using the Poisson probability distribution. Visual and weed ratings were analyzed using the multinomial probability distribution, and all mulch treatment comparisons were estimated. Trends over data recording dates were determined using regression models for all responses. All significances were at $\alpha = 0.05$ unless otherwise indicated.

Results

Fresh and aged pecan shell mulches had similar pH to pine bark (Table 3.1). In addition to an acidic pH, aged and fresh pecan shell mulches contained C, Ca, Fe, Mn, and Zn, and other nutrients desirable for crop production. Fresh shells had the highest C percentage, while the aged pecan shells and pine bark were similar. Aged pecan shells and pine bark had comparable moisture percentages, while fresh pecan shells had a lower moisture percentage. Particle size distribution for fresh and aged pecan shells showed that both shell types were finely textured, with size distribution by weight of predominately in the 1.4 to 2.0 mm range (Table 3.2). Size distribution for pine bark by weight was mainly within the 6.35 to 12.7 mm range (Table 3.3).

New cane counts and plant heights showed linear increasing trends over time (Tables 3.4; 3.5). Plants treated with aged pecan shell mulch were taller than plants without mulch, and all other treatments had similar heights (Table 3.5). Plant size index increased linearly over time (Table 3.6). Plants treated with 7.6 cm of pine bark mulch were larger than plants without mulch, while all remaining treatments had similar PSI (Table 3.6).

Only the mulch treatment and days after planting main effects were significant for visual plant ratings (VPR). There was no difference between the two researchers that conducted the ratings. Counts of VPR decreased linearly with increasing days after planting (DAP) indicting that plant vigor decreased over time (Table 3.7). As observed with the PSI measurements, plants treated with 7.6 cm of pine bark mulch appeared more vigorous than plants grown without mulch, though plants in the 15.2 aged pecan shell treatment were similar (Table 3.8). All remaining treatments had comparable VPR ratings. All treatments resulted in plants rated more vigorous than those grown without mulch. Treatment depth, regardless of mulch type, had similar ratings across all mulch treatments.

Based on critical nutrient levels for rabbiteye blueberries (Krewer and NeSmith, 2006), foliar nutrient levels (Table 3.9) for all treatments showed deficiencies in iron and copper. Additionally, plants in the no mulch and 7.6 cm pine bark treatments had phosphorous levels below the recommended range. Nitrogen was deficient in the 15.2 cm aged pecan shell and 15.2 cm pine bark mulch treatments. Leaf SPAD readings were lower in the 7.6 cm aged and no mulch treatments than all remaining treatments, which were similar (Table 3.10).

No mulch had the highest soil temperature and the two pine bark treatments had lower temperatures (Table 3.11). All pecan shell treatments had lower temperatures than no mulch, but higher temperatures than both pine bark treatments. Mulch depth did not affect soil temperature; however, for the soil-mulch interface (Table 3.12), mulch depth influenced temperature in fresh shells and pine bark, as the 15.2 cm fresh shells and pine bark treatments had lower temperatures than the 7.6 cm mulch treatments. Both treatment depths were similarly higher in the aged shell treatments. As observed with soil temperature, the 15.2 cm pine bark treatment had lower soil-mulch interface temperatures than either pecan shell mulch type; however, the 15.2 cm fresh shells was similar to the 7.6 cm pine bark (Table 3.12). There was also difference between shell mulch age. The 15.2 cm fresh pecan shell treatment had a lower temperature than the 15.2 cm aged shell treatment.

Over a 5-mo. period all mulch treatments had a consistently higher SMC than no mulch (Table 3.13). For the first 4 mos., all mulch treatments performed comparably, except no mulch, which consistently had a lower SMC. Data from month 5; however, showed there were some changes within the mulch treatment's SMC. The 15.2 cm aged pecan shell mulch treatment had a higher SMC than the 7.6 cm pine bark, whereas the remaining mulch treatments were similar.

Weed density increased linearly over the duration of the study (Table 3.14). The WDR at the end of the study, 206 DAP, showed that all mulch treatments had lower weed density than no mulch (Table 3.14). Throughout the study, the highest level of weed control was observed in the 15.2 cm treatments, though by 164 and 206 DAP, the 15.2 cm aged shell treatment had increased in weed density, and was comparable all mulch treatments (Table 3.14). Out of the 7.6 cm treatments, the pine bark treatment had a lower WDR 164 DAP, but had a similar WDR to 7.6 fresh and aged shell treatments at the end of the study 206 DAP.

Discussion

Weed density and prominent species

At 206 DAP all mulch treatments had lower WDR than no mulch, which consistently had higher ratings (Table 3.14). By July 2016, the no mulch plots were completely covered with weeds, and the 7.6 cm pine bark, fresh and aged pecan shell mulches showed some weed encroachment, while the 15.2 cm treatments were nearly devoid of weeds. Predominant weed species were similar across treatments and included large crabgrass (*Digitaria sanguinalis* L.), common ragweed (*Ambrosia artemisiifolia* L.), Virginia buttonweed (*Diodia virginiana* L.), wild blackberry (*Rubrus* L.), bahiagrass (*Paspalum notatum* L.), and common bermudagrass (*Cynodon dactylon* (L.) Pers.).

It is hypothesized that in the 2017 growing season, the 7.6 cm treatments will have increased weed coverage, which is consistent with the findings of Stafne et al. (2009), who observed that the 5.1 cm (2 in) pecan shell mulch treatments had increased weed coverage in the study's second year. The increase in weed density was attributed to settling and decomposition of the thin mulch layer. By the study's third year, weed density in the 10.2 and 15.2 cm (4 and 6 in) shell mulch treatments had an increased weed density, indicating that after three growing seasons the deeper shell mulch treatments needed reapplication. A study that evaluated hazelnut (*Corylus avellana* L.) husk mulch as a weed management tactic in hazelnut orchards, concluded that applying mulch at either a low or high depth (5 cm and 10 cm) resulted in decreased weed density when compared with no mulch (Mennan and Ngouajio, 2012); however, a higher level of weed control was observed in the 10 cm application. The findings in these studies are consistent with the conclusions derived in this experiment, and indicate that pecan shell waste could provide fruit producers with an additional organic weed management tool.

Mulch chemical and physical characteristics

In addition to weed control, pecan shell mulch has the advantage of biodegradability, during which the mulch may release nutrients and improve soil organic matter content. Primary factors that influence the suitability of a mulch as a food source for decomposer organisms are carbon, energy sources, nutrient content, and chemicals that may either inhibit or stimulate decomposer activity (Duryea et al., 1999). Due to a low carbohydrate food quality, high lignin concentration, and low respiration rate, pine bark decays slowly in the landscape (Duryea et al., 1999; Krewer and Ruter, 2009; Skroch et al., 1992). In Georgia, pine bark's rate of decomposition translates to an approximate loss of 2.5 cm per year (Krewer and Ruter, 2009). While the decay rate of pecan shells was not determined in this study, the nutrient analysis conducted on the three mulches showed that the fresh and aged pecan shell mulches had similar nutrient content to pine bark (Table 3.1). The similarities in composition between pecan shells and pine bark may indicate that pecan shells have a decomposition rate comparable to pine bark. Depending on how quickly pecan shells decompose in southeastern United States landscapes, there may be a reduction in costs associated with re-application.

Pine bark’s contribution to soil acidification coupled with excellent weed control are the main drivers for the successful adoption of pine bark mulch in southeastern blueberry production (Krewer and Ruter, 2006). The pecan shell was described as a “hard lignocellulosic” material containing approximately 40% lignin with cellulose and hemicellulose as secondary components (Hernández-Montoya et al., 2011). Primary chemical groups in the pecan shell were also determined as acidic due to the concentration of acidic phenolic and carboxylic groups. These findings were consistent with the nutritional analysis conducted on the pecan shells used in this study, as the analysis showed that fresh and aged shells had an acidic pH that was comparable to pine bark. Thus, all three mulches exhibited a pH favorable for blueberry production. Additional studies reinforce the conclusion that pecan shells are naturally acidic. Wang and Pokorny (1989) determined that pecan shells were acidic (pH 4.8) when used as a container substrate component, and Stafne et al., (2009) reported that soil pH beneath the pecan shell mulch treatments decreased throughout the study. The naturally low pH of pecan shells indicates that pecan shell mulch has the potential to work in concert with the growth requirements of plant species that need acidic growing conditions. Pecan shell mulch may also reduce or eliminate any need to add sulfur to maintain a pH favorable for blueberry production (Stafne et al., 2009).

In addition to an acidic pH, the primary nutrients contained in pecan shells were carbon, calcium, iron, manganese, zinc, and other elements (Table 3.1). Wang and Pokorny (1989) observed that soluble salts and water-extractable elements in pecan shells were low, and that the shell's nutrient levels of phosphorous and potassium may contribute to a container plant's nutrition, though the duration of the contribution was undefined. There are differing viewpoints on whether nutrients released into the soil profile by decomposing organic mulches contribute to plant growth. Odneal and Kaps (1990) observed that extractable nutrients from pine bark amended soil did not appear to be taken up by highbush blueberry plants, and that the decomposing pine bark primarily contributed to plant growth through improved soil structure, rather than chemically. Contrarily, Stafne et al. (2009) determined from a plant tissue analysis that pecan shell mulch treatments increased N, K, and Zn content in peach tree foliage during the study's first year. Considering the first two years are the most critical for a newly established blueberry planting (Braswell et al., 2015), added nutrients during the first year may help newly set plants establish into the landscape; however, because the 'Krewer' rabbiteye blueberries used in this study were newly set and suitable leaf tissue limited, only one plant tissue analysis was conducted.

In the landscape, mulch particle size was found to influence the level of weed control (Richardson et al., 2008). In this study, the particle size distribution of fresh and aged pecan shells compared to pine bark was substantial (Figure 3.3). The fresh and aged shell mulches were finely textured whereas the pine bark mulch had a larger particle size. Richardson et al. (2008) observed that due to relatively large particle size, low fertility, and hydrophobic properties, milled pine bark provided an environment unhospitable for weed seed germination. This conclusion was reinforced in this study's weed density evaluation; however, despite the smaller particle size of the shell mulches, there did not appear to be a difference in weed control success, though the 15.2 cm aged shell mulch began to develop slightly more weeds than the 15.2 cm fresh shell and pine bark mulches 164 and 206 DAP (Table 3.14).

Soil moisture and temperature

The application of surface mulch was observed to impact soil moisture (Clark and Moore, 1991; Nesmith, 2003; Skroch, 1992; Spiers, 1986). Aside from weed suppression, the main effect of mulch in this study was most likely due to its effect on soil moisture. The SMC readings over a five-month period (May-September) showed that all mulch treatments consistently had a higher SMC than no mulch (Table 3.13). For the first four months, all mulch treatments had comparable moisture content. Data from month five showed that no mulch remained the treatment with the lowest SMC; however, there were some soil moisture changes across the mulch treatments. During the last month of measurement, the 15.2 cm aged shell mulch treatment had a higher SMC than the 7.6 cm pine bark treatment. The remaining mulch treatments were similar. During September, the Auburn/Opelika area received a total of 1.5 cm (0.59 in) of precipitation, which was less than the average amount of precipitation for that month (9.1 cm [3.6 inch]). It is hypothesized that the moisture percentage and particle size of the mulch treatments was a factor in soil moisture retention during September. While the moisture percentage of the aged pecan shell mulch was comparable to pine bark, it was more than twice as high as the fresh pecan shell mulch. The relatively high moisture percentage of the aged shell mulch combined with its fine particle size may have played a role in preventing evapotranspiration.

In addition to the possibility of nitrogen depletion, an increase in mulch depth may pose a risk to plant health during periods of excessive precipitation. Observations from a study that evaluated pecan shell mulch at varying depths under peach trees revealed that the 15.2 cm (6 in) pecan shell mulch treatment resulted in soil waterlogging and subsequent peach tree death (Stafne et al., 2009). Rather than attributing tree mortality to pecan shells specifically, it was conjectured that tree death was more likely due to the peach root system's intolerance of chronically wet soils and the deep mulch layer coupled with record rainfall during the 2007 season.

Mulches also have the potential to influence root zone temperature (Abbott and Gough, 1987; Norden, 1989; Spiers, 1995). Though data from this study did not show that mulch depth affected soil temperature, it did show that mulched plants had a lower soil temperature than those grown without mulch; mulch depth did have an impact on the soil-mulch interface temperature (Table 3.12). Mulching blueberries was found to promote more uniform root distribution near the surface of the soil profile (Gough, 1980 and Spiers, 1986). In this study, soil-mulch interface temperature measurements showed that the 7.6 cm fresh pecan shell and pine bark treatments had higher soil-mulch interface temperatures than when applied at 15.2 cm. Aged shell temperature was similarly higher at both depths. As with soil temperature, both pine bark treatments had lower soil-mulch interface temperatures than the fresh and aged pecan shell mulch treatments. There was also a difference between shell mulches, as the 15.2 cm fresh shell treatment had a lower soil-mulch interface temperature than the 15.2 cm aged shell treatment. Considering the blueberry's shallow-rooted nature, roots growing within the soil-mulch interface may be more susceptible to drought damage and soil temperature extremes than roots growing deeper into the soil profile. The optimum soil temperature for highbush blueberry root growth was determined to be between 14 °C and 18 °C (Abbott and Gough, 1987), and that blueberry plant growth continues linearly with increasing soil temperature up to 30 °C (Bailey and Jones, 1941), which was consistent with the findings of this study.

Plant growth

The mulch treatments imposed in Mar. 2016 were not in place long enough to drastically influence plant growth during the first year; however, new cane counts and plant height both increased linearly over time. The lower PSI in no mulch was consistent with the findings of NeSmith and Krewer (1995), who reported that vegetation-free areas of 0.6 m^2 and 1.8 m^2 surrounding rabbiteye blueberry bushes resulted in greater growth indices when compared to areas with no weed control. Blueberry plant height, fresh and dry weights, and root weight were also higher for plants grown with mulch than those grown without mulch (Patten et al., 1988). While all treatments in this study, except the 7.6 pine bark treatment, yielded plants with a similar PSI, it is hypothesized that there would have been greater observable differences in plant growth between the mulched and no mulch treatments had the experimental site not suffered from persistent pest pressure by a generalist leaf tier or leafroller, family *Tortricidae*, (Figure 3.4) and the blueberry terminal borer, *Recurvaria* spp. (Figure 3.5).

Injury to the mature blueberry orchards surrounding the experiment site at Randle Farms was superficial; however, by mid-season the injury to the newly set 'Krewer' plants was severe. The blueberry terminal borer injury was observed as a conspicuous dieback of shoot terminals. Though secondary growth somewhat compensated for the tip dieback, plant growth was nonetheless hindered, as the infestation persisted throughout the growing season. At the height of the leafroller infestation, some plants were nearly defoliated. *Bacillus thuringiensis* (Bt) dust was applied at the recommended rate as a control tactic; however, the populations remained high in the surrounding (untreated) blueberry orchards, which provided an opportunity for recurring infestation of the experiment site. Insect damage was uniform across all treatments, thus it was hypothesized that the recurrent apical dieback may have been uniform across all treatments.

Additionally, the VPR may have been influenced by the pest damage, as plant injury worsened as the season progressed. The degree of plant injury corresponds with the negative linear trend observed in VPR counts as the growing season progressed (Table 3.7).

Summary and conclusions

Pecan shell mulch could provide blueberry growers with an organic mulch alternative to pine bark for weed control. As expected, WDR in the no mulch treatment was the highest. The mulch treatments applied at 7.6 cm began to show more weed encroachment toward the end of the growing season, indicating that a thin mulch layer may need to be reapplied frequently. Pecan shell mulch applied at a 15.2 cm depth had a higher soil-mulch interface temperature than pine bark, and though negative ramifications were not observed on plant growth during the first-year evaluation, continued temperature monitoring during the dormant and growing seasons is recommended. SMC was consistently higher in all mulch treatments than the control, indicating that pecan shell mulch’s effect on soil moisture retention is comparable to pine bark mulch. The PSI and VPR evaluated the overall vigor and robustness of the plants (wood and vegetation), but did not reflect precociousness, as these plants were not allowed to produce fruit. In future years, it is recommended that flower bud counts be recorded from the outermost 15.2 cm (6 in) of growth on each shoot during dormancy to document fruiting potential for the following growing season. While the VPR indicated that plants growing in the pine bark treatments and 15.2 cm aged pecan shells were healthier, the PSI showed that while the 7.6 cm pine treatment was larger than no mulch, plant growth across all mulch treatments was similar. Data observed from no mulch; however, was consistent for both the PSI and VPR, which showed that no mulch not only yielded small plants, but also the most poorly rated plants in terms of overall health and vigor.

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Table 3.1. Mulch nutrient analyses mean and standard deviation of fresh pecan shells, aged pecan shells, and milled pine bark mini-nuggets.[z]

Measurement	Unit	Fresh shells[y]	Aged shells[x]	Pine bark[w]
pH	NA	5.03 ± 0.05	4.63 ± 0.01	4.57 ± 0.01
Moisture	%	24.04 ± 0.79	55.45 ± 0.50	59.42 ± 0.83
Ash	%	1.77 ± 0.02	2.28 ± 0.21	0.72 ± 0.06
C	%	38.87 ±0.49	21.95 ± 0.23	21.08 ± 0.44
N	%	0.36 ± 0.02	0.27 ± 0.01	0.20 ± 0.00
P	%	0.01 ± 0.01	0.01 ± 0.01	0.00 ± 0.00
K	%	0.17 ± 0.03	0.00 ± 0.00	0.02 ± 0.01
Ca	%	0.46 ± 0.05	0.31 ± 0.01	0.08 ± 0.00
Mg	%	0.00 ± 0.00	0.00 ± 0.00	0.02 ± 0.00
Al	ppm	55.17 ± 7.46	148.59 ± 25.59	331.73 ± 7.70
B	ppm	5.97 ± 0.97	3.40 ± 0.29	1.97 ± 0.42
Cu	ppm	9.83 ± 0.88	5.98 ± 1.28	3.28 ± 1.07
Fe	ppm	82.16 ± 16.01	109.19 ± 16.85	81.15 ± 5.07
Mn	ppm	42.16 ± 4.07	31.90 ± 2.9	24.79 ± 0.39
Na	ppm	312.08 ± 110.78	140.90 ± 13.78	113.62 ± 39.15
Zn	ppm	5.69 ± 1.26	10.04 ± 4.6	9.88 ± 5.14

[z] Analyses by Auburn University Soil, Forage, and Water Testing Laboratory, Auburn, AL.

[y] Pecan shells obtained from the 2015 harvest, Whaley Pecan Company, Inc., Troy, AL.

[x] Pecan shells obtained from the 2014 harvest, Whaley Pecan Company, Inc., Troy, AL.

[w] Pine bark mini-nuggets obtained from West Fraser Mills, Opelika, AL.

Table 3.2. Particle size distribution of fresh pecan shell and aged pecan shell mulches[z] as determined by screening mulch material through a series of sieves[y].

U.S. standard sieve number	Opening diameter (mm)	Size distribution (% by wt.)	
		Fresh shells	Aged shells
4	4.75	24.3	28.8
10	2.0	47.5	57.2
14	1.4	25.0	18.4
Pan	<1.4	3.2	2.6

[z] Fresh pecan shells and aged pecan shells (Whaley Pecan Company. Inc., and pine bark mini-nuggets were oven-baked for 14 days at 105 °C at Paterson Greenhouse Complex, Auburn University, Auburn, AL.

[y] [4.75, 2.00, and 1.40 mm (0.19, 0.08, 0.06 in)].

Table 3.3. Particle size distribution of milled pine bark mini-nuggets[z] as determined by screening mulch through a series of mesh sieves[y].

		Size distribution (% by wt.)
U.S. standard mesh	Opening diameter[y] (mm)	Milled pine bark mini-nuggets
1 in.	25.4	24.3
1/2 in.	12.7	47.5
1/4 in.	6.35	25.0
Pan	<6.35	3.2

[z] Pine bark mulch (West Fraser Mills, Opelika, AL) was oven-baked for 14 days at 105 °C at Paterson Greenhouse Complex, Auburn University, Auburn, AL.

[y] [24.5, 12.7, and 6.35 mm (1, 0.5, and 0.25 in)].

Table 3.4. Cane counts of *Vaccinium virgatum* ‘Krewer’ over days after planting[y] in the 2016 growing season (May–September)[z].

0	1.6
30	1.6
60	1.6
90	1.6
120	2.1
150	2.3
180	2.3
Sign.[x]	L***

[z] Only the days after planting main effect was significant at $\alpha = 0.05$.

[y] DAP = days after planting on 2/26/2016.

[x] Significant (Sign.) linear (L) trend using orthogonal contrasts at $\alpha = 0.001$ (***).

Table 3.5. Effects of mulch treatments and days after planting on plant height of *Vaccinium virgatum* ‘Krewer’ in the 2016 growing season (May–September)[z].

Treatment	Depth (cm)	Height[y] (cm)	DAP[x]	Height (cm)
Aged shells	7.6	54.1 a[w]	68	50.0
Fresh shells	7.6	50.5 ab	103	51.1
Pine bark	7.6	52.3 ab	130	50.3
Aged shells	15.2	52.3 ab	164	52.3
Fresh shells	15.2	54.9 a	206	53.6
Pine bark	15.2	51.8 ab	Sign.[v]	L**
Control	NA	44.2 b		

[z] Only the mulch and days after planting main effects were significant at $\alpha = 0.05$.

[y] Height determined by measuring plant from the crown to the top of the main shoot.

[x] DAP = days after planting on 2/26/2016.

[w] Least squares means comparisons among mulches (lower case in column) using the simulated method at $\alpha = 0.05$.

[v] Significant (Sign.) linear (L) trend using orthogonal contrasts at $\alpha = 0.01$ (**).

Table 3.6. Effects of mulch treatments and days after planting on plant size index of *Vaccinium virgatum* 'Krewer' in the 2016 growing season (May–September)[z].

Treatment	Depth (cm)	PSI[y] (cm)	DAP[x]	PSI (cm)
Aged shells	7.6	39.6 ab[w]	68	36.8
Fresh shells	7.6	37.3 ab	103	38.1
Pine bark	7.6	40.6 a	130	36.8
Aged shells	15.2	39.4 ab	164	39.1
Fresh shells	15.2	37.8 ab	206	39.1
Pine bark	15.2	39.4 ab	Sign.[v]	L*
Control	NA	31.8 b		

[z] Only the mulch and days after planting main effects were significant at $\alpha = 0.05$.

[y] PSI = ([height + widest width + width perpendicular to widest width]/3).

[x] DAP = days after planting on 2/26/2016.

[w] Least squares means comparisons among mulches (lower case in column) using the simulated method at $\alpha = 0.05$.

[v] Significant (Sign.) linear (L) trend using orthogonal contrasts at $\alpha = 0.05$ (*).

Table 3.7. Effect of days after planting on visual rating counts within each rating category.[z] Ratings were conducted by two researchers[y].

	Rating scale counts[x]				
DAP[w]	1	2	3	4	5
101	2	2	31	39	34
136	2	5	26	50	25
164	2	6	41	49	10
206	3	21	38	38	8
Sign.[v]					L***

[z] Only the mulch and days after planting main effects were significant at α = 0.05.

[y] There was no difference between the two raters.

[x] 1 = near death, 2 = stunted growth and poor vigor, 3 = average vigor, 4 = good health, 5 = extremely healthy and vigorous.

[w] DAP = days after planting on 2/26/2016.

[v] Significant (Sign.) linear (L) trend using orthogonal contrasts at α = 0.001 (***).

Table 3.8. Effects of mulch treatments on visual plant rating counts within each rating category[z]. Ratings were conducted by two researchers[y].

Treatment	Depth (cm)	Rating scale counts[x] 1	2	3	4	5	Sign.
Aged shells	7.6	0[w]	1	24	19	12	bcd[v]
Fresh shells	7.6	0	3	24	30	7	de
Pine bark	7.6	0	0	10	40	14	a
Aged shells	15.2	0	4	12	24	16	ab
Fresh shells	15.2	0	6	17	29	12	bcde
Pine bark	15.2	0	2	18	28	16	abc
Control	NA	9	18	31	6	0	f

[z] Only the mulch and days after planting main effects were significant at α = 0.05.

[y] There was no difference between the two raters.

[x] 1 = near death, 2 = poor vigor, 3 = average vigor, 4 = good vigor, 5 = extremely vigorous.

[w] Reported are counts of ratings for each mulch treatment.

[v] Comparisons among mulches (lower case in column) using estimate statements at α = 0.05.

Table 3.9. Nutrient levels [z] of *Vaccinium virgatum* 'Krewer' plant leaf tissue[y] grown in fresh pecan shells, aged pecan shells, and milled pine bark mulches at two mulch depths.

		Treatment						
		7.6 cm depth			15.2 cm depth			
Nutrient	Unit	Fresh	Aged	Pine	Fresh	Aged	Pine	Control
N	%	1.77	1.73	1.72	1.72	1.55	1.68	1.79
P	%	0.11	0.10	0.09	0.16	0.12	0.11	0.10
K	%	1.1	1.12	0.95	0.90	0.96	0.94	0.80
Ca	%	0.65	0.60	0.55	0.55	0.57	0.65	0.64
Mg	%	0.32	0.30	0.28	0.29	0.31	0.33	0.32
S	%	0.67	0.59	0.54	0.56	0.55	0.71	0.59
Al	ppm	202.0	144.0	126.0	154.0	125.0	167.0	177.0
B	ppm	32.2	29.0	20.2	28.1	31.0	24.9	20.3
Cu	ppm	1.4	0.9	0.7	0.5	1.1	0.8	1.2
Fe	ppm	44.9	36.1	33.8	35.8	32.8	39.9	49.2
Mn	ppm	188.0	184.0	177.0	214.0	214.0	214.0	238.0
Zn	ppm	23.9	27.4	26.8	29.3	34.4	32.4	36.0

[z] Leaf tissue samples were collected in July and analyzed by Brookside Laboratories, Inc., New Bremen, OH.

[y] Recently matured leaf tissue samples were collected for tissue nutrient analysis from each 'Krewer' plant in treatment plots (14 samples per treatment). Because of small plant size, leaf tissue was limited, thus there was no replication of these measurements.

Table 3.10. SPAD readings[z] by treatment following mulch application under *Vaccinium virgatum* ‘Krewer’ rabbiteye blueberries.[y]

Treatment	Depth (cm)	SPAD
Aged shells	7.6	46.5 b[x]
Fresh shells	7.6	49.5 a
Pine bark	7.6	49.6 a
Aged shells	15.2	49.5 a
Fresh shells	15.2	50.9 a
Pine bark	15.2	51.2 a
Control	NA	45.4 b
Sign.[w]		Qu.***

[z] May to Sept. 2016, leaf chlorophyll content were nondestructively measured weekly using a Minolta Chlorophyll Meter Spad-502. The most recently mature leaves from the middle portion of a shoot were measured.

[y] Only the mulch and days after planting main effects were significant at $\alpha = 0.05$

[x] Least squares means comparisons among mulches (lower case in column) using the simulated method at $\alpha = 0.05$.

[w] Significant (Sign.) quartic (Qu) trend using orthogonal contrasts at $\alpha = 0.001$ (***).

Table 3.11. Mulch treatment soil temperature measurements taken from July to Sept. 2016 at a 15.2 cm depth[z].

Treatment	Depth (cm)	Temperature (°C)	DAP[y]	Temperature (°C)
Aged shells	7.6	27.6 b[x]	153	27.7
Fresh shells	7.6	27.6 b	187	28.3
Pine bark	7.6	26.9 c	215	26.3
Aged shells	15.2	27.8 ab	Sign.[w]	Q***
Fresh shells	15.2	27.7 ab		
Pine bark	15.2	26.7 c		
Control	NA	28.2 a		

[z] Only the mulch and days after planting main effects were significant at α = 0.05.

[y] DAP = days after planting on 2/26/2016.

[x] Least squares means comparisons among mulches (lower case in column) using the simulated method at α = 0.05.

[w] Significant (Sign.) linear (Q) trend using orthogonal contrasts at α = 0.001 (***).

Table 3.12. Mulch treatment soil-mulch interface[y] temperature measurements taken from July to Sept. 2016[z].

Treatment	Depth (cm)	Temperature (°C)	DAP[x]	Temperature (°C)
Aged shells	7.6	28.9 a[w]	153	28.6
Fresh shells	7.6	29.1 a	187	29.2
Pine bark	7.6	27.7 b	215	26.9
Aged shells	15.2	28.7 a	Sign.[v]	Q***
Fresh shells	15.2	28.1 b		
Pine bark	15.2	27.0 c		

[z] Measured where the bottom of the mulch layer meets the surface of the soil profile.

[y] Only the mulch and days after planting main effects were significant at $\alpha = 0.05$.

[x] DAP = days after planting on 2/26/2016.

[w] Least squares means comparisons among mulches (lower case in column) using the simulated method at $\alpha = 0.05$.

[v] Significant (Sign.) quadratic (Q) trend using orthogonal contrasts at $\alpha = 0.001$ (***).

Table 3.13. Soil moisture[z] content by treatment following mulch application under *Vaccinium virgatum* ‘Krewer’ rabbiteye blueberries.[y]

		Treatment						
Month	DAP[x]	Aged	Fresh	Pine	Aged	Fresh	Pine	Control
		7.6 cm depth			15.2 cm depth			
1	61-87	13.2 a[w]	13.8 a	12.9 a	13.4 a	14.2 a	14.0 a	5.6 b
2	96-114	17.8 a	17.1 a	17.5 a	18.2 a	18.1 a	18.1 a	13.4 b
3	123-143	17.7 a	17.6 a	17.0 a	17.8 a	17.8 a	17.1 a	13.4 b
4	150-171	19.2 a	17.0 a	17.1 a	18.0 a	18.3 a	17.3 a	13.7 b
5	180-199	16.0 ab	15.7 ab	14.5 b	17.7 a	15.7 ab	15.4 ab	8.8 c
	Sign.	Q***	Q***	Q***	Q***	Q***	Q***	Q***

[z] Soil moisture was measured at a 7.6 cm depth below the mulch layer.

[y] The mulch by days after planting interaction was significant at $\alpha = 0.05$.

[x] DAP = ranges of days after mulch treatments were applied on 3/4/2016.

[w] Least squares means comparisons among mulch treatments (lower case in rows) using the simulated method at $\alpha = 0.05$. ns = not significant.

[v] Significant (Sign.) quadratic (Q) trend using orthogonal contrasts at $\alpha = 0.001$ (***).

Table 3.14. Weed density[z] by treatment following mulch application under *Vaccinium virgatum* ‘Krewer’ rabbiteye blueberries 103–206 DAP[y].

Treatment	Depth (cm)	DAP				Sign.[x]
		103	136	164	206	
Aged shells	7.6	1.0 b[w]	1.0 b	1.0 b	1.0 b	L***
Fresh shells	7.6	1.0 b	1.0 b	1.0 b	1.0 b	L***
Pine bark	7.6	1.0 b	1.0 b	0.0 c	1.0 b	L***
Aged shells	15.2	0.0 c	0.0 c	0.5 bc	0.5 bc	L***
Fresh shells	15.2	0.0 c	0.0 c	0.0 c	0.0 c	NS
Pine bark	15.2	0.0 c	0.0 c	0.0 c	0.0 c	NS
Control	NA	2.0 c	4.0 a	4.0 a	4.0 a	L***

[z] Only the mulch and days after planting main effects were significant at $\alpha = 0.05$.

[y] DAP = days after planting on 2/26/2016.

[x] Significant (Sign.) linear (L) trend using orthogonal contrasts at $\alpha = 0.001$ (***).

[w] Least squares means comparisons among mulches (lower case in column) using the simulated method at $\alpha = 0.05$.

Figure 3.1. Weed density ratings were based on subjective, visual observations on a 1 to 5 scale that approximated weed coverage within each mulch treatment's subplot area: (left to right) 1 = no weeds, 2 = 1-24% weed coverage, 3 = 25-49% weed coverage, 4 = 50-74% weed coverage, and 5 = 75-100% weed coverage. The total area the frame occupied was 0.58 m^2 (6.25 ft^2).

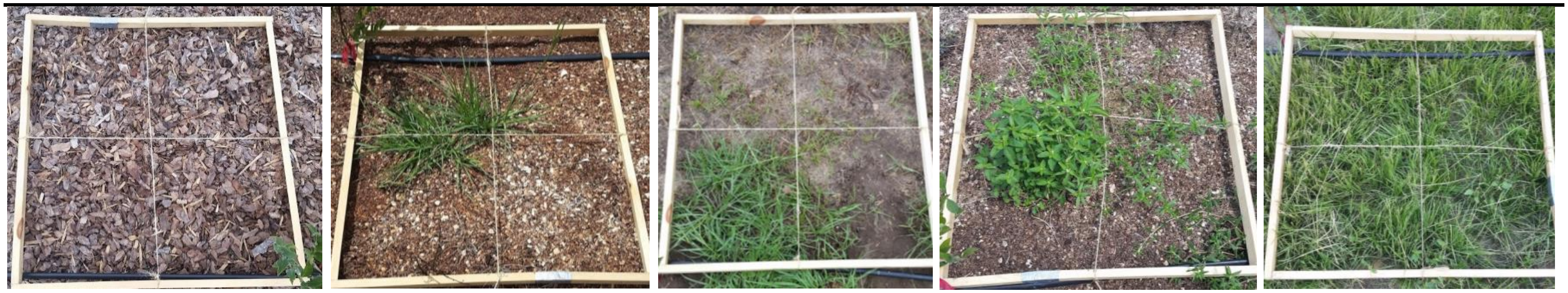

Figure 3.2. Visual plant ratings were based on subjective, visual observations on a 1 to 5 scale that approximated plant vigor within each mulch treatment’s subplot area: (left to right): 1 = near death, 2 = poor vigor, 3 = average vigor, 4 = good vigor, and 5 = extremely vigorous.

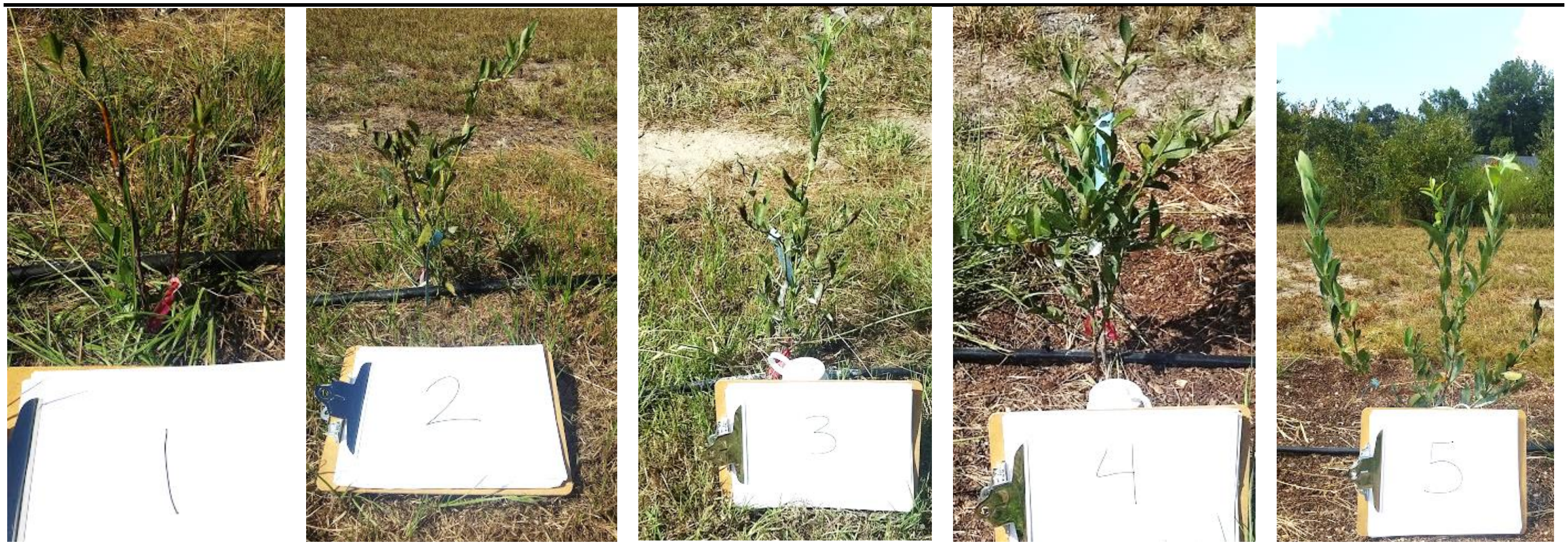

Figure 3.3. Particle size distribution by mulch type.

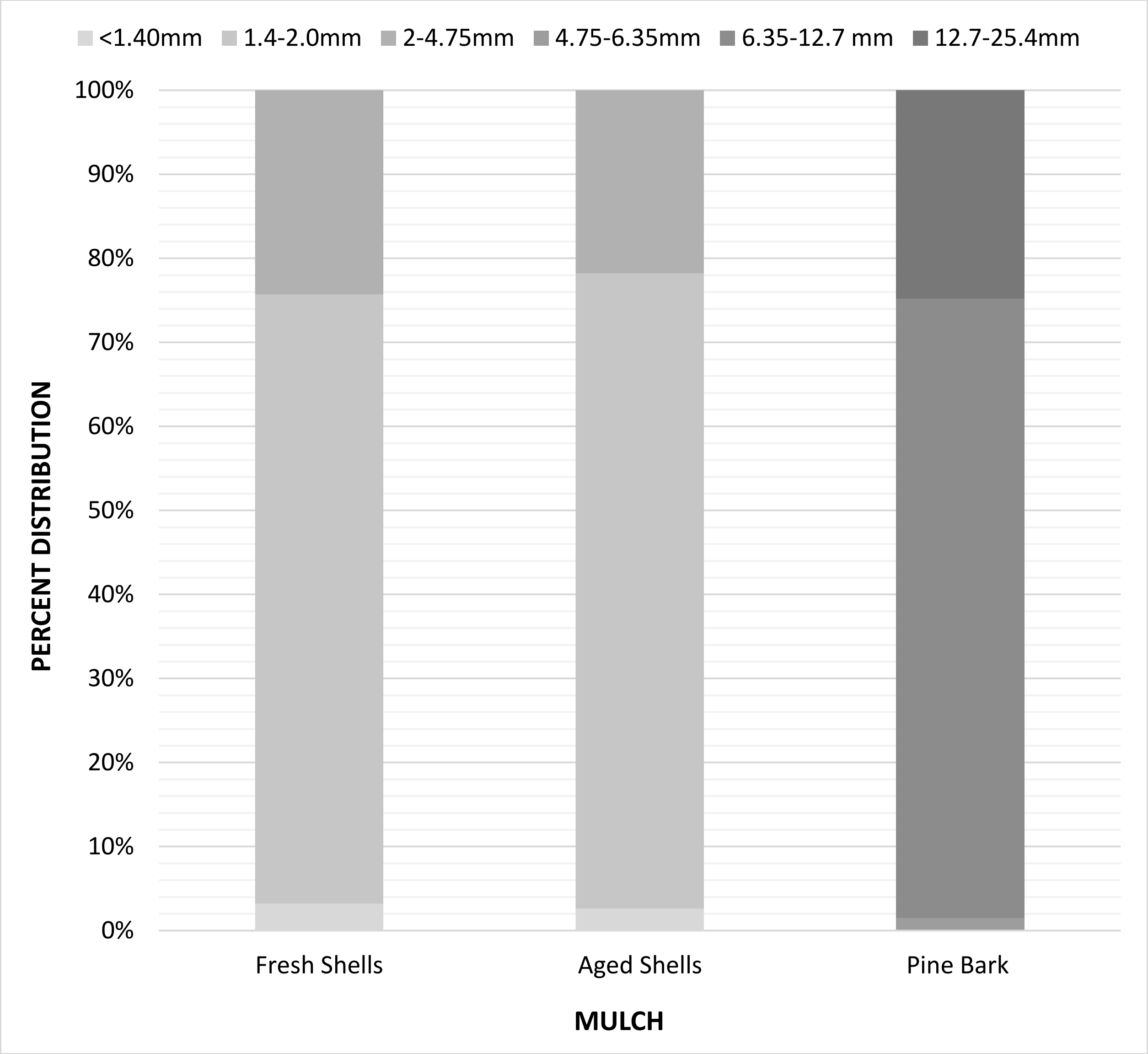

Figure 3.4. Leafroller larvae feeding on *Vaccinium virgatum* ‘Krewer’ rabbityeye blueberry. The species of leafroller was unidentified, but considered a generalist in the family *Tortricidae*.

Figure 3.5. Blueberry terminal borer (*Recurvaria* spp.) injury to *Vaccinium virgatum* ‘Krewer’ rabbiteye blueberry. Injury was observed as a conspicuous dieback of shoot terminals.

CHAPTER IV

Root Distribution of ‘Brightwell’ and ‘Premier’ Rabbiteye Blueberries as Influenced by Pecan Shell Mulch

Introduction

The success of a blueberry planting is linked to site physical, chemical, and meteorological conditions. Though rabbiteye blueberries (*Vaccinium virgatum* Aiton syn. *V. ashei* Reade) were found to prosper in the nutrient-poor mineral soils found throughout the southeastern United States, they grew best in sands and loams high in organic matter (Braswell et al., 2015). Compared with taproot systems, plant species with fibrous roots are often considered less problematic to transplant; however, this generalization has exceptions. While the native ericaceous species mountain laurel (*Kalmia latifolia* L.) produces a fibrous root system, it periodically does not survive transplanting into the landscape (Wright et al., 2004). Similarly, optimal transplant survival of members of the *Vaccinium* genus, such as the blueberry, can also be challenging. By nature, blueberries possess a fibrous, shallow root system devoid of root hairs (Eck, 1988), which may predispose them to water stress (Lyrene, 1997).

Generally, plant growth is most commonly limited in transplants due to water stress (Price et al., 2011). Thus, the rapid initiation of new roots (Wright et al., 2004) and resistance to water stress (Hicklenton et al., 2000) were critical factors in the effectiveness of transplanting, making the establishment of a healthy root system in mineral soils with depleted organic matter critical for the survival of newly set blueberry transplants. Despite the influence of roots on plant growth and survival, relatively little is known of their growth patterns under natural conditions (Bhar et al., 1970). Data on root growth and root system architecture are often not collected because most methods are time consuming, destructive, or expensive (Wright and Wright, 2004).

Temperature, shoot growth, and seasonality were factors found to influence root growth in raspberry plants (*Rubrus idaeus* L.) (Atkinson, 1973) and plum (*Prunus salicina* Lindl.) (Bhar et al., 1970); however, studies focused on the nature of bush fruit root systems were scarce. This is particularly true for the cultivated blueberry. While it is known that the blueberry root system is shallow and fibrous (Austin, 1982; Braswell et al., 2015; Himelrick et al., 2002; Spiers, 1995), and there are many documented benefits of blueberries responding positively to surface mulch (Burkhard et al., 2009; Clark and Moore, 1991; Fonsah et al., 2008; Julian et al., 2012; NeSmith, 2003); relatively few studies have strictly focused on investigating blueberry root system distribution and architecture.

Results of several studies supported the use of organic materials in blueberry production. Burkhard et al. (2009) reported that incorporation of pine bark, peat, and sawdust were commonly used as soil amendments in conventional highbush blueberry culture. Such amendments were found to promote uniform root development (Spiers, 1986), and to enhance soil aeration and water-holding capacity (Haynes and Swift, 1986). In addition to organic soil amendments, thickly applied organic surface mulches (7–12 cm) after planting are also commonly used (Burkhard et al, 2009), as they are ideal for regulating soil temperature (Spiers, 1995) and moisture extremes (Spiers, 1986). Mulches were also found to improve blueberry transplant root development (Hicklenton et al., 2000), a key factor in transplant success.

The root system of highbush blueberry predominantly composed of fine roots that were concentrated at a 12–25 cm depth within the drip line (Gough, 1980). While the rabbiteye blueberry's root system was observed penetrating more easily and deeply into the soil profile than the highbush blueberry (Himelrick et al., 2002), the rabbiteye blueberry root distribution is nonetheless shallow with roots rarely growing deeper than 40 cm (16 in) (Sánchez and Demchak, 2003). Most roots developed within the top 20–30 cm (8 to 12 in) in the soil, of which approximately 90% were located within the blueberry canopy's dripline (Gough, 1980; Sánchez and Demchak, 2003). Patten et al. (1988) and Spiers (1998) also observed a shallow root system restricted predominantly to the top 40 cm of the soil profile. The growth of mature, mulched highbush blueberry plants was found to have a synergistic relationship between roots and shoots (Abbott and Gough, 1987). The growth rate of white unsuberized roots were most limited by soil temperatures outside the range of 14–18 °C, and root and shoot growth decreased during fruit maturation and harvest.

When plants are transplanted into the landscape, uninterrupted plant growth is dependent on the formation of new roots outside of the original root ball (Wright et al., 2004). Thus, understanding root system growth, development, and architecture are important factors that influence transplant survival and production success (Wright and Wright, 2004). Observation and measurement of roots as they grow is useful in determining root growth preferences, as is studying the location and depth of root formation (Jackson, et al., 2005). Several instruments were used in the past to study root growth, including the rhizotron (Bohm, 1979; Huck and Taylor, 1982), portable rhizotron (Pan et al., 1998), and the rhizobox (Wenzel et al., 2001); however, these instruments are relatively expensive and limited in their ability to provide information. Other methods of measuring root growth were generally restricted to observation via subjective visual rating scales or by dry weight analysis, with both methods being destructive (Jackson et al., 2005).

The Horhizotron^{TM}, a horizontal root growth measurement instrument developed cooperatively between Auburn University and Virginia Tech, is newer and relatively inexpensive. Wright and Wright (2004) reported that all materials used in the design were available at building supply stores, and the cost was less than $50.00 per unit. A key factor that makes the Horhizotron^{TM} desirable is that it provides a simple, non-destructive means of measuring root growth under a variety of rhizosphere conditions. Unlike other container-type rhizotrons where roots are not visible until they reach the edge of the container, the Horhizotron^{TM} is constructed of glass, which allows observation of the rate and direction of root growth into the surrounding landscape (Wright and Wright, 2004). The design also allows the effect of multiple substrates to be evaluated on an individual plant simultaneously.

Pine bark is one of the most commonly used mulches and substrate amendments in the horticulture industry; however, concern regarding cost, supply, and consistency has motivated the search for suitable alternatives in crop production (Jackson et al., 2005). From 2013 to 2015, approximately 156 million kg (343 million lb) of the *Carya illinoinensis* (Wangenh.) C. Koch (pecan) harvest was shell waste (National Agricultural Statistics Service, 2016). Most production is in the southern United States, with Georgia being the leading producer for the past 3 years. In 2015, Georgia produced 42 million kg (93 million lb) of pecans. The harvest was valued at $200 million and accounted for approximately 36% of the total utilized production in the United States (National Agricultural Statistics Service, 2016). Because shell waste is a natural byproduct of the commercial pecan industry, the supply is annually renewed. Shell waste may be used in the horticulture industry either as a mulch or container substrate component. While phytotoxic substances and inadequate available water in shell-based substrates were suspected of stunting growth of tomato plants (*Lycopersicon esultentum* Mill. ‘Rutgers’) (Wang and Pokorny, 1989), pecan shells as a mulch under peach trees (*Prunus persica* L. ‘Loring’) were found to provide acceptable weed suppression (Stafne et al., 2009). Thus, the objective of this research was to investigate the effects of pecan shell mulch on the rabbiteye blueberry root system architecture as compared to the industry standard (milled pine bark), using the Horhizotron^{TM}.

Materials and Methods

Horhizotron^{TM}

The Horhizotron^{TM} is a non-destructive root measurement instrument that allows a container-grown plant to be fitted within four quadrants around a container plant's original root ball (Wright and Wright, 2004). Each quadrant is constructed of two panes of glass that form a wedge-shape. An overhead view of the Horhizotron^{TM} (Figure 4.1) depicts the four quadrants as they extend outward from the original root ball in a star-like configuration. The Horhizotrons^{TM} used in this research had four quadrants constructed from two 3.2 mm (1/8 in) thick glass panes (20.3 × 26.7 cm [8 × 10.5 in]) that were held together on the top and bottom with vinyl j-channels, and sealed with water-proof caulk (Wright and Wright, 2004). Each Horhizotron^{TM} had an aluminum base (0.6 m × 0.6 m × 0.3 cm [2 ft × 2 ft × 0.125 in]) that was attached to a wooden frame (5.1 × 5.1 cm [2 × 2 in]) constructed from treated lumber. Drainage holes were made in the bottom, center of each Horhizotron^{TM} where the root ball sat, and within each quadrant to ensure proper drainage.

To exclude light and protect the root system from temperature extremes, exterior walls were placed around the Horhizotrons^{TM} (Figure 4.2). The walls were comprised of foam insulation board 1.9 cm (3/4 in) with an aluminum foil exterior and plastic interior (Wright and Wright, 2004). Walls were assembled into one unit by connecting them with top and bottom j-channels, and then fastened into place by fitting them into a 2.5 cm (1 in) rim around the perimeter of the aluminum base. Upper lids for each Horhizotron^{TM} were made from two sections of foam insulation board (Figure 4.3) with a portion cut out to expose the substrate surface immediately around the plant stem, which allowed for easy removal of the lids.

Experimental Design

The experiment was arranged in a randomized complete block design. Each Horhizotron^{TM} represented an individual block, and there were six blocks per cultivar. The rabbiteye blueberry cultivars ‘Brightwell’ and ‘Premier’ were evaluated because they are two widely grown cultivars in Alabama and the southeastern United States. There were four treatments distributed randomly among each Horhizotron^{TM} unit’s four quadrants. The treatments consisted of the three mulches used in the field study at Randle Farms, Auburn, AL (lat. 32° 31’ N; long. -85° 26’ W USDA hardiness zone 8a): fresh pecan shells from the 2015 harvest, aged pecan shells from the 2014 harvest, and pine bark mini-nuggets. An unamended 4:1 pine bark:sand substrate treatment was included with the purpose of adding a “no mulch” control.

Treatment Application

On 26 Apr. 2016, six mature 11.4 L (3 gal) container plants each of ‘Brightwell’ and ‘Premier’ rabbiteye blueberry (Petals from the Past, Jemison, AL) were removed from their containers and placed into the center of separate Horhizotrons^{TM} (volume 3.7 L) on a greenhouse bench at the Paterson Greenhouse Complex at Auburn University, Auburn, AL. Roots had established throughout the plant’s original container profile and touched the edge of the substrate-container interface, but were not circling. When placed into the Horhizotrons^{TM}, root balls of all plants were undisturbed and positioned snugly against the inner point of each wedge-shaped quadrant composed of two glass panes (20.3 × 26.67 cm [8 × 10.5 in]) (Wright and Wright, 2004).

Each of the four quadrants surrounding the root ball were then filled with 10 cm (4 in) of a 4:1 pine bark:sand (v/v) substrate amended per cubic yard with 2.3 kg (5 lb) of Peafowl® 25-4-8 (Piedmont Fertilizer Company, Inc., Opelika, AL) and 0.7 kg (1.5 lb) Micromax® (Scotts Co., Marysville, Ohio). No lime was added to the substrate to maintain the acidic soil conditions required by *V. virgatum*. Once each of the four quadrants was filled with the appropriate amount of substrate, each quadrant was gently hand-watered to allow for substrate settling. The remaining space in the Horhizotron™ quadrants was then filled with 7.6 cm (3 in) of one of the randomly assigned four treatments.

Though the technique used to apply the mulch treatments left the plants at-grade in the Horhizotrons™, layering the treatments on top of the substrate was intended to simulate the modified above-soil grade mulching practice used in conventional commercial blueberry operations, wherein the root ball is fully in the soil profile, and the organic mulch layer is applied above-grade. The unamended pine bark:sand substrate (no mulch) control treatment was intended to represent traditional at-grade planting without an organic mulch layer. After planting, each plant's root ball and quadrants were hand-watered as needed with tap water to keep roots moist.

Data Collection

Measuring shoot growth was unnecessary due to the design of the Horhizotron™ (each individual plant grew in all four mulch treatments simultaneously); however, initial size indices of plant canopies ([height + widest width + width perpendicular to widest width]/3) were measured to document a baseline for plant size (Price et al., 2009). As new roots grew out of the original root ball and along the glass panes of each quadrant profile (2 panes per quadrant), the horizontal root lengths (parallel to the base of the Horhizotron™) of the five longest roots visible along each glass pane of a quadrant were measured weekly. A transparent 1 cm × 1 cm grid was placed on the surface of the glass panes on each quadrant to assist with observation and measurement of the five longest roots on either side of a quadrant. Though not actual root lengths, but rather lateral lengths, horizontal root length (HRL) measurements represented lateral root penetration into the substrate and mulch treatments after transplanting (Price et al., 2009). Root depth (RD) measurements represented root penetration vertical to the base of the Horhizotron^{TM} and was also documented using the transparent grid. Roots growing into the substrate layer and the mulch treatment layer were not measured separately.

HRL measurements of ‘Brightwell’ and ‘Premier’ began 45 days after transplanting (DAP), and done once weekly thereafter using the same method. Over the course of the study, root measurements discontinued when roots in one substrate reached the end of the Horhizotron^{TM} quadrant (26 cm). When HRL measurements ceased for *V. virgatum* ‘Brightwell’ on 5 Aug. 2016 (101 DAP) and *V. virgatum* ‘Premier’ on 12 Aug. 2016 (108 DAP), final size indices of the canopies were measured, which was determined by measuring plant height from the crown to the top of the main shoot, and by taking cross sectional diameters parallel and perpendicular to the row ([height + widest width + width perpendicular to widest width]/3). Plants of *V. virgatum* ‘Brightwell’ were removed from Horhizotrons^{TM} for root harvest on 7 Sept. 2016 (132 DAP) and *V. virgatum* ‘Premier’ on 12 Sept. 2016 (137 DAP).

Roots in each quadrant were cut from the original root ball where the substrate and treatment met the root ball. To observe the difference in root growth within the mulch treatments versus the substrate portions of the quadrants, roots that grew in the mulch layers were separated from the roots that grew in the substrate layers. Substrate and treatment root layers were then separately washed and dried for 48 h at 66 °C, and weighed to determine root dry weight (RDW) in substrate and mulch treatment portions separately.

Statistical Analysis

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). Blueberry cultivars were analyzed as separate experiments. Root length and depth were analyzed as a randomized complete blocks design with repeated measures on dates, root number as sub-samples, and Horhizotron^{TM} face was a random variable in the model. Least squares means comparisons among mulches were determined using the simulated method. Linear, quadratic, or cubic trends over dates were determined using qualitative-quantitative model regressions. All significances were at $\alpha = 0.05$ unless otherwise indicated.

Results

'Premier'

HRL for *V. virgatum* 'Premier' increased quadratically in all mulch treatments (Table 4.1; Figure 4.4). At the end of the experiment (108 DAP), HRL in the control was higher than in fresh shells, while HRL in aged shells and pine bark were similar (Table 4.1; Figure 4.4). Root depth (RD) varied cubically, except for the control, which was quadratic (Table 4.2; Figure 4.5). At 108 DAP, the roots in control were more concentrated near the surface of the quadrant profile than in the fresh shells and pine bark, while root distribution within the aged shells were similar (Table 4.2). Root dry weight (RDW) was similar among all quadrant substrate layers, but varied within the mulch (treatment) layers. RDW within the mulch layer was higher in aged shells than pine bark, though fresh shells and the control were similar (Figure 4.6). Differences in RDW within the mulch layer did not impact total root dry weight (mulch layer RDW + substrate layer

RDW), as total RDW was similar across treatments (Figure 4.6). Plants were uniform in size throughout the experiment, with an average initial growth index of 48 cm, and final growth index of 110 cm (data not shown).

'Brightwell'

HRL for *V. virgatum* 'Brightwell' increased quadratically in all treatments but the control, which was cubic (Table 4.1; Figure 4.7). At the end of the experiment (101 DAP), HRL measurements showed roots in control and pine bark had advanced further from the original root ball into the quadrant profile than those of the fresh pecan shell and aged pecan shell mulches (Table 4.1; Fig 4.7). Root depth (RD) increased cubically in all treatments (Table 4.2; Figure 4.5). At 101 DAP, RD measurements showed that roots were concentrated more deeply into the quadrant profile in pine bark and fresh pecan shell mulches than in the aged shells and the control, which had more shallow root growth (Table 4.2; Figure 4.8). Root dry weight (RDW) was similar among all quadrant substrate layers, but differed within the mulch layers. Aged pecan shell mulch had a higher mulch layer RDW than pine bark and fresh shells, though the control was similar to aged and fresh shells (Figure 4.9). Total RDW was impacted by root growth distribution trends, as total RDW was similarly higher in the aged pecan shell and the control, and similarly lower in the fresh pecan shell and pine bark treatments (Figure 4.9). Plants were uniform in size throughout the experiment, with average initial growth index of 47 cm, and final growth index of 113 cm (data not shown).

Discussion

As observed in a previous study using the Horhizotron^{TM}, small spaces between the substrate and glass panes at the end of each quadrant air pruned roots as they grew into them, ceasing growth at that point (Wright et al., 2007). Roots tended to initiate further away from the original root ball towards the quadrant profile's end (26 cm) in the control and pine bark treatments (Figures 4.4; 4.7), which corroborated with previous observations (Wright et al., 2007). Roots may have proliferated into a smaller portion of the quadrant profile, as the pine mulch layer resulted in a lower RDW for both cultivars. This could have allowed carbon allocation to fewer roots so the roots that were present could grow longer. This hypothesis was reinforced by results observed in the pine bark treatments for the mulch layer root dry weight (RDW), as the pine bark treatments had a low mulch layer RDW for both cultivars (Figures 4.6, 4.9); however, an impact on total RDW due to a lower mulch layer RDW was only observed in 'Brightwell.'

At the end of the study, pine bark and fresh pecan shells had deeper RD trends in 'Brightwell,' but was similarly as deep as the aged and fresh pecan shell mulches in 'Premier'. Contrastingly, the quadrants that contained aged pecan shell mulch control generally had a shallower RD in both cultivars. For 'Premier', RD began to separate between treatments at 66 DAP (Figure 4.5). By 73 DAP, trends in RD between each treatment were distinctive, and root growth was maintained at those respective depths for the remainder of the study (Figure 4.5). For 'Brightwell,' RD was differentiated between treatments by 52 DAP (Fig 4.8). Treatments remained at those respective depths throughout the remainder of the experiment; however, the RD trend observed with 'Premier' was more pronounced in 'Brightwell.' Like with 'Premier,' the quadrants that contained the control had a shallow RD but aged was similar, leaving the quadrants that contained pine bark and fresh pecan shells with the deepest roots.

Regarding root density, the RDW in the substrate layer was similar across all treatments, regardless of cultivar. This pattern of root distribution supported previous findings (Haynes and Swift, 1986; Hicklenton et al., 2000) that well-drained substrates composed of organic (bark) and inorganic (sand) are effective in promoting blueberry root growth. Conversely, root growth within the mulch layer varied across not only treatment, but also cultivar. In general, the differences observed between mulch layer RDW for ‘Premier’ were not pronounced. Mulch layer RDW for ‘Premier’ showed that aged pecan shell mulch had a higher RDW than pine bark, but the control and fresh pecan shells performed similarly. While differences in root distribution amongst the mulch layers based on RDW for ‘Premier’ was quantifiable, those differences did not impact total RDW, which was similar across all treatments (Figure 4.6).

One difference observed between cultivars was the variances in root distribution within the mulch layer. Treatment differences between mulch layer RDW were more pronounced for ‘Brightwell’ than those observed in ‘Premier.’ Mulch layer RDW in ‘Brightwell’ was distinctively higher in aged pecan shells than in the fresh pecan shells and pine bark. While mulch layer RDW did not influence a quadrant’s total RDW for ‘Premier,’ those differences did impact total RDW for ‘Brightwell’. The same trends observed in RD and mulch layer RDW for ‘Brightwell’ was reflected in total RDW. Quadrants that contained aged pecan shell mulch and the control had a higher total RDW than quadrants that contained fresh pecan shell and pine bark mulch (Figure 4.9).

When organic mulches were tested as a cultural practice with blueberry transplants, they were found to have a higher water stress tolerance (Hicklenton et al., 2000), and a more even root distribution extending from the plant crown (Spiers, 1986). Another blueberry root distribution study estimated that soil moisture and temperature were major limiting factors in blueberry root growth, and observed that when mulches were used, most blueberry roots were concentrated under the mulched areas where soil moisture was prevalent and soil temperature reduced (Spiers, 1998). These findings were consistent with the results derived from the RDW of the substrate layers (below all mulch treatments), regardless of cultivar (Figure 4.6, Figure 4.9). While the control mulch layer used in this study had comparable RDW to aged pecan shell mulch RDW in ‘Brightwell’ and ‘Premier’, it is hypothesized that had the control treatment been a true bare-ground treatment imposed in a field-setting, the RDW would have likely been lower, as plant height, fresh and dry weights, and root weight have been observed to be greater in blueberry plants that were mulched than for those that were grown without mulch (Clark and Moore, 1991; Gough, 1980, Patten et al., 1988, and Spiers, 1995).

Another observation derived from the root distribution in this study was the general lack of roots that grew into the pine bark mulch layer as compared to the aged pecan shell mulch layer in both cultivars. This trend in root growth corroborated with the results of previous studies that evaluated blueberry root distribution under mulch (Gough, 1980; Shutak and Christopher, 1952). Gough (1980) observed that no roots were found growing in the undecomposed layers of sawdust mulch, which was an approximately 10 cm thick. Rather, the greater amount of the feeder roots were found growing below the mulch, beginning at a depth of 11 cm and increasing in density to a depth of 13 cm. These findings indicated that the depths at which the roots were found corresponded with the lower layers of undecomposed mulch and the upper layers of partially decomposed mulch. Similarly, a previous study observed limited blueberry root growth within the sawdust mulch layer itself; rather most roots were found growing in the lower, decomposed layers of the mulch closest to the soil surface (Shutak and Christopher, 1952). Root distribution trends in this study showed that for ‘Brightwell’, root development within the aged shell mulch resulted in a higher RDW than that achieved in the fresh shell and pine bark mulches. While differences in RDW in ‘Premier’ were not as prominent as observed in ‘Brightwell’, more feeder roots established within the aged pecan shell mulch layer than in the pine bark. Considering the aged pecan shells used in this study were procured from the 2014 harvest, and had partially decomposed, it is hypothesized that the smaller particle size (Figure 4.10) of the aged shell mulch coupled with the level of decomposition created a more hospitable environment for feeder roots to develop than did the pine bark mulch.

Horhizotrons^{TM} were chosen for this experiment because not only did they provide a nondestructive means for examining how blueberry root growth was influenced by pecan shell mulch, but also because each individual plant grew into the separate treatments simultaneously. Since all the plants used in this experiment were grown under similar conditions, it was surmised that the possibility of plant stress brought on by separate rhizosphere conditions was unlikely. Thus, this experiment indicated that the growth and development of the rabbiteye blueberry root system is neither hindered by fresh pecan shell mulch nor aged pecan shell mulch as compared with milled pine bark.

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Table 4.1. Effect of mulch type on final horizontal root length (HRL[z]) of *Vaccinium virgatum* 'Premier' (108 DAP[y]) and 'Brightwell' (101 DAP) growing in Horhizotrons™ in a greenhouse in Auburn AL.

	'Premier'	
Treatment[x]	HRL (mm)	Sign.[v]
Fresh pecan shells	185.2 b[w]	Q***
Aged pecan shells	209.0 ab	Q***
Pine bark mini-nuggets	192.7 ab	Q***
Control	213.8 a	Q***
	'Brightwell'	
Treatment[x]	HRL (mm)	Sign.[v]
Fresh pecan shells	181.5 b[w]	C***
Aged pecan shells	194.4 b	C***
Pine bark mini-nuggets	212.9 a	C**
Control	218.6 a	Q*

[z] HRL = root length measured parallel to the ground.

[y] DAP = days after planting in Horhizotron™ (Wright and Wright, 2004).

[x] Treatments were 7.6 cm of fresh pecan shells, aged pecan shells, pine bark, or unamended pine bark:sand substrate applied on top of 10 cm of pine bark:sand substrate in Horhizotron™ quadrants.

[w] The mulch treatment was significant at α = 0.05.

[v] Significant quadratic (Q) trends using regression models at α = 0.05 (*), α = 0.01 (**), and 0.001 (***). Significant cubic (C) trends using regression models at α = 0.01(**) or 0.001 (***).

Table 4.2. Effect of mulch type on final root depth (RD[z]) measured from the surface of the soil profile of *Vaccinium virgatum* 'Premier' (108 DAP[y]) and 'Brightwell' (101 DAP) growing in Horhizotrons™ in a greenhouse in Auburn AL.

	'Premier'	
Treatment[x]	RD (mm)	Sign.[v]
Fresh pecan shells	127.0 a[w]	C***
Aged pecan shells	110.2 ab	C***
Pine bark mini-nuggets	127.7 a	C**
Control	100.2 b	Q*
	'Brightwell'	
Treatment[x]	RD (mm)	Sign.[v]
Fresh pecan shells	122.6 b[w]	C*
Aged pecan shells	116.8 b	C*
Pine bark mini-nuggets	138.4 a	C***
Control	115.0 a	C***

[z] RD = root length measured perpendicular to the ground.

[y] DAP = days after planting in Horhizotron™ (Wright and Wright, 2004).

[x] Treatments were amended substrate in bottom 10 cm and fresh pecan shells, aged pecan shells, pine bark, or unamended pine bark:sand substrate in upper 7.6 cm in Horhizotron™ quadrants.

[w] The mulch treatment was significant at $\alpha = 0.05$.

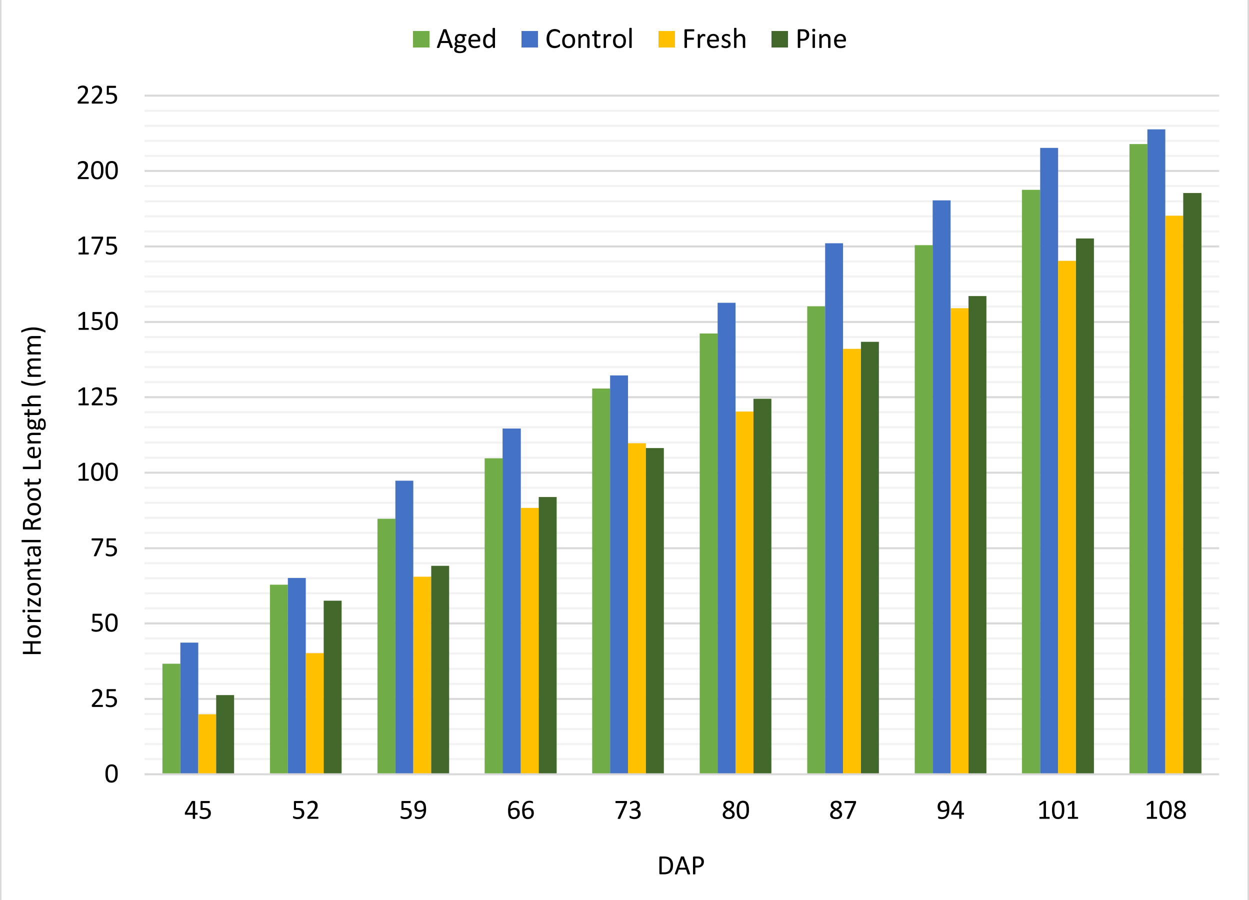
[v] Significant quadratic (Q) trend using a regression model at $\alpha = 0.05$ (*). Significant cubic (C) trends using regression models at $\alpha = 0.05$ (*), $\alpha = 0.01$(**), and 0.001 (***).

Figure 4.1. Horhizotron^{TM} has four wedge-shaped quadrants that extend out from the root ball. Quadrants are constructed of glass panes connected by vinyl j-channels. The aluminum base onto which the glass panes are attached is fastened to a treated wood frame.

Figure 4.2. To exclude light and protect the root system from temperature extremes, exterior walls were constructed from foam insulation board and placed around each Horhizotron^{TM}.

Figure 4.3. Upper lids for each Horhizotron^{TM} were made from foam insulation board with a portion cut out around the plant stem.

Figure 4.4. Effect of mulch type (treatment^z) on horizontal root length (HRL^y) of *Vaccinium virgatum* ‘Premier’ (45–108 DAP^x) growing in Horhizotrons^{TM} in a greenhouse in Auburn, AL.

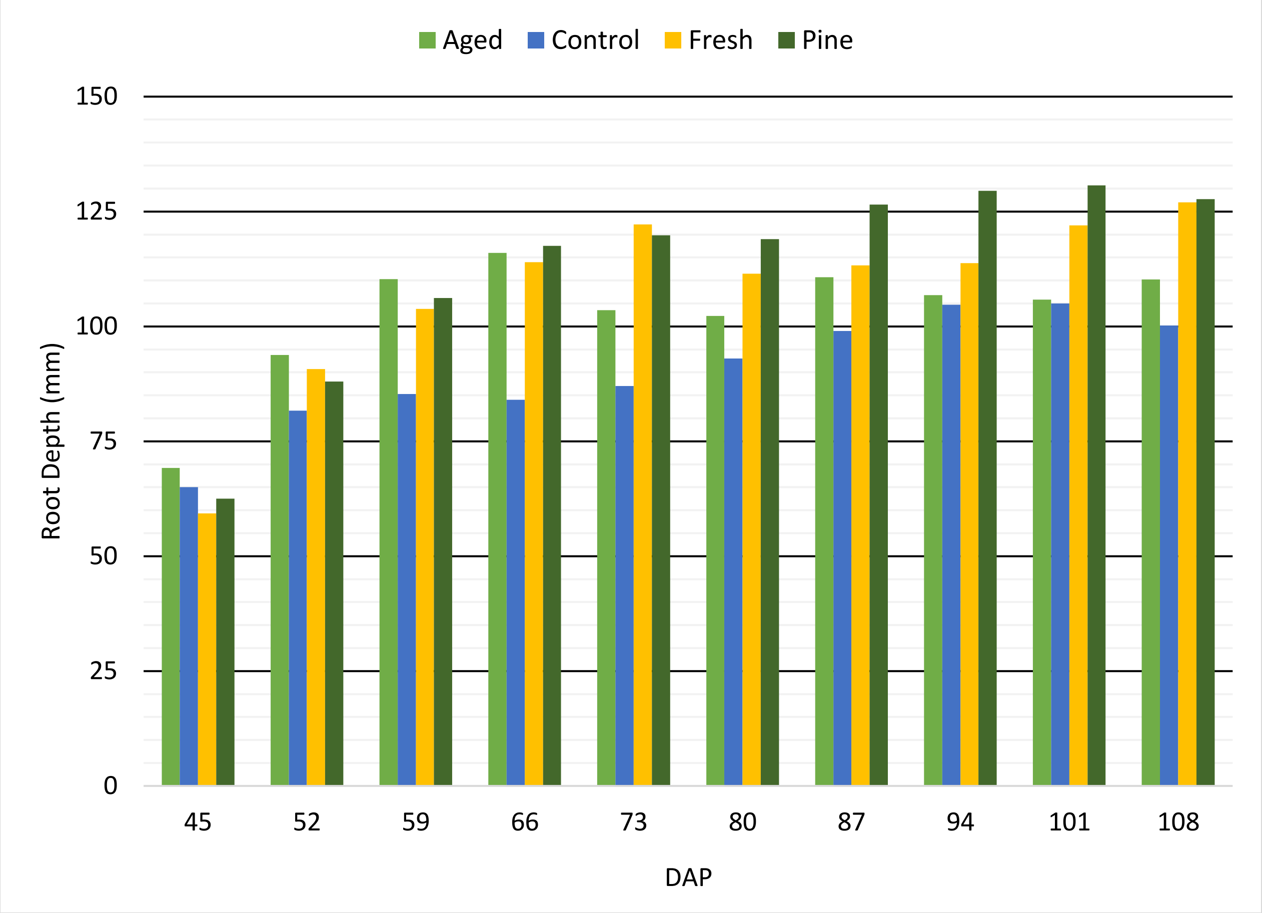


^{z}Treatments were 7.6 cm of fresh pecan shells, aged pecan shells, pine bark, or unamended pine bark:sand substrate applied on top of 10 cm of pine bark:sand substrate in Horhizotron^{TM} quadrants.

^{y}HRL = root length measured parallel to the ground.

^{x}DAP = days after planting in Horhizotron^{TM} (Wright and Wright, 2004).

Figure 4.5. Effect of mulch type (treatment^z) on root depth (RD^y) of *Vaccinium virgatum* 'Premier' (45–108 DAP^x) growing in Horhizotrons^{TM} in a greenhouse in Auburn, AL.



^{z}Treatments were 7.6 cm of fresh pecan shells, aged pecan shells, pine bark, or unamended pine bark:sand substrate applied on top of 10 cm of amended pine bark:sand (v/v) substrate in separate Horhizotron^{TM} quadrants.

^{y}RD = vertical root growth measured as it grew from the substrate surface into the quadrant profile towards the Horhizotron^{TM} base. Roots longer than 75 mm were in the substrate layer.

^{x}DAP = days after planting in Horhizotron^{TM} (Wright and Wright, 2004).

Figure 4.6. Root dry weight (RDW) of *Vaccinium virgatum* 'Premier'. Roots were divided into mulch (fresh shells, aged shells, pine bark, and control) and substrate layers, then washed separately to determine RDW. Total RDW = mulch layer RDW + substrate layer RDW. Least squares means comparisons among mulch treatments and substrate layers using the Shaffer-simulated method at α = 0.05. ns = not significant. Total RDW not significant at α = 0.05. All plants were grown in Horhizotrons^{TM} in a greenhouse in Auburn, AL.

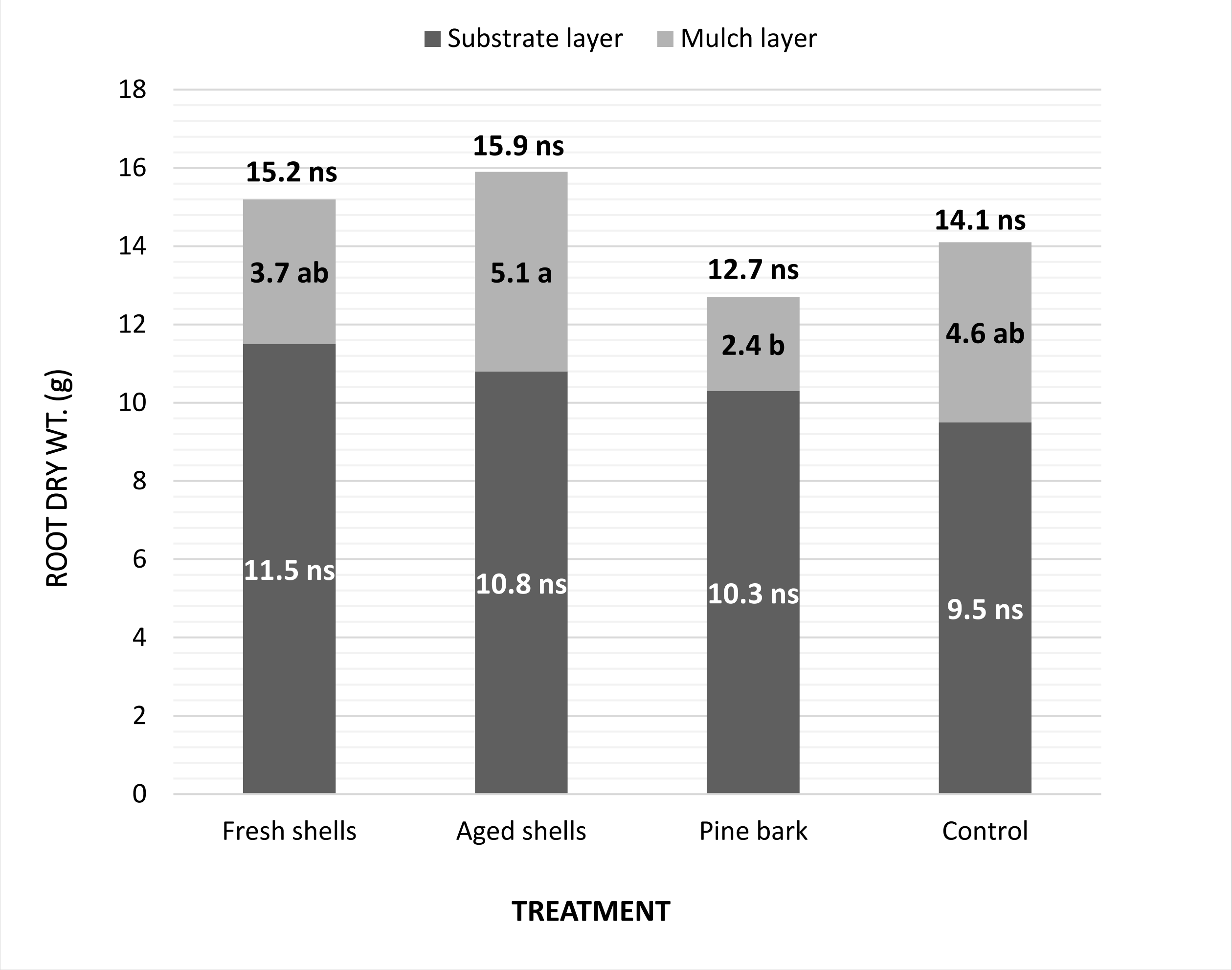
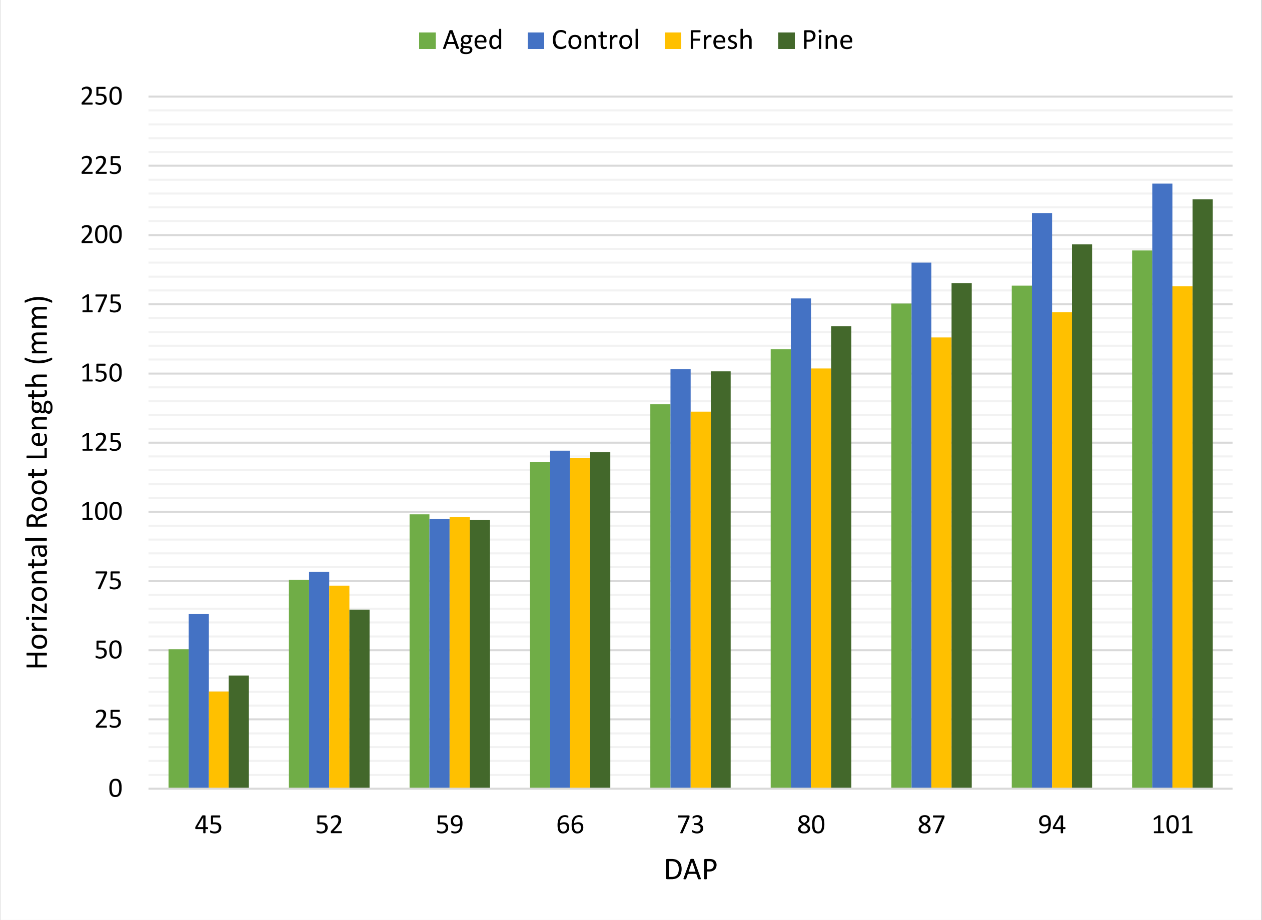


Figure 4.7. Effect of mulch type (treatment[z]) on horizontal root length (HRL[y]) of *Vaccinium virgatum* 'Brightwell (45–101 DAP[x]) growing in Horhizotrons™ in a greenhouse in Auburn, AL.

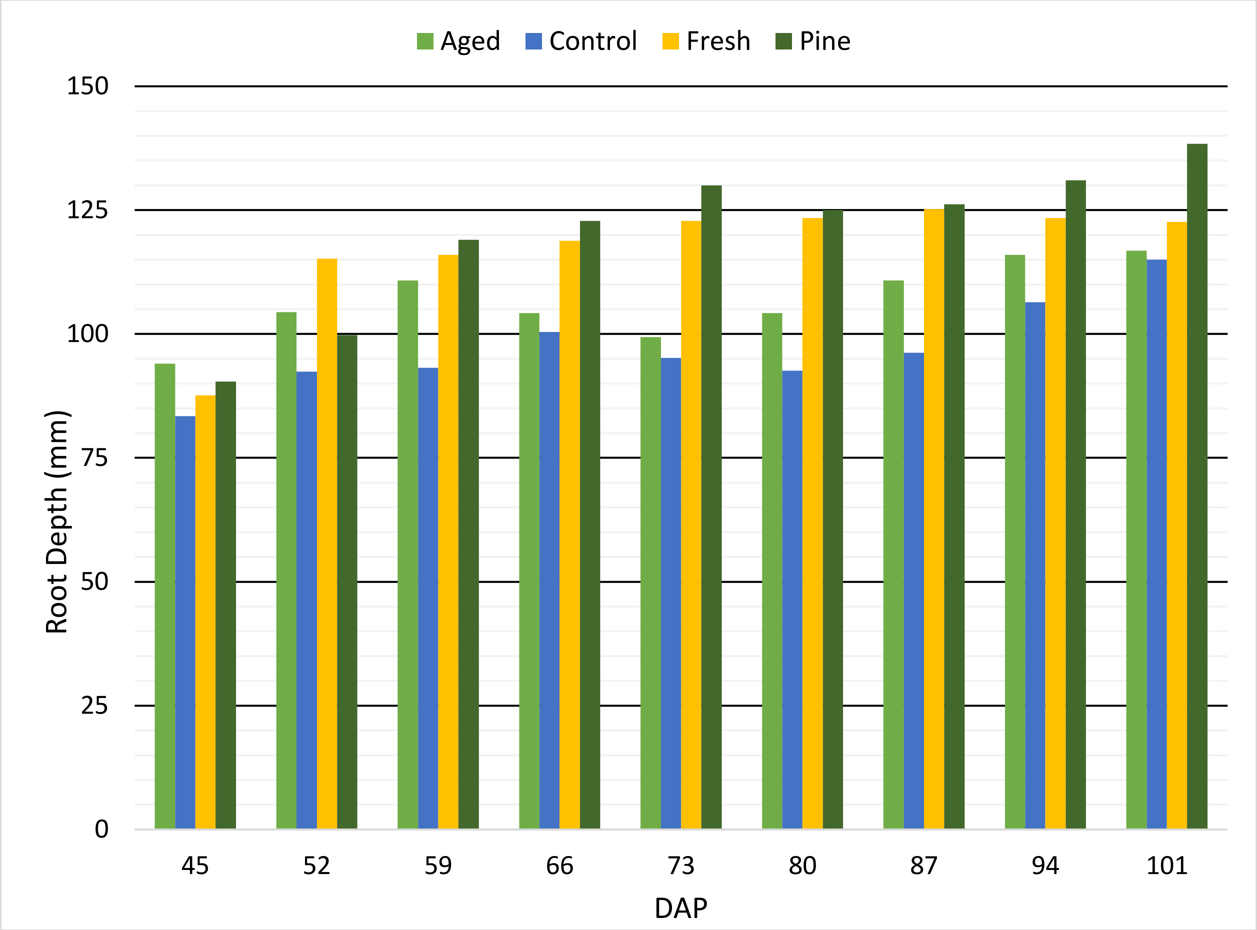


[z] Treatments were 7.6 cm of fresh pecan shells, aged pecan shells, pine bark, or unamended pine bark:sand substrate applied on top of 10 cm of amended pine bark:sand (v/v) substrate in separate Horhizotron™ quadrants.

[y] HRL = root length measured horizontal to the ground.

[x] DAP = days after planting in Horhizotron™ (Wright and Wright, 2004).

Figure 4.8. Effect of mulch type (treatment[z]) on root depth (RD[y]) of *Vaccinium virgatum* 'Brightwell (45–101 DAP[x]) growing in Horhizotrons^{TM} in a greenhouse in Auburn, AL.



[z] Treatments were 7.6 cm of fresh pecan shells, aged pecan shells, pine bark, or unamended pine bark:sand substrate applied on top of 10 cm of amended pine bark:sand (v/v) substrate in separate Horhizotron^{TM} quadrants.

[y] RD = vertical root growth measured as it grew from the substrate surface into the quadrant profile towards the Horhizotron^{TM} base. Roots longer than 75 mm were in the substrate layer.

[x] DAP = days after planting in Horhizotron^{TM} (Wright and Wright, 2004).

Figure 4.9. Root dry weight (RDW) of *Vaccinium virgatum* 'Brightwell'. Roots were divided into substrate and mulch (fresh shells, aged shells, pine bark, and control) layers, then washed separately to determine RDW. Total RDW = mulch layer RDW + substrate layer RDW. Least squares means comparisons among mulch treatments and substrate layers using the Shaffer-simulated method at α = 0.05. Total RDW not significant at α = 0.05. All plants were grown in Horhizotrons^{TM} in a greenhouse in Auburn, AL.

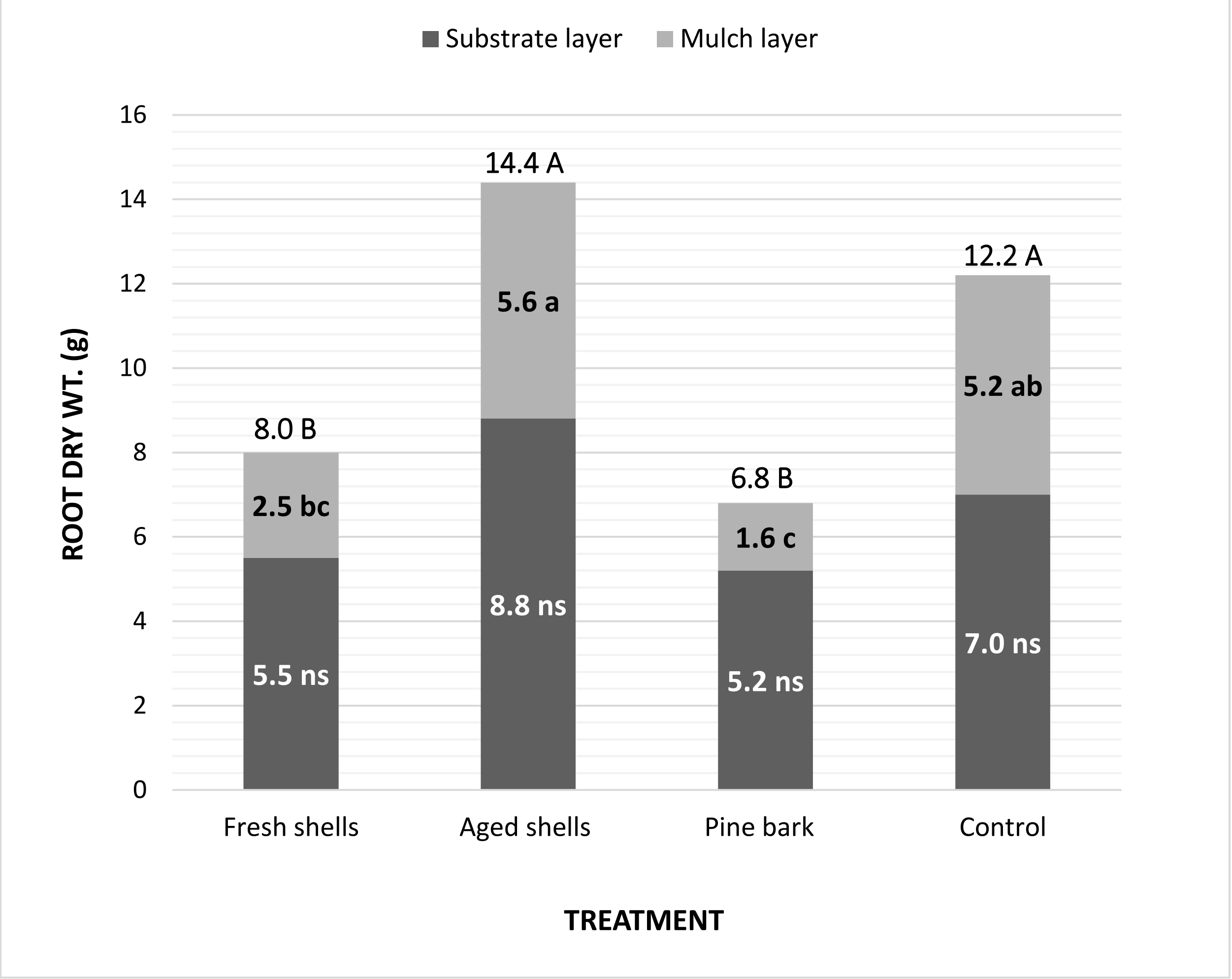
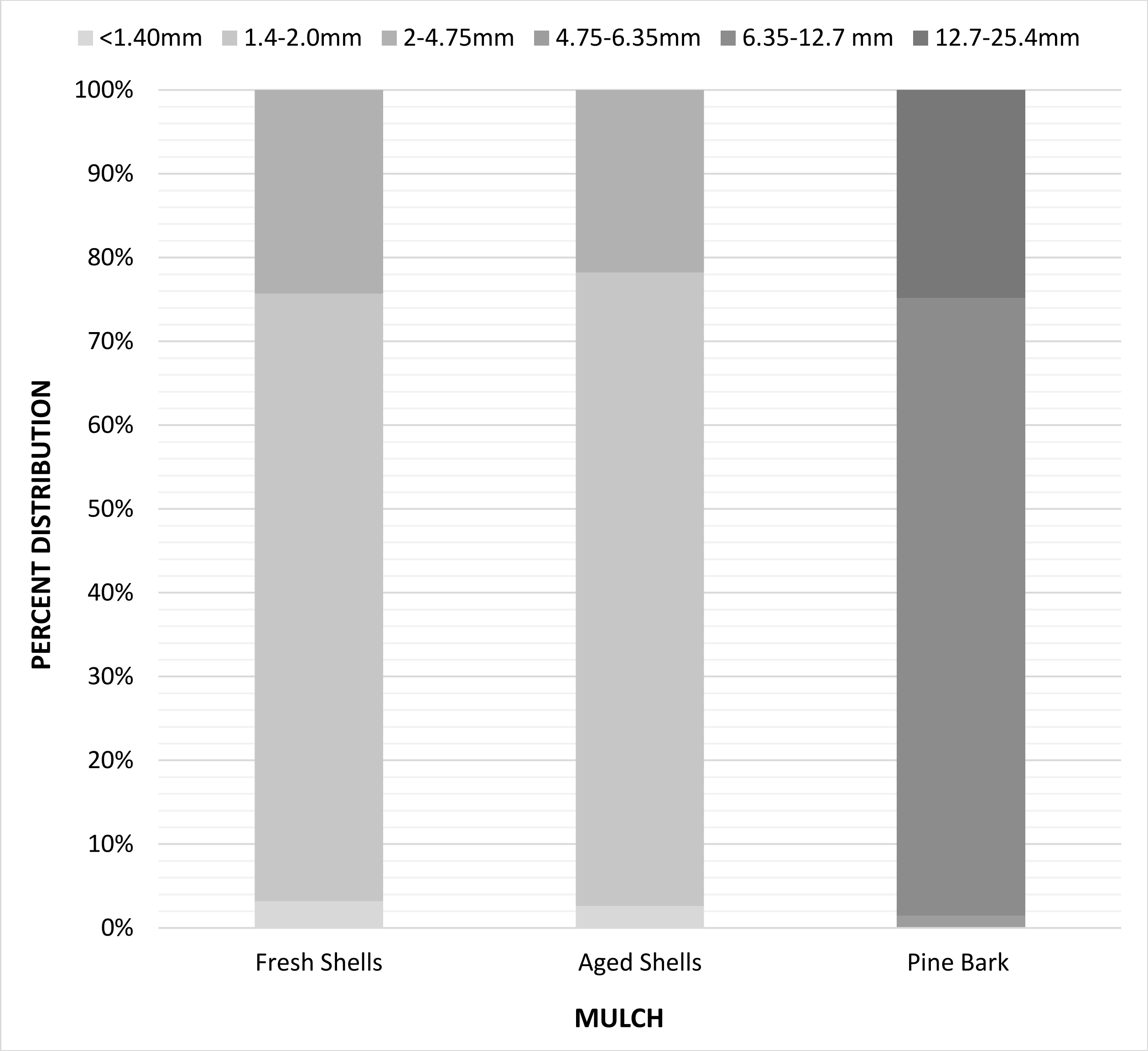


Figure 4.10. Particle size distribution by mulch type.



CHAPTER V

Effect of Pecan Shell Mulch Age and Depth on Weed Control of Crabgrass (*Digitaria sanguinalis*), Common Ragweed (*Ambrosia artemisiifolia*), and Spotted Spurge (*Euphorbia maculata*)

Introduction

Proper weed management is critical for good production in many small fruit and berry crops (Krewer et al., 2009; Pritts and Kelly, 2001). Blueberry plants that are not fully established were most susceptible to competition for water, nutrients, sunlight, and spatial resources (NeSmith and Krewer, 1995), with weed control being most crucial during an orchard's first two years of establishment (Braswell et al., 2015). In addition to stunted growth and increased instance of plant mortality, weeds decrease harvesting efficiency and interfere with general orchard maintenance. Weeds also have the potential to reduce an orchard's aesthetic appeal, which can be particularly damaging to Pick-Your-Own (PYO) operations that interact directly with clientele, and depend on positive consumer perceptions and experiences (personal observation). In many commercial operations, growers use herbicides to manage unwanted vegetation in their cropping systems, with some of the more commonly used chemicals including, but not limited to simazine, sethoxydim, glyphosate, hexazinone, and terbacil (Burkhard et al., 2009). However, some herbicides, largely those that are non-selective, can cause non-target injury, and are restricted from use in certain production systems, making weed control in organic operations more challenging. Accordingly, 3.8 L (1 gal) size container plants are generally recommended for transplanting because weeds can rapidly overcome smaller plants (Fonsah et al., 2008).

Strategies to manage competing vegetation in agricultural production systems are a key management component for most plant crops. Despite the development of herbicides and integrated pest management (IPM) systems, weeds remain a persistent threat. One explanation for the unrelenting weed pressure on farming systems is offered by Buhler (2002), who asserted that the development of effective IPM programs for weeds have been relatively sluggish when compared to the development of other IPM disciplines. NeSmith and Krewer (1995) had similar observations concerning the expansion of the rabbiteye blueberry industry in the southeastern United States, and described that among the many uncertainties accompanying blueberry orchard establishment, one of the most detrimental was competing vegetation and its associated effects during the first few years of establishment. Nearly a decade later, a survey was conducted concerning commercial blueberry production in North America wherein respondents disclosed that weed problems were present in nearly all production areas (Strik, 2006). Considering weeds are major pests in many agricultural systems, growers should not rely on a single weed control tactic, but utilize an integrated management program designed to eliminate existing populations and reduce future weed seed germination.

While there are advantages to chemical weed control, there are pitfalls in fruit production. A large portion of the new growth in a rabbiteye blueberry plant either comes from the canes that emerge from its stoloniferous root system, or from canes that sprout from renewal pruning (Fonsah et al., 2008). This type of growth is highly sensitive to herbicides, which makes chemical weed control not only challenging but also expensive for blueberry growers. Pre-harvest intervals (Stafne et al., 2009), and restrictions made by certified organic production standards (Bond and Grundy, 2001), also limit the use of herbicides in blueberry operations.

Alternatively, thickly applied surface mulches were found to serve as an effective cultural weed management option (Burkhard et al., 2009).

Aside from the benefit of weed control, there are other reasons why blueberries respond positively to surface mulch. Some of the major benefits of mulching includes soil moisture retention and the subsequent expansion of the effective root zone (Spiers, 1986), insulation of soil from temperature extremes (Clark and Moore, 1991; Spiers, 1995), soil conservation (Bond and Grundy, 2001), weed suppression (Merwin et al., 1995), and a carbon-rich soil profile that improves soil structure and serves as a habitat for beneficial soil organisms as the mulch decomposes (Yang et al., 2002). Spiers (1998) deemed mulching southern highbush blueberries as the most essential cultural practice in the Gulf States regions of the United States.

To date, pine bark mulch was the preferred mulch in Southeastern blueberry production systems chiefly due to excellent weed control, availability (Richardson et al., 2008), and the degree to which it works in concert with the blueberry anatomy (Krewer and Ruter, 2009). However, despite the benefits, inconsistent and potentially unreliable supplies coupled with fluctuating cost has motivated the evaluation of alternatives (Jackson et al., 2005; Lu et al., 2006). Amongst those alternatives is pecan shell waste, though scientific evaluations of their suitability as a mulch (Stafne et al., 2009) or substrate amendment (Wang and Pokorny, 1989) were few. If pecan shells could be successfully marketed to the blueberry industry as a viable organic mulch, then growers may be provided with an alternative, acidifying, organic mulch that could have a significant impact on the sustainability of the industry. Thus, the purpose of this experiment was to determine the level of weed control that can be obtained by using pecan shell mulch on crabgrass (*Digitaria sanguinalis* L.), common ragweed (*Ambrosia artemisiifolia* L.), and spotted spurge (*Euphorbia maculate* L.). Pine bark mulch was also included in the evaluation to provide a commercial standard for control of these problematic weed species.

Materials and Methods

Experimental Design

This research was conducted in containers on the nursery pad at the Paterson Greenhouse Complex at Auburn University in Auburn, AL. The experiment was initiated on 13 May 2016. The study was arranged in a completely randomized design. Treatments consisted of the three mulches used in the field study at Randle Farms, Auburn, AL (lat. 32° 31’ N; long. -85° 26’ W USDA hardiness zone 8a): fresh pecan shells from the 2015 harvest, aged pecan shells from the 2014 harvest (Whaley Pecan Company, Inc., Troy, AL), and pine bark mini-nuggets at two depths 7.6 and 15.2 cm (3 and 6 in), and a non-treated control (no mulch) for a total of seven treatments. Three weed species, crabgrass (*Digitaria sanguinalis*), common ragweed (*Ambrosia artemisiifolia*), and spotted spurge (*Euphorbia maculata*), were tested. Each weed species received all seven treatments. Each treatment was replicated seven times for a total of 49 containers per weed species.

Treatment Application

The pecan shells were milled, finely textured, and mostly free of residual nut meat. Pine bark mini-nuggets (West Fraser Mills, Opelika, AL) were also selected for this experiment to serve as a standard commercial treatment for comparison.

The fresh and aged pecan shell mulches were oven-baked at the Auburn University Paterson Greenhouse Complex for 14 days at 105 °C. The fresh and aged pecan shells were then sieved through a series of wire screens [4.75, 2.00, and 1.40 mm (0.19, 0.08, 0.06 in) screens] to ascertain particle size distribution ratios (Figure 5.1). The pine bark mulch was also oven-baked for 14 days at 105 °C, and sieved through a series of wire screens [24.5, 12.7, and 6.35 mm (1, 0.5, and 0.25 in) screens] to determine particle size distribution (Figure 5.1). Particles that remained on the surface of each sieve were weighed and percentage (by weight) was calculated.

On 9 May 2016, 26 L (7 gal) containers were filled 12.7 cm (5 in) from the top with a 4:1 pine bark:sand (v/v) substrate amended per cubic yard with 2.3 kg (5 lbs) of Peafowl® 25-4-8 + 2% Iron + Slow Release Nitrogen (Piedmont Fertilizer Company, Inc., Opelika, AL) and 0.7 kg (1.5 lbs) Micromax® (Scotts Co., Marysville, Ohio). Containers were placed on the nursery pad and irrigated twice daily for 3 days with 2.5 cm (1 in) of water to allow for substrate settling. Germination tests were conducted for each weed species in paper towels prior to the experiment's initiation. The tests indicated that all weed species had a germination rate of at least 90%. Each container was seeded with 25 seeds of spotted spurge, crabgrass, or common ragweed directly to the surface of the substrate on 13 May 2016. Mulch treatments were imposed immediately after seeding.

Data Collection

Three evaluation periods record treatment efficacy and longevity of weed control over the growing season. Each evaluation period allowed weeds to grow for approximately 30 days after seeding or until they had reached adequate maturity prior to producing seed. At each evaluation period, weeds, if present, were counted and the shoots were cut at mulch (substrate level in control containers) level. Fresh and dry weights were recorded. One week after weed harvest, the containers were sprayed with paraquat (Gramoxone® Inteon, Syngenta Crop Protection, Greensboro, NC) to eliminate any escapes. One week post-paraquat application the second evaluation period was initiated by reseeding directly onto the surface of the mulch (or substrate in control containers) with 25 seeds of the same weed species used previously. This process was repeated once more to initiate the third (final) evaluation period.

Statistical Analysis

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). Weed species were analyzed as separate experiments. Fresh and dry weights were analyzed as a completely randomized design, and weed counts were analyzed as a completely randomized design separately by dates. Where residual plots and a significant covariance test of homogeneity among treatments was significant, a RANDOM statement with the GROUP option was used to correct heterogeneity. In many cases, an analysis could not be completed because of too little data. Weed counts were analyzed using the Poisson, generalized Poisson, or negative binomial probability distribution depending on which distribution resulted in a Pearson chi-square / DF value closest to 1.0. Least squares means comparisons were determined using the simulated method. All significances were at $\alpha = 0.05$.

Results

Data for the first evaluation period was collected on 22 June 2016. Results showed that all mulch treatments, regardless of depth, resulted in complete control of each weed species (Tables 5.1, 5.2, 5.3). No other differences in mulch type or depth were observed. Due to minimal germination during the first run, analysis of fresh and dry weights was not feasible.

Unlike the first evaluation period, during the second evaluation cycle the seeds were sown on top of the mulch or substrate for control containers. Data was collected on 12 August 2016. For crabgrass, weeds established more successfully in the 7.6 cm (15 in) aged pecan shell mulch than in the other treatments (Table 5.1). No significant differences between weed species and mulch treatment were observed for ragweed (Table 5.2). All pecan shell mulch treatments performed similarly to the control for spotted spurge, while the pine bark treatments resulted in the fewest weeds (Table 5.3). Due to stunted growth across all treatments, analysis of fresh and dry weights was not feasible.

Data from the third evaluation period was collected on 28 Sept. 2016. The seeds were broadcasted on top of the mulch or substrate for control containers. Data showed that all treatments performed similarly for crabgrass (Table 5.1). For ragweed (Table 5.2), both pecan shell mulch treatments resulted in the fewest weed counts, while the 7.6 cm pine bark mulch treatment had the highest. All remaining treatments had a similar number of weed seedlings. For spotted spurge (Table 5.3), pine bark continued to have the lowest seedling counts in the 7.6 cm treatment; however, the 15.2 cm pine treatment had a higher seedling count than in the previous evaluation period. The aged pecan shell treatments and the 15.2 cm fresh pecan shell treatments yielded the highest weed counts.

Discussion

Considering that weed emergence is generally inversely related to seed depth (Burkhard et al., 2009), the degree of weed control tends to increase with mulch depth. Thus, placement of the weed seed below the mulch treatments for the first evaluation period likely contributed to the lower germination rate. These findings reaffirm the importance of considering mulch layer thickness, as surface mulches inhibit weed growth by excluding light from the soil surface and serving as a physical barrier that hinders weed seedling emergence (Bond and Grundy, 2001).

Results from the second evaluation period differed from the first. All mulch treatments, including the control, were equally successful in suppressing crabgrass except for the 15.2 cm aged pecan shell treatment. All treatments performed similarly for ragweed (Table 5.2). Results for spotted spurge indicated that pecan shell mulch, regardless of type, were least effective in weed suppression, as all pecan shell treatments had higher weed counts than either pine bark mulch treatment (Table 5.3). Findings from the final evaluation period showed that there were no differences between treatments for crabgrass. Ragweed was the only weed species throughout the experiment that had a higher number of weed seedlings in a pine bark treatment. Rather, the lowest weed counts were in the 7.6 and 15.2 cm fresh pecan shell treatments. Weed germination in spotted spurge showed the most consistency between evaluation periods. These findings suggest that ragweed may have a higher sensitivity to fresh pecan shells than aged pecan shells. As observed in the second evaluation period, weed counts in spotted spurge were highest in the aged pecan shell mulch treatments. Fresh pecan shell mulch treatments had comparable weed counts to aged, though the 15.2 cm fresh pecan shell treatment had slightly lower counts in the final evaluation period. This could partially be attributed to the smaller particle size of aged pecan shells (Figure 5.1) coupled with higher moisture content than that of the fresh pecan shells (Table 5.4).

Though the recommended thickness of the mulch band in a blueberry orchard varies depending on species and region, most sources recommend a minimum of 7.6 cm (3 in). Braswell et al. (2015) recommended that mulch should be 10 to 15 cm (4 to 6 in) deep and cover at least a 1.2 m band centered on the plant row. Similarly, Himelrick et al. (2002) recommended an application of 8 to 15 cm (3 to 6 in). Hence, the thickness of the mulch layers in this experiment were imposed at 7.6 and 15.2 cm (3 to 6 in) depths. Further research is recommended to analyze specific decomposition rates of pecan shells, as this information could be valuable to growers and other members of the horticulture industry that are interested in evaluating pecan shells as a mulch. Additional evaluation of potential allelopathic effects on weed species and specialty crops is also recommended, as some mulches, particularly when fresh, were found to reduce weed populations by allelopathic chemicals that may harm sensitive non-targets (Duryea et al., 1999). Lastly, cost analysis research should be conducted to help establish adoption and implementation of pecan shell mulch from an economic perspective. Common weed control practices in commercial blueberry production consist primarily of a series of preemergent and postemergent herbicide applications. Non-chemical weed control tactics, such as mulches, could decrease damage to non-target plants and beneficial organisms, reduce potential environmental concerns, and decrease labor and chemical expenditures. With increasing interest in soil conservation and intensified efforts to exercise environmental stewardship, many growers are already employing management practices that can reduce their operation’s chemical footprints (Bond and Grundy, 2001; Merwin et al., 1995). Because of these production trends a renewed interest in mulch is emerging. If the use of pecan shells as a mulch could be made economical, then pecan shell mulch in either field or container production settings may decrease cost and reduce instances of non-target injury and environmental impacts.

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Table 5.1. Effect of mulch type and depth on weed counts of crabgrass (*Digitaria sanguinalis*).

Treatment	Depth (cm)	Evaluation[z] 1	Evaluation[y] 2	Evaluation[x] 3
Aged shells	7.6	0 b	1 b	1 ^{ns}
Fresh shells	7.6	0 b	2 b	1
Pine bark	7.6	0 b	1 b	0
Aged shells	15.2	0 b	4 a	2
Fresh shells	15.2	0 b	2 b	2
Pine bark	15.2	0 b	2 b	1
Control	NA	14 a	1 b	0

[z] First evaluation period initiated on 13 May 2016. Data recorded on 22 June 2016, 40 days after treatment.

[y] Second evaluation period initiated on 7 July 2016. Data recorded on 12 Aug. 2016, 36 days after treatment.

[x] Third evaluation period initiated on 23 August 2016. Data recorded on 28 Sept. 2016, 36 days after treatment.

Table 5.2. Effect of mulch type and depth on weed counts of common ragweed (*Ambrosia artemisiifolia*).

Treatment	Depth (cm)	Evaluation[z] 1	Evaluation[y] 2	Evaluation[x] 3
Aged shells	7.6	0 b	5 [ns]	3 ab
Fresh shells	7.6	0 b	4	1 b
Pine bark	7.6	0 b	7	7 a
Aged shells	15.2	0 b	6	3 ab
Fresh shells	15.2	0 b	4	1 b
Pine bark	15.2	0 b	5	5 ab
Control	NA	10 a	5	3 ab

[z] First evaluation period initiated on 13 May 2016. Data recorded on 22 June 2016, 40 days after treatment.

[y] Second evaluation period initiated on 7 July 2016. Data recorded on 12 Aug. 2016, 36 days after treatment.

[x] Third evaluation period initiated on 23 August 2016. Data recorded on 28 Sept. 2016, 36 days after treatment.

Table 5.3. Effect of mulch type and depth on weed counts of spotted spurge (*Euphorbia maculata*).

Treatment	Depth (cm)	Evaluation[z] 1	Evaluation[y] 2	Evaluation[x] 3
Aged shells	7.6	0 b	13 a	9 a
Fresh shells	7.6	0 b	11 a	6 ab
Pine bark	7.6	0 b	13 b	2 b
Aged shells	15.2	0 b	17 a	12 a
Fresh shells	15.2	0 b	13 a	10 a
Pine bark	15.2	0 b	4 b	4 ab
Control	NA	18 a	15 a	5 ab

[z] First evaluation period initiated on 13 May 2016. Data recorded on 22 June 2016, 40 days after treatment.

[y] Second evaluation period initiated on 7 July 2016. Data recorded on 12 Aug. 2016, 36 days after treatment.

[x] Third evaluation period initiated on 23 August 2016. Data recorded on 28 Sept. 2016, 36 days after treatment.

Table 5.4. Mulch nutrient analyses mean and standard deviation of fresh pecan shells, aged pecan shells, and milled pine bark.[z]

Measurement	Unit	Fresh shells[y]	Aged shells[x]	Pine bark[w]
pH	NA	5.03 ± 0.05	4.63 ± 0.01	4.57 ± 0.01
Moisture	%	24.04 ± 0.79	55.45 ± 0.50	59.42 ± 0.83
Ash	%	1.77 ± 0.02	2.28 ± 0.21	0.72 ± 0.06
C	%	38.87 ±0.49	21.95 ± 0.23	21.08 ± 0.44
N	%	0.36 ± 0.02	0.27 ± 0.01	0.20 ± 0.00
P	%	0.01 ± 0.01	0.01 ± 0.01	0.00 ± 0.00
K	%	0.17 ± 0.03	0.00 ± 0.00	0.02 ± 0.01
Ca	%	0.46 ± 0.05	0.31 ± 0.01	0.08 ± 0.00
Mg	%	0.00 ± 0.00	0.00 ± 0.00	0.02 ± 0.00
Al	ppm	55.17 ± 7.46	148.59 ± 25.59	331.73 ± 7.70
B	ppm	5.97 ± 0.97	3.40 ± 0.29	1.97 ± 0.42
Cu	ppm	9.83 ± 0.88	5.98 ± 1.28	3.28 ± 1.07
Fe	ppm	82.16 ± 16.01	109.19 ± 16.85	81.15 ± 5.07
Mn	ppm	42.16 ± 4.07	31.90 ± 2.9	24.79 ± 0.39
Na	ppm	312.08 ± 110.78	140.90 ± 13.78	113.62 ± 39.15
Zn	ppm	5.69 ± 1.26	10.04 ± 4.6	9.88 ± 5.14

[z] Analyses by Auburn University Soil, Forage, and Water Testing Laboratory, Auburn, AL.

[y] Pecan shells obtained from the 2015 harvest, Whaley Pecan Company, Inc., Troy, AL.

[x] Pecan shells obtained from the 2014 harvest, Whaley Pecan Company, Inc., Troy, AL.

[w] Pine bark mini-nuggets obtained from West Fraser Mills, Opelika, AL.

Figure 5.1. Particle size distribution by mulch type.