

THE GROWTH AND PRODUCTIVITY OF *RIBES NIGRUM* UNDER VARIOUS LEVELS  
OF SHADE AND THE IMPLICATIONS FOR MULTIFUNCTIONAL WOODY  
POLYCULTURES

BY

ERIC WOLSKE

THESIS

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Master's Committee:

Professor Bruce Branham, Advisor  
Associate Professor Sarah Taylor Lovell  
Associate Professor Gary Kling

## Abstract

Black currants (*Ribes nigrum*) are an important horticultural crop across Europe and parts of Asia. In the United States, however, they have been relegated to a niche market, with little practical use to date. Much of this is due to the illegality of production throughout much of the 20<sup>th</sup> century, as it was an alternate host to the white pine blister rust (*Cronartium ribicola* J.C. Fisch In Rabh.), which caused extensive damage to the white pine (*Pinus strobus*) lumber industry. Upon legalization in the latter half of the 20<sup>th</sup> century, black currants have been making a slow comeback. The major interest in black currants stems from the unique taste and the perceived health benefits. Black currant berries contain a vast array of mineral nutrients that are much higher than many of the major fruits and berries currently in production, with a vitamin C content over three times as high as that found in oranges on a per weight basis. Additionally, they contain high levels of antioxidants due to a large content of phenolic compounds, particularly flavonols and anthocyanins. The stability in frozen storage, as well as the ease of production and machine harvest, mean black currants have a significant potential to provide a new crop to farmers in the Midwest United States. With newly proposed systems for agricultural production focusing on polycultures of perennial crops, a major gap in research is found in the understory layers of these systems. The understory is a unique habitat with intense plant competition for nutrients and water, and most importantly, light. While much is known about plant response mechanisms in these environments, little is known about how crops may perform in these environments. Black currants have been proposed as potential understory crops, but little research has been performed to determine actual agronomic productivity in these environments.

An experiment was conducted in Urbana, IL to determine black currant viability in understory environments by exposing black currants to a range of artificial shading. The results of the study indicate black currants can maintain good yields in light to medium levels of shade, with no yield difference found between full sun and up to 65% shading. Additionally, the berries maintained good quality up to the 65% shade level, with sugar levels, acidity, and overall size similar to the control plants. The leaf morphology and height changes under shading were congruent to previous research on plant plasticity responses to shade stress in plants. The major issues found in the study was an increase in plant injury as shading increased, pointing to a need for plant breeding for increased resilience to understory environments to further push for productive plant species in perennial polyculture systems.

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## CHAPTER 1: BLACK CURRANTS

### 1.1 Horticulture

Black currants, *Ribes nigrum*, belong to the genus *Ribes* L. and the family Grossulariaceae (previously in family Saxifragaceae) (Hummer and Barney 2002). Black currants share the *Ribes* genus with over 150 different species, all small shrubs and bushes, including the cultivated red currant (*Ribes rubrum*) (Brennan 2006). The ancestors of black and red currants originated mainly from Europe, Scandinavia, and the Russian Federation, whereas plants in the *Ribes* genus are found across the globe, with species of black currants found in South America, Asia, Northwest Africa, and North America (Hummer and Dale 2010). Most *Ribes* species are cultivated for medicine and food, with some having horticultural value as landscape and ornamental plants (Brennan 2006).

Black currants are a 1.5 to 2 meter tall shrub with aromatic leaves grown for their piquant berries (Hummer and Barney 2002). The leaves are lobed, up to 10 cm long and wide, and contain small yellow, sessile, aromatic glands underneath. Up to 10 white flowers are born on 10 cm drooping racemes that form shiny, black fruit up to 10 mm in diameter (Hummer and Barney 2002; Brennan 2006). Flowers are mainly pollinated by wild bees and bumble bees that are active in the early spring when the flowers bloom (Bratsch and Williams 2009). However, honey bees have been recommended to help in pollination at a rate of 1 hive per acre (Hummer and Barney 2002). Most black currant varieties are self-fertile, but yield and berry size are increased from cross-pollination (Bratsch and Williams 2009). It's recommended that anywhere from 1-20% of the plants in an orchard be pollinator species for optimum yields (Hummer and Barney 2002).

While the cultivated black currant (*Ribes nigrum*) is the main cultivated black currant, there are other black currant species including the Russian *Ribes dikuscha*; the North American species *Ribes americanum*, *Ribes hudsonianum*, *Ribes petiolare*, and *Ribes bracteosum*; the east Asian species *Ribes ussuriense*; the east Siberian *Ribes pauciflorum*; and the Chilean species *Ribes valdivianum*. Many of these other black currant species have been used in breeding programs to increase pest and disease resistance, increase juice quality, polyphenols, and ascorbic acid, and reduce bloom freeze damage (Brennan 2006).

Black currants produce a dark-purple, medium-to-small-sized berry with a unique scent and flavor, high color pigments, high anthocyanins, and high vitamin C content (Hummer and Barney 2002). The vitamin C content has been reported as being 3-4 times as high as oranges and over 50 times as high as apples (Dale 2000), with values ranging from 50 to 250 mg ascorbic acid per 100 grams fresh weight with some wild species containing up to 800 mg per 100 grams fresh weight (Hummer and Dale 2010). The majority of black currants (roughly 80%) are cultivated for juice, while the remaining crop is used for fresh eating, jams and preserves, desserts and confectionary, teas, liqueurs and wine, yogurt and other dairy-products, and scented goods such as candles and perfumes (Dale 2000; Hummer and Dale 2010; Brennan 2006). In addition to the fruits, the aromatic black currant leaves are also harvested for tea, flavoring, and medicinal extracts. The buds can be harvested for their high polyphenol content and can be found dried and ground and sold as health supplements, or the essential oils extracted for the perfume industry (Brennan 2006). Finally, the seeds leftover after juicing can be used for their oil that contains a high content of gamma-linolenic acid (GLA), with up to 20% the total fatty acid composition being GLA (Brennan 2006; Hummer and Barney 2002; Dale 2000).

Currently, the largest producers of black currants are the Russian Federation and Poland, with Ukraine, France, the United Kingdom, Germany, Finland, Denmark, New Zealand, and Hungary also contributing as the top ten black currant producing countries (FAO 2014; Brennan 2006). Black currants have been cultivated for 400 years, originally regarded as a medicinal crop used by herbalists, and by the late 1800's were regarded as a food crop to be used as a jelly (Hummer and Barney 2002).

## **1.2 History**

The first note of black currant introduction in the United States was on the 16<sup>th</sup> of March, 1629 in Massachusetts. In 1770, currants were being sold by Prince Nurseries in Flushing, New York along with red and white currants (Hummer and Dale 2010). In 1826, there were five black currant cultivars listed as being horticulturally significant (Hummer and Barney 2002). By the mid 1850's, 25 different cultivars of European currants were described and available for purchase, and in 1925, Hedrick (1925) reported 185 currant cultivars in existence globally, with 109 of those selected or developed in North America (Hummer and Dale 2010). By 1919, 2,952 hectares of *Ribes* were being grown in the United States. However, with the discovery of white

pine blister rust and its deleterious effect on white pine forestry in the early 1900's, a ban was enacted in the United States (Hummer and Barney 2002)

The white pine blister rust (*Cronartium ribicola* J.C Fisch In Rabh.) was imported from Asia (Hummer and Dale 2010) and was first recognized in the United States in 1906 in Geneva, New York. The white pine blister rust was found to affect not only the eastern white pine (*Pinus strobus*) in subsection *Strobi*, but also the limber pine (*Pinus flexilis*), foxtail pines (subsection *Balfourianae*) and stone pines (subsection *Cembrae*). At the time, white pine was a valuable timber crop due to its easily-worked wood and large seeds. Before the discovery of white pine blister rust, white pines were already being severely depleted east of the Mississippi River due to overlogging and the lumber industry was focusing their logging efforts on the white pine forests of the northwest for the mines and railroads. The eastern white pine (*Pinus strobus*) was first brought to Europe in the late 1800's and early 1900's where it was grown particularly in Germany. While the white pine blister rust was found in Europe and affected trees, the Europeans valued black currants over the fast growing timber species and thus, no eradication programs were enacted. In America, however, a government campaign favored the white pine forestry industry and an eradication program was enacted in 1917 by the USDA with a subsequent ban on currant cultivation. The eradication effort was intended to protect selected white pines from infection by removing all wild *Ribes* species within a designated area and was occasionally done preventatively before the outbreak occurred (Geils et al. 2010). In 1966, the federal law banning currant production in the United States was rescinded. However, in many states and counties, the ban was still in effect (Bratsch and Williams 2009). By 1986, the white pine blister rust control efforts were considered a success and no longer a constraint in proper white pine silviculture (Geils et al. 2010).

In the 1940's and 1950's, Canadian researcher A.W Hunter crossed the European black currant variety 'Kerry' with native black currants (*Ribes ussuriense*) with a Cr gene for rust immunity to eventually breed the cultivars 'Consort', 'Crusader', and 'Coronet'. While these varieties were found to be resistant to the white pine blister rust, they were still highly susceptible to powdery mildew (*Sphaerotheca mors-uvaw* (Schw.) Berk.), low yielding, and considered unsuitable for the European juice market (Hummer and Barney 2002). Interestingly enough, the bred 'Consort' still remains one of the most antioxidant rich of the modern black

currant varieties, with the highest reported levels of total phenolics and total anthocyanins (Moyer et al. 2002).

### 1.3 Superfood

Many studies have been conducted examining the chemical composition of black currant fruits, leaves, buds, and seeds. In particular, black currant berries have been known for their health benefits since at least the 1600's, as their original use was as a medicine before it became a common food item (Hummer and Barney 2002; Brennan 2006). In modern times, the research focus has shifted to the quality, health, and nutrition of black currant berries grown in a wide-range of geographic locations across many years and cultivation technique, and with the various cultivars. Compared to other fruit, black currants continue to be regarded as one of the best berries for overall human-health, with the polyphenol content among the highest in over 143 common fruit and vegetables (Karjalainen et al. 2008). Mineral nutrients in black currants are especially good sources of calcium, potassium, magnesium, and iron (Magazin et al 2011). Compared to blueberries, grapes, cranberries, and oranges, black currants have the highest level of calcium, iron, magnesium, phosphorous, potassium, zinc, and Vitamin C (Table 1.1). The vitamin C (ascorbic acid) content of black currants is 3 times as high as oranges, the antioxidant potential is greater than blueberries, and the potassium content is similar to bananas. (USDA-ARS-National Nutrient Database for Standard Reference Release 28). Additionally, due to the high levels of antioxidants, the ascorbic acid in blackcurrants appears to be more stable than in other fruits (Brennan 2006; Cyboran et al. 2014).

In a study comparing the health-quality of black currants, blueberries (*Vaccinium corymbosum*), raspberries (*Rubus idaeus*), red currants (*Ribes rubrum*), and cranberries (*Vaccinium oxycoccus*), Borges et al. (2010) found that black currants had the highest antioxidant capacity and the highest levels of anthocyanins and ascorbic acid. Benvenuti et al. (2004) found that black currants had higher total polyphenols and total anthocyanins than blackberries (*Rubus fruticosus*), raspberries, and red currant, but the content was lower than chokeberries (*Aronia melanocarpa*). The ascorbic acid content, however, was the highest among all the berries tested. In a similar study, Moyer et al. (2002) tested 107 genotypes from *Ribes*, *Rubus*, and *Vaccinium* for their total polyphenols, total antioxidants, and total antioxidant capacity by Oxygen Radical Absorbing Capacity (OREC) and Ferric Reducing Antioxidant



Power (FRAP). Black currants had a higher mean total anthocyanin content (229 mg total anthocyanins/100g) than any of the *Rubus* genotypes and the same mean total anthocyanin content of *Vaccinium* genotypes (230 mg total anthocyanins/100g). The mean total phenols for black currants was higher than the overall mean total phenols for both *Rubus* and *Vaccinium*, with the black currant cultivar 'Consort' having the highest level (1342 mg total polyphenols/100g) of all the genotypes tested in the study. Black currant antioxidant activity as measured by OREC and FRAP was also found to have some of the highest values of all species tested with only black raspberry (*Rubus occidentalis* L.), wild rabbiteye blueberry (*Vaccinium ashei*), clove currant (*Ribes odoratum*), and the Chilean black currant (*Ribes valdividatum*) having higher values. Finally, in a study testing the ascorbic acid content, total flavonol content, and the three major flavonols found in berries, black currants were found to have the highest level of combined ascorbic acid and total flavonols on a fresh weight basis than any of the 18 other berries tested. The total flavonols were only higher in bog whortleberry, lingonberry, and cranberry (Häkkinen et al. 1999).

The high antioxidant capacity found in black currants originates from their high content of vitamin C and high content of polyphenolics, particularly anthocyanins and flavonols (Karjalainen et al. 2008). Milivojevic et al. (2012) found that anthocyanins were the predominant polyphenolic group in black currants. Borges et al. (2010) found that anthocyanins accounted for 73% of the antioxidant capacity in black currant berries, while ascorbic acid contributed 18%. Of the anthocyanin antioxidant capacity contribution, 47% came from delphinidins and 23% came from cyanidins. Of the anthocyanins, Slimestad and Solheim (2002) found that over 97% were from cyanidin-3-*O*-glucoside, cyanidin-3-*O*-rutinoside, delphinidin-3-*O*-glucoside, and delphinidin-3-*O*-rutinoside. Pelargonidin-3-*O*-glucoside, pelargonidin-3-*O*-rutinoside, peonidin-3-*O*-glucoside, peonidin-3-*O*-rutinoside, petunidin-3-*O*-glucoside, petunidin-3-*O*-rutinoside, malvidin-3-*O*-glucoside, malvidin-3-*O*-rutinoside, cyanidin-3-*O*-arabinoside, cyanidin-3-*O*-(6''-p-coumarolglucoside), and delphinidin-3-*O*-(6''-p-coumarolglucoside) accounted for the remaining 3% of anthocyanins. Flavonol content of black currants is predominately myricetin and quercetin, with low amounts of kaempferol (Mikkonen et al. 2001).

A study conducted by Heiberg et al. (1992) found that, averaged across 10 black currant varieties, sugar content was 45% fructose, 40% glucose, and 15% sucrose and the acidity content was 88% citric acid and 12% malic acid. Milivojevic et al. 2012 found similar ratios in a study

comparing four different varieties over a two year period, with fructose accounting for 42% of total sugars, glucose accounting for 52% of total sugars, and sucrose accounting for 6% of total sugars. Acidity, however, was different, with a composition of 65% citric acid, 30% malic acid, and 5% tartaric acid.

The high mineral nutrients, polyphenolics, and ascorbic acid found in black currants vary among growing seasons (Lindhard Pedersen 2005; Magazin et al. 2011; Nes et al. 2011; Vagiri et al. 2013) and between cultivars (Lindhard Pedersen 2005; Nes et al. 2011; Rumpunen et al. 2011; Mikkonen et al. 2001; Milivojevic et al. 2012; Vagiri et al. 2013; Moyer et al. 2002; Bakowska-Barczak and Kolodziejczyk 2011). Rumpunen et al (2011) found that the coefficient of variation among 21 different black currant accessions for total catechins was 34% and for total anthocyanins was 14%. For the major anthocyanins, the variation was 12% for C3R, 22% for D3O, 29% for D3G, and 45% for C3G. Changes in sugar and acidity ratios across harvest dates within a season, however, appear to show very small changes (Heiberg et al. 1992), but the flavonol content was found to change drastically as fruit ripened, with myricetin only detected in fully ripe fruit (Mikkonen et al. 2001). Additional research has also shown significant differences in aroma compounds among multiple varieties of black currants (Christensen and Pedersen 2006) and large variation among cultivars in total essential oil content and over different developmental phases of the black currant shrub (Dvaranauskaite et al. 2009).

Aroma compounds are important for flavor and berry satisfaction in consumers and are typically measured in food as volatile compounds and as odors. In a study by Varming et al. (2004), 59 different aroma compounds were detected using nasal impact frequency profiling with 44 of the aroma compounds identified as known compounds. The main compounds identified as effecting aroma were esters and terpenes. In another study by Christensen and Pedersen (2006), 45 total volatile compounds were identified and quantified from 13 black currant varieties. While the qualitative differences between the varieties was rather minor, the quantitative differences were quite significant. In particular, large differences were noted between the group of aliphatic esters, methyl- and ethyl butanoate and methyl- and ethyl hexanoate, which are important compounds responsible for much of the “fruity” flavor of black currant berries. This result led the authors to conclude that variety selection is a larger determining factor for black currants sensory qualities than cultivation technique or fertility, with growing conditions simply helping bush performance and yield instead.

Black currant polyphenolics and ascorbic acid are impacted by geographic location. In a study by Vagiri et al. (2013) comparing black currant cultivars in a northern latitude and a southern latitude, ascorbic acid, total phenols, total anthocyanins, and soluble sugars were highest in the south, whereas phenolic acids and titratable acidity were found to be higher in the north. Individual polyphenol content was also different across geographical locations, with cyanidin-3-*O*-glucoside, quercetin glucoside, and kaempferol glucoside were highest in the north, whereas delphinidin-3-*O*-glucoside, delphinidin-3-*O*-rutinoside, cyanidin-3-*O*-rutinoside, myricetin malonylglucoside, and quercetin malonyl glucoside were higher in the south. When compared across years, Lindhard Pedersen (2005) found that the juice of 36 different varieties of black currants contained higher levels of soluble solids, ascorbic acid, and anthocyanins in warm and dry seasons.

Black currant leaves are an important source for teas and nutritional extracts. The extracts contain high levels of antioxidants and are good for the food and cosmetic industry as a replacement for synthetic antioxidants (Cyboran et al. 2014). Like berries, leaves have also had rather extensive research on nutritive compounds and phytochemical content. While the dominant polyphenol in fruits are anthocyanins, the dominant polyphenols in leaves are flavonols (Tabart et al. 2011; Cyboran et al. 2014). Cyboran et al (2014) found that leaf polyphenols are less than half of fruit polyphenols but still show a 30% higher antioxidant activity due to the higher levels of flavonols, while Tabart et al. (2006) found a higher content of phenolics but also found a higher antioxidant content in leaves than in fully ripe berries. Additionally, on a per branch basis, Tabart et al. (2006) also found that total phenolics and antioxidant capacity was over 20 times higher for the leaves than the fruit. Of the flavonols in leaves, quercetin was dominant, with the levels of myricetin varying widely, and with kaempferol only in low amounts. Rutin was the most concentrated glycoside and most abundant flavonol. The most abundant anthocyanidin in black currant leaves was petunidin. In a study conducted by Vagiri et al. (2015), the major flavonols in black currant leaves were quercetin-malonyl glucoside, kaempferol-malonyl glucoside isomer, and kaempferol-malonyl glucoside. Yang et al. (2015) found that quercetin and kaempferol were the major flavonol aglycones with only trace amounts of myricetin found, and that the 12 major flavonol glucosides identified accounted for 86-93% of the total of 27 flavonol glucosides found in black currant leaves. Liu et al. (2014) also confirmed that glycosides of quercetin and kaempferol were dominant in black currant leaves

and that quercetin-3-*O*-rutinoside, quercetin-3-*O*-galactoside, quercetin-3-*O*-glucoside, kaempferol-3-*O*-rutinoside, kaempferol-3-*O*-glucoside, quercetin-3-*O*-(6"-malonyl glucoside) and kaempferol-malonylhexoside were the most abundant flavonol. In a study conducted by Nour et al. (2014), the most abundant mineral in black currant leaves was calcium, followed by potassium and magnesium, and a lower level of sodium. High contents of iron and magnesium were also found.

Harvested buds are an additional source of polyphenolic compounds to be used in the extract market and for essential oils. These buds contain a high content of highly shelf-stable polyphenols, with the flavonols (58-70% of total flavonols as quercetin) and flavan-3-ols dominating and a good source of hydroxycinnamic acids, mainly neo-chlorogenic and chlorogenic acids (Ieri et al. 2015). Essential oil is also an important constituent of the black currant shrub, being responsible for flavoring and aroma enhancement in food and cosmetics. The potential for essential oil is also high, with 0.6-1.8% essential oil extracted by weight. The main chemical constituents are hydrocarbons (38-55%) and oxygenated terpenes (30%), with some 50 volatile compounds found (Dvaranauskaitė et al. 2009). Another study by de Toro (1994) found 123 substances with 66 of these identified. The main substance found was monoterpene hydrocarbons (80%) and sesquiterpene hydrocarbons (12%). The standard black currant "odor" was attributed to 4-methoxy-2-methyl-2-mercaptobutane. The approximate bud yield per hectare per year is about 400 kg, with roughly 50-100 kg of buds needed for 1 liter of essential oil production.

The seeds are typically a by-product of black currant fruit processing, but provide a valuable source of polyphenolics and oil with a high antioxidant value. The oil content of seeds ranges from 27 to 33%, with 44 triacylglycerols identified in the oil extract. The most intriguing component of black currant seed oil is the gamma-linolenic acid, which varies between 11-17% among cultivars. Additionally, black currant seed oil is found to be a good source of tocopherols and phytosterols, with quercetin-3-*O*-glucoside and *p*-coumaric acid being the main phenolic compounds (Bakowska-Barczak et al. 2009). The gamma-linolenic acid found in black currant seeds is shown to help hypertension, diabetes, and cancer (Bakowska-Barczak et al. 2009). The rich polyphenolic composition and high antioxidant activity of leaf and fruit extracts protect the plant and food products from the harmful effects of free radicals and prevent oxidative stress (Cyboran et al. 2014). In particular, the flavonol quercetin found in high quantities in black

currants has anti-tumor properties (Elattar et al. 2000) and the anthocyanins delphinidin-3-*O*-glucoside and delphinidin-3-*O*-rutinoside have also been found to have anti-cancer, pro-apoptotic effect on leukemia Jurkat cells (Leon-Gonzalez et al. 2015). Black currant extracts from leaves, buds, and fruits have shown strong antioxidant activities using classic in vitro assays DPPH, TEAC, ORAC, and ESR based on DPPH and ABTS radicals and have shown strong antioxidant potentials using cellular models, cellular antioxidant activity assays, haemolysis assays, endothelial cell, and polymorphonuclear neutrophils. The antioxidant effect is strongest from leaves and buds due to the correlation with total polyphenolic content of the extracts compared to fruit extracts (Tabart et al. 2012).

Black currant are a rich source of biologically active compounds including anthocyanins, proanthocyanidins, quercetin, myricetin, phenolic acids, and isorhamnetin, as well as ascorbic acid, which all contribute to the inhibition of certain cancers, and the inhibition of cardiovascular and inflammation related diseases (Karjalainen et al. 2008; Tabart et al. 2012). Several studies have demonstrated that black currant juice can prevent inflammation in obese individuals (Benn et al. 2014), but this effect is less strong than in lingonberry or cranberry juice (Kivimaki et al. 2012). When examining berry fruit teas, Savikin et al (2014) found that essential oils from decoction showed moderate activity against human cervix adenocarcinoma HeLa and human melanoma Fem-X cells, while essential oils from infusions showed high cytotoxicity only on chronic myelogenous leukemia K562, pointing to a strong role for black currant berry teas to provide cytotoxic activity in mutated cells.

The potential role of black currant juice for brain health has also been studied (Karjalainen et al. 2008). The findings show that anthocyanins are considered the most potent neuroprotective compound in soft fruits, of which black currants have some of the highest values. Additionally, many flavonols, particularly quercetin, are responsible for the inhibition of reactive oxygen species formed by beta-amyloid proteins, thus reducing oxidative stress-induced neuronal cell membrane damage. Quercetin, along with isorhamnetin and anthocyanins, is known to reduce blood pressure and improve blood flow, suggesting a potential protective function against the development of vascular types of dementia.

The very high potassium to sodium ratio in the berries and the leaves is beneficial for human health and is related to lower incidences of hypertension (Cyboran et al. 2014) and is

partly responsible for the high levels of electrolytes found in black currant juice (Kivimaki et al 2012).

#### **1.4 Cultivation**

Although currants are grown in Canada, they are rarely grown in the United States. Regardless, research and experience have shown currants capable of growing throughout the native range of *Ribes americanum* and *Ribes hirtellum*, from New Brunswick and Alberta to New Mexico and West Virginia when provided adequate moisture (Barney 1996). Black currant production requires between 800 to 1600 hours below 7°C to remove the bud dormancy, which makes cultivation possible in all states except Florida, Louisiana, and Hawaii (Dale 2000; Hummer and Barney 2002; Bratsch and Williams 2009). Inadequate chilling results in uneven bud break and poor fruit quality (Brennan 2006). Dale (2000) estimated that North America could potentially support up to 40,000 hectares (100,000 acres) of *Ribes* production.

Black currants perform best on well-drained soil with high organic matter and a slightly acidic pH between 5.5 and 7.0 (Hummer and Barney 2002) with raised bed plantings sometimes effective on poorly drained soil (Bratsch and Williams 2009).

Black currants are typically planted in the spring as soon as the ground can be worked, as the leaves can withstand temperatures down to -6.5° C. They can also be planted in the early fall to allow root formation and plant establishment before winter (Hummer and Barney 2002), but mulching should be done to reduce winter frost heaving effects. Black currants are typically propagated with 15-25 centimeter hardwood cuttings taken from dormant plants in the late fall through late winter (Brennan 2006). At planting, it is best to soak the roots for 1-2 hours before planting and to root prune damaged and inappropriate roots. When placing the plants in the ground, burying 1-3 buds will help encourage root growth and stem rejuvenation. Shoot pruning down to 6-10 inches after planting in the spring can also help encourage new stem development. Flowers and fruit set should be removed in the first year of planting (Bratsch and Williams 2009). Black currants are typically harvested in the third year with full production typically being reached in the fourth or fifth year (Milivojevic et al. 2012).

The majority of the fruit is harvested from one and two year old wood (Hummer and Dale 2010). Black currants are grown both as an individual bush and in closer spacing as a hedgerow. When grown individually, spacing is typically 1-1.5 m within row, with pruning to keep the

number of stems down to 10 to 15 and to maintain a cup shape for optimal light penetration, airflow and harvesting ease. Roughly 4 strong, one-year old stems are selected every year with the remaining one-year old stems removed and any stem over three years is removed (Bratsch and Williams 2009). For mechanical harvest, a hedgerow system is preferred with black currant varieties preferentially selected for compact growth (Hummer and Dale 2010). In these systems, the spacing is 30-35 cm apart within rows and 3 m apart between rows with pruning reduced to outward branching. Orchards are then cut to the ground every 2 or 3 years up to every 5 to 10 years and allowed to rejuvenate (Brennan 2006; Hummer and Barney 2002; Bratsch and Williams 2009). As the plant density increases, vegetative growth per plant decreases. In the first few harvests, yield per plant remains the same, thus higher density plantings show greater yield per hectare. As the plants mature and gain in size, the yield per bush increases with plant spacing and thus the yield per hectare is lowest at medium density plantings (Nes 1979).

Some researchers have proposed a high-density, biennial production system where the black currants are harvested with a combine-style harvester that removes berries and cuts the stems to the ground in the third year after planting. They are then allowed to grow vegetatively in the fourth year and the process repeats itself in the fifth year (Olander 1993). Another advantage to this method is the removal of the woody stems, which could be used for mulching or as a fuel source. The multi-stem black currant shrubs have a higher proportion of bark with a higher nitrogen content (1.25%) than most woodchips and a higher heating value (19.41 MJ.kg) comparable to other woodchips (De Toro 1994).

In hot and dry climates, partial shade, soil mulch, and adequate irrigation are essential for black currant production. In these environments and in most environments in North America, black currants grow exceptionally well on the cooler north and northeast slope exposures. The northern slopes and shaded environments also help reduce risk of frost by delaying early spring bloom (Bratsch and Williams 2009; Dale 2000).

Adequate water is needed for black currants to flower and yield properly, with roughly 1 inch per week needed from bloom until harvest and periodically after harvest during periods of drought (Bratsch and Williams 2009). Irrigation is most important from flowering until harvest, particularly during dry periods when rainfall is not adequate (Ostermann and Hansen 1988). However, maintaining adequate moisture in the fall during floral and leaf initiation is also important for keeping an optimal number of strigs and flowers per node (Cerekovik et al. 2014).

Soil moisture is best maintained at 15-20% on a stony silt loam, particularly in the establishment years and early years. Under 15% soil moisture, berry yield begins to drop while maintaining soil moisture above 20% can be difficult and expensive. Irrigation does little to reduce soluble solids and only effects berry weight in the first few years after planting (McCarthy and Stroker 1988). Drought tolerance among black currants is variety dependent (Cerekovik et al. 2014).

Mulching can also be used to help maintain proper soil moisture by reducing water loss. Mulching increases root and shoot growth and helps encourage roots near the soil surface while maintaining roots deeper in the soil (Larsson and Jensen 1996; Larsson et al. 1997). Mulching can also be useful in increasing plant yield and black plastic can be an effective mulch (Dale 2000; Rhodes and Tabley 1983). Wood chips can be used, but care should be taken to ensure proper nitrogen is added to the woodchips to prevent nitrogen deficiency and to reduce nitrogen immobilization (Larsson et al. 1997). Woodchip and other organic mulches can be effective in reducing soil temperature, maintaining soil moisture, and suppressing weeds when 5-10 cm is added around the base of the black currant or within rows out to the dripline (Bratsch and Williams 2009).

While mulches can be used to prevent weeds, herbicides are typically used to maintain a weed free strip under the black currants out to the dripline. Mechanical cultivation can also be used but care must be taken to keep cultivation no deeper than 5 cm to prevent root damage in the shallow-rooted black currants (Hummer and Barney 2002; Bratsch and Williams 2009). The critical weed-free period for currants is from the beginning of vegetation in the spring until the shoots stop growing in late July (Rhodes 1984). In between rows, cover crops are typically grown for ease of maintenance with little impact on the black currants growth, as long as the cover crops are kept at least a foot outside the black currant dripline (Pedersen 1997; Brennan 2006; Bratsch and Williams 2009), with no difference found between the type of cover crop grown (Lindhart Pedersen 2001). Bratsch and Williams (2009) reported that the use of clovers as inter-row cover crops can lead to untimely nitrogen release in the late fall as the clovers die-back. Different weed species growing under the dripline, however, may have varying impacts on fruit quality, brix, pH, sugars, ascorbic acid, and anthocyanins as found in preliminary research by Miller et al. (2012).

Black currants require fertilization, but the rates required are best determined on a site-by-site basis. In some areas, fertilizer is best applied in a single application in the spring (Hobson



et al. 2012). Other researchers have found little effect between application in the spring or summer and little effect on whether the fertilizer was applied through fertigation or broadcast (Opstad et al. 2007). Regardless of spring or early summer fertilizer applications, applying fertilizer in late summer or early fall can result in increased and continued black currant growth when plants should be preparing for dormancy, resulting in a greater susceptibility to winter damage (Bratsch and Williams 2009). Mature currants typically require around 100 kg of nitrogen, 20 kg of phosphorous, and 40 kg of potassium per year per hectare. To properly determine nutrient levels on individual sites, leaf samples should be collected in early August after shoot growth has ceased and tested for foliar nutrients (Hummer and Barney 2002).

Fruiting requires between 120-140 frost-free days which results in black currants being harvested between mid-to-late June to late July for black currants grown in North America. Black currants ripen over a range of 1-2 weeks. For machine harvest, ethephon is sometimes applied to the crops 1-2 weeks before harvest to ensure ease and maximum yield at harvest. Harvesting is responsible for 60-70% of the labor needs in commercial operations (Hummer and Barney 2002).

Black currants are tolerant of spring frosts, a trait that could be further improved through breeding (Dale 1987). The shrubs are hardy to between -40° C and -60° C (Dale 2000; Hummer and Barney 2002) with some varieties cold hardy up to USDA zone 2 (Bratsch and Williams 2009). The early bloom of black currants, however, is not immune to the cold and spring frosts with temperatures less than -2° C damaging the blooms (Brennan 2006; Bratsch and Williams 2009). High solar irradiation can cause leaf sunburn while temperatures above 30 degrees Celsius can cause leaf flagging and temperatures above 35 degrees Celsius for 3 or more days can cause fruit drop, particularly near ripening (Bratsch and Williams 2009; Harmat et al. 1990).

The main disease of black currants in North America is powdery mildew, called American gooseberry mildew in Europe, with leaf spot and white pine blister rust causing minimal damage (Dale 2000; Bratsch and Williams 2009). Powdery mildew is most commonly controlled with applications of sulfur from budbreak through pre-harvest (Hummer and Barney 2002). Other control options are to remove diseased and damaged shoot tips in late fall (Hummer and Barney 2002). Horticultural mineral oil applications every 2-4 weeks have also been shown to be effective in reducing powdery mildew severity in vegetative growth when compared to

controls (Hummer and Picton 2001). Proper disease control can help optimize juice phytochemistry and quality (Nwankno et al. 2012).

Black currant berries are well suited to storage with tougher, thicker skin than most berries, maintaining good quality for 1-2 weeks in refrigerated environments and up to a year while frozen (Hummer and Barney 2002). While frozen, black currant polyphenols have shown to remain stable with no significant decrease in flavonoids, procyanidins, and antioxidant potential up to 9 months (Bakowska-Barczak and Kolodziejczyk 2011). In fact, freezing has been shown to increase anthocyanin levels in the pressed juice as the freezing process helps break down cell walls in the skins for optimal extraction (Kampuse et al. 2001). Freeze drying black currant leaves and buds is an effective method for plant tissue storage, with little effect on antioxidant capacity when dried products are stored at room temperature (Tabart et al. 2007). Microencapsulation of black currant parts has also been shown to be an effective method for long term storage of antioxidant and bioactive-compound rich food additives (Bakowsk-Barczak and Kolodziejczyk 2011).

### **1.5 Multifunctional Polycultures and the Understory Niche**

Multispecies agricultural systems have been theorized to provide a vast array of functions and services to the environment, ecosystem, and human self-preservation. Proposed benefits include enhanced landscape productivity, ecological services, and economic profitability and stability (Malezieux et al. 2009). One term to describe these types of agricultural systems is multifunctional polycultures, with a focus on shifting our agricultural paradigm from monoculture, single-purpose, annual cropping systems towards polyculture, multi-functional, perennial cropping systems. These systems include both woody and herbaceous perennials in agroforestry systems, managed wetlands, and extensive cover cropping during the 6-8 months when traditional agricultural systems would remain bare (Jordan and Warner 2010).

Multifunctional polycultures extend not only to agricultural systems designed for human food, fuel, and fiber, but to animal feed and grazing systems, parks and recreation, and conservation efforts (Lovell et al. 2009). While integrating these systems directly into the full farm landscape is possible, the main focus is on the marginal land on the farm: woodlots, wooded fencerows, field edges, hedgerows, riparian habitats and areas at increased risk for flooding (Jordan and Warner 2010). These areas are already unsuitable or subprime for conventional crops and

agricultural systems and are capable of providing increased landscape benefits with limited to no risk to the main crops. In fact, the farm site sustainability can be increased by focusing on the marginal land by conserving soil and water and reducing run-off, increasing water quality, carbon sequestration, and biodiversity, and reducing incidents of flooding (Jordan and Warner 2010). Other benefits to the farm site are reduced wind damage, enhanced site aesthetics, and shaded environments for workers and farm animals (Malezieux et al. 2009).

One particular benefit of increased biodiversity at the farmscale level is an increase in pollination and pest management. This can be accomplished by selecting plant species that sustain beneficial organisms and provide alternate feed for pest species instead of beneficial crop species (Philips et al. 2014). The concept of trap crops, plants grown to attract and hold pests away from crops of interest, has been shown to greatly reduce pest pressure and crop damage by diverting pest species while also providing habitat to retain predator species (Malezieux et al. 2009; Philips et al. 2014). Approximately 99% of all pests are naturally controlled by native enemy species, with the average pest species having 10-15 natural enemies, and some pests such as gypsy moth (*Lymantria dispar*) having up to 100 different natural enemies and predators (Pimentel et al. 1997).

Habitat loss and fragmentation has also led to a reduction of beneficial insects and pollinators. An estimated one-third of the world's food production is reliant on pollination and in North America, up to 4000 bee species are capable of pollination. Thus, proper conservation of the environments and ecosystems is integral to future landscape resilience (Pimentel 1997). Polyculture pest and disease resistance is attributed to the dilution effect of the host species, the physical barriers presented by the multilayered systems, and the increased phytochemical and predator effects utilized by the diversified plant species (Malezieux et al. 2009). By increasing the number of species grown on a farm site, it's possible to increase endangered species conservation and reduce the current extinction rate, estimated at somewhere between 1,000 to 10,000 times higher than the naturally occurring extinction rate (Jordan and Warner 2010; Pimentel et al. 1997).

While simply growing an increased amount of perennials in these marginal lands is possible, focusing on productive plantings that provide additional farm income is possible. By mixing productive food crops within a system, a potential overyielding effect may occur, whereby the combined yield overall of the crops grown together is greater than the yield

potential of any of the crops grown in monoculture. The concept of intercropping shows potential for overyielding, with studies showing the intercropping of legumes with grain species can lead to an increase in grain quality. Additionally, the shading effect provided by an overstory can increase the quality of the shaded understory crop, as is the case with shade-grown coffee and fodder (Malezieux et al. 2009).

A major issue in polyculture and mixed cropping systems is the plant-plant competition exerted on one another. Light availability is a major component of plant competition resulting in reduced plant productivity and yield for the shaded plant. The concept of overyielding is typically attributed to greater light use efficiency on the site overall. By filling individual ecological niches within the built ecosystem, plant competition can be reduced while facilitating increased site productivity. Two distinct ecological niches exist within these larger, multilayered polyculture systems: the overstory and the understory. In the understory, the greatest competition comes from changes in light quantity and light quality (Malezieux et al. 2009). In natural ecosystems, the understory is inhabited by plants that are shade tolerant, capable of efficient utilization of the reduced light amounts and quality (Boardman 1977; Valladares et al. 2016).

The understory has some benefits as well as set-backs for the plants growing in these environments. The understory tends to have cooler temperatures in the daytime and warmer temperatures at night due to the overstories obstruction of convective and radiative heat loss and canopy penetration (Valladares et al. 2016). Some other benefits of a proper overstory include improved soil fertility, reduced soil erosion, increased soil water content from reduced evaporation, increased water infiltration rates, and groundwater lift and distribution through root systems (Bayala et al. 2015). Soil moisture also tends to be higher overall due to reduced evaporation, but the canopy can intercept 10-30% of the precipitation, particularly during light rain, fog and dew. Additionally, in dry years, the effect of increased root competition can lead to drier soil conditions in the understory (Valladares et al. 2016). A major issue with the understory environment is higher air humidity and reduced light infiltration through the canopy, increasing the risk of fungi and herbivory damage, which can further reduce the amount of light the plant receives (Valladares et al. 2016; Kater et al. 1992; Bayala et al. 2015; Valladares and Niinemets 2008; Gommers et al. 2013).

Plants have adapted to the reduced light irradiance and quality in one of two ways: shade avoidance or shade tolerance. Shade avoidance is favored by shade-intolerant species and

involves physiological adjustments to escape the understory environment, typically apical dominance for increased stem, internode, and petiole elongation and reduced branching, leaf expansion and development, and yield (Roig-Villanova and Martinez-Garcia 2016; Villanova et al. 2016). While an effective strategy for breaking through an overstory canopy, this level of plant plasticity is unsustainable for the plant and may be fatal to the plant if the overstory canopy is not breached before the plant uses all available carbon resources. Shade tolerance is favored by shade-tolerant species and involves maximizing net carbon gain through photosynthetic efficiencies and leaf plasticity, and enhanced persistence and investments in storage and defense. This typically involves leaves spreading out to increase leaf area while reducing leaf density, larger, richer chloroplasts with a higher ratio of chlorophyll b to chlorophyll a, and a reduced apical dominance with lower stem elongation (Boardman 1977; Gommers et al. 2013; Roig-Villanova and Martinez-Garcia 2016; Villanova et al. 2016).

Overall, greater plant plasticity is found in shade intolerant plant species that adapt their growth quickly to avoid the shaded conditions, while shade tolerant plants tend to be more plastic in morphological adaptations for light capture optimization (Bayala et al. 2015; Valladares and Niinemets 2008). This is also due to the fact that shade tolerant species maintain a lower relative growth rate than shade intolerant species, both under shade conditions and in open conditions. Thus, the overall change in plant phenotypic plasticity is minimal at best (Gommers et al. 2013; Valladares and Niinemets 2008).

The adaptations for shade tolerance tends to be negatively associated with drought tolerance, with shade tolerance favoring foliar biomass allocation and drought tolerance favoring root biomass allocation. For this reason, the shade tolerance of a plant can be directly affected by the water availability to the plant. The soil water balances and available soil nutrients are an indirect effect of the overstory on the understory environment. Shade tolerance and intolerance exist along a spectrum, with plants either being shade tolerant and high light intolerant and considered shade plants or being shade intolerant and high light tolerant and considered a sun plant. The damage to plants under excessive light irradiance include plant desiccation and UV radiation stress (Valladares et al. 2016; Valladares and Niinemets 2008).

Previous research has been conducted on the effects of shading on the growth and productivity of crop species. Much of the research has been conducted in regions with high levels of solar irradiance and heat, using shade netting as a method to reduce both parameters. In

grapes, this treatment with shade resulted in decreased meristem growth and reduced total shoot biomass by 20% (Greer et al. 2010), along with a reduction in leaf weight, volume, density, and thickness but little effect on leaf area (Heuvel 2004). Additional research on grapes grown in shaded conditions has found that the level of total anthocyanins in grapes are unaffected by shading, but a shift in the individual anthocyanins was observed (Human and Bindon 2008). In coffee, it has been noted that coffee grown under shade trees has increased cupping quality and flavor, with larger, heavier berries produced with a minimal decrease in yield. Additionally, plant performance was increased due to improved photosynthesis and morphological changes favoring an increased leaf area index (Bote and Struik 2011). In blueberries, Kim et al. (2011) found that shading decreased the number of shoots per shrub but increased the individual shoot length, while increasing leaf area and decreasing leaf thickness. As the level of shading increased, the plant yield decreased, with final results indicating shading level should be no more than 60% for blueberries to remain economically viable. In a study by Roper et al. (1995) on the timing and intensity of shading on cranberries, it was found that the most significant effect of shading on cranberry yield was during fruit set.

Previous studies on black currant shade tolerance have found cultivar specific differences in shade adaptation and performance (Djordjevik et al. 2014; Šavikin et al. 2013). In areas with high levels of irradiance, berry damage was reduced under shading with fairly comparable yields across shaded and unshaded treatments. Soluble solids and flower buds per shoot were highest in the open treatments but ascorbic acid was found to be highest under light green shade netting. Dark green shade netting caused a loss of radical scavenging activity (Djordjevik et al. 2014). In another study by Šavikin et al. (2013), shaded environments resulted in a decrease in berry flavonoids, phenolic acids, and anthocyanin compounds but had little effect on the radical scavenging activity against DPPH radicals. While all varieties had lower amounts of total phenolics under shading, the variety Ben Sarek had increased flavonols, phenolic acids, and anthocyanins under shade. Both studies showed promising results for black currant shade performance. While some of the berry qualities were decreased under shading, the berries still represented a good source of polyphenols and remained economically viable for growers. In another experiment, Toldam-Andersen and Hansen (1993) found that 50% shade resulted in little statistical difference in black currant shoot and leaf growth; internode length increased under

shade with a resultant increase in shoot length, the number and weight of leaves was unaffected, and root growth decreased.

## 1.6 Table

**Table 1.1** Common nutrients compared across common fruits and berries. Data from FAO 2014.

Nutrient value per 100 g, raw							
	Black currant	Blueberries	Grapes	Cranberry	Oranges	Blackberries	Bananas
Calcium (mg)	55	6	10	8	43	29	5
Iron (mg)	1.54	0.28	0.36	0.23	0.13	0.62	0.26
Magnesium (mg)	24	6	7	6	11	20	27
Phosphorous (mg)	59	12	20	11	23	22	22
Potassium (mg)	322	77	191	80	166	162	358
Zinc (mg)	0.27	0.16	0.07	0.09	0.08	0.53	0.34
Vitamin C (mg)	181	9.7	3.2	14	59.1	21	8.7



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## **CHAPTER 2: EFFECTS OF VARYING LEVELS OF ARTIFICIAL SHADE ON THE PHENOLOGY, PHYSIOLOGY, AND YIELD OF BLACK CURRANTS (*Ribes nigrum*)**

### **2.1 Abstract**

Multifunctional Woody Polycultures have been proposed as a more ecological-friendly system of production agriculture that relies on woody perennials grown within a mix of other perennial crop species. However, little research has been conducted on productive shade tolerant crops that can fill the understory niche in these systems. An experiment was conducted on *Ribes nigrum* L. cv 'Consort' to measure the physiological and growth response to various levels (0, 35%, 45%, 65%, and 85%) of artificial shade. The study was located at the University of Illinois Fruit Research Farm in Urbana, IL. This 2-year experiment was initiated in 2016 on 4-year-old black currants. In 2016, there was a 5% reduction in yield from 65% shade, with 85% shade reducing yield by 28%. Fruit ripening phenology was impacted, with a delayed onset of initial fruit ripening by up to 20 days. Brix and berry size was statistically similar across all shade levels. Plant height remained statistically similar while leaf morphology shifted significantly. In 2017, yield was reduced 11% at 65% shade and 57% at 85% shade. Fruit ripening was less affected by shading with only a 5 day delay in fruit ripening in the 85% and 65% shade treatments. Berry weight favored shading, with the shaded treatments weighing more than the control, but volumes were not different. Brix was lowest in the 85% treatment and was similar for the remaining treatments. Plant height increased under shade, with the control lower than the shaded treatments. These results indicate a rapid response to immediate shading after floral and vegetative cell initiation in year one and better long-term adaptation to shade in year two. Based upon these results, black currants can produce excellent yields under partial shading making them a potentially valuable component of a multi-species agroforestry system as an edible understory crop.

### **2.2 Introduction**

In the Midwest United States, the primary agricultural systems are annual monocultures of seed crops. These systems are productive but generate a number of negative consequences including land degradation, loss of soil fertility, nutrient and pesticide leaching into waterways, and significant greenhouse gas emissions (Josiah et al 2004). An alternative form of agricultural

production may be needed in the not too distant future that is both resilient to the changing climate and functions similar to a closed ecological system. One option is to model agricultural systems after the Midwestern Oak Savanna that was the dominant ecosystem throughout the Midwest. We have termed this system Multifunctional Woody Polyculture (MWP) (Lovell et al 2017).

Multifunctional woody polyculture is a potential alternative to current agricultural production system. The benefits of MWP systems include reduced soil erosion and nutrient runoff, carbon sequestration instead of carbon emissions, resiliency to climate fluctuations, and increased biodiversity (Jordan and Warner 2010). Agricultural landscapes can be designed to produce an agricultural product while also aiding in environmental services and functionality (Lovell et al. 2009). Perennial crops have an advantage over annual crops due to greater biomass accumulation from a single planting, reduced inputs required per season, conservation of soil from year-round cover, and elimination of annual tillage practices. Polycultures have an advantage over monocultures for several reasons, including increased diversity, potential overyielding and economic diversification. In a side-by-side study, Davis et al. (2012) found that the combined yield and ecosystem benefits from a diverse cropping system could meet or exceed the same performance of a less diverse cropping system while using less synthetic agrichemical inputs. Intercropping systems have exhibited reduced pest pressure and crop damage when compared to a strictly monoculture system (Coolman and Hoyt 1993).

While perennial polyculture is our ultimate goal, research is needed to explore the individual crop components and their relationship to the overall agroecosystem. In addition to ecosystem benefits and agricultural production, these species provide many other services such as windbreaks, riparian buffers, and alley-cropping arrangements (Josiah et al. 2004). In alley-cropping systems, the standard herbaceous annuals, such as corn (*Zea mays*) or soybean (*Glycine max*), are planted between rows of woody perennials, such as chestnut (*Castanea mollissima*) or hazelnut (*Corylus avellana*). The limiting factor in these systems however, is the availability of light due to intercrop competition, which results in a distinct overstory and understory niche.

Black Currants (*Ribes nigrum*) are an agricultural berry crop that is a potential candidate as an understory crop. The berry is highly nutritious with high levels of ascorbic acid (Vitamin C) and flavonoids, leading to high antioxidant levels (Gopalan et al. 2012). The major flavonoids are the flavonols myricetin and quercetin (Mikkonen et al. 2001), and the anthocyanins cyanidin-

3-glucoside, cyanidin-3-rutinoside, delphinidin-3-glucoside, and delphinidin-3-rutinoside (Brennan 2008). Black currants typically contain 130-200 mg/100 mL juice of ascorbic acid, and with breeding, these values are estimated to reach over 350 mg/100 mL juice (Brennan 2008). Black currants are also used for jams, jellies, liqueurs, teas, extracts, and additives. Black currants are primarily grown in the European nations of Russia, Germany and Poland with 2005 global production of 1017 tons. Currants were grown in America up until the 1920's, but a disease that targeted both currants and the white pine tree (*Pinus* subg. *Strobus*) swept through the region, resulting in the banning of black currant cultivation in America to save the white pine timber industry (Hummer and Dale 2010). The availability of resistant varieties of black currant, along with a reduced role of white pines in modern day forestry, creates an opportunity for a comeback of currants. Increased consumer interest in health foods, combined with a growing demand for more sustainable agricultural practices, leaves black currants in position to fill a growing niche in the health food market. However, in the United States and Canada, black currant production is low, at an estimated 60-120 tons per year (Brennan 2008).

In terms of polyculture production systems, currants have the potential to produce a valuable product in the shaded understory niche. The quick growth to maturity, three to five years, makes this perennial crop a good choice in the staggered maturation of the key species in the polyculture systems. Currants can withstand cold temperatures and fruit early, ideal traits in the Midwest United States (Hummer and Dale 2010). Additionally, currants naturally occur in understory environments and are known to produce and grow well under shaded conditions (Bratsch and Williams 2009; Djordjevik et al. 2014; Harmat et al. 1990; Šavikin et al. 2013; and Toldam-Andersen and Hansen 1993). However, empirical research has been limited in determining the agricultural potential of black currants grown under the shade of an over-story of larger-sized fruit and nut trees. Sunlight is necessary to provide the required energy for biomass production. Most agricultural crops require full sunlight for optimum yields, an issue when considering the potential of agricultural production underneath large trees in agroforestry. Previous research has found reduced lighting to affect currant physiology, including impacts on flower initiation and number and length of nodes being produced (Toldam-Andersen and Hansen 1993). Light intensity also affects fruit firmness, flavor, and secondary metabolites (Šavikin et al. 2013). Past research also found that shade netting resulted in decreased fruit damage due to a reduction of light intensity that causes sunburn and plant stress. Shade netting was found to delay

flower set and ripening time of black currants for 5-10 days, with greater shade resulting in an increase in fruit clusters. However, with shading, there was a reduction in berry sucrose and glucose sugars, with an increase in citric acid in deep shade (Djordjevik et al. 2014). In another experiment, Toldam-Andersen and Hansen (1993) found that 50% shade resulted in little statistical difference in black currant shoot and leaf growth; internode length increased under shade with a resultant increase in shoot length, the number and weight of leaves was unaffected, and root growth decreased. As for yield, they found a significant decrease in yield, with 50% shade causing an 8% decrease in yield when compared to the open control.

An effective multifunctional woody polyculture system will require crops that produce adequate yield under partial shade. Black currants have potential as an understory crop, with healthy, marketable, good-yielding fruit and shade tolerance. However, there is a paucity of research on the effects of shade on black currant physiology and agricultural potential in the Midwestern US. The objectives of our research were to study the impact of shade on black currant growth and yield.

### **2.3 Materials and Methods**

This study was conducted in 2016 and 2017 on the Woody Perennial Polyculture project site at the University of Illinois Fruit Farm in Urbana, Illinois. Soil types present are a Flanagan series (fine, smectitic, mesic Aquic Argiudolls) and a Thorp series (fine-silty, mixed, superactive, mesic Argiaquic Argialbolls). The existing site had east-west orientation with 4-year old *Ribes nigrum* L. cv 'Consort' set at 1.2 m spacing between plants and 4.8 m spacing between rows. Plants were fertilized in spring 2016 with urea at a rate of 112 kg N/ha and in spring 2017 with poultry manure at a rate of 112 kg N/ha, because the site is being converted to organic production. Disease was treated with applications of mineral oil (Ultra-Pure, BASF Corporation, NC, USA) applied as needed from mid-May until mid-August. Weeds were removed in a 1.2 meter band around plants using glyphosate, dicamba, and light tillage in 2016 and with light-tillage only in 2017. Pruning was done during dormancy to select roughly four 1-year stems, four 2-year stems, and four 3-year stems for an average of 10-12 stems per plant post-pruning.

Four artificial shade treatments were used with one open control. Shade netting at stated levels of 20% white, 30% black, 50% black, and 70% black (Dewitt Company, Sikeston, Missouri, USA) were placed over six currant plants. Shade cloth PAR values were measured at

37%, 45%, 65%, and 83% respectively and are reported as 35%, 45%, 65%, and 85%. Metal conduit was used to create a gothic frame structure 3 m wide and 1.8 m high in the center and slanting down to 0.9 m at the edges. The shade structure extended past the end plants by 0.9 m. A 90% black shade netting treatment was used initially in 2016 but due to site limitations, this was replaced with the 20% white shade netting three months after the initial site set-up in February, in early May before full flower bloom.

Experimental design was a randomized complete block with four blocks. Each treatment consisted of six plants, with the outer two plants serving as buffers and data collected from the center four plants. The shade netting was installed in early spring before full leaf out on March 12<sup>th</sup> in 2016 and removed after leaf fall in late November and was installed in late spring before full flower break on April 13<sup>th</sup> in 2017.

### *Measurements and Analyses*

Soil moisture was measured weekly from mid-May until August using a TH2O Portable soil moisture probe (Dynamax Inc. Fresno, CA, USA). Two readings were collected from the center of each plot and averaged across the season for each plot prior to analysis. PAR sensors were installed in each treatment in block A and were averaged across the year.

Berry ripeness was tracked from first berry color change to full peak ripeness. Veraison is a term used in viticulture to describe the onset of ripening and describes the change of color of the berries. Percent veraison was recorded as the percent of berries with purple coloring and was visually estimated every week for each plant and averaged by plot. When the site average was 70% veraison, soluble solids were measured and tracked weekly until harvest and recorded as °Brix. Soluble solids were measured in the field using an Atago Digital Hand-held “Pocket” Refractometer PAL-1 (Atago USA, Inc, Bellevue, WA, USA) by selecting berries from the middle of the stem and the middle of the strigs in 2016. In 2017, 4 berries per plant were selected from the middle of the stem and the middle of the strigs at random for a total of 16 berries per plot that were taken to the laboratory for analysis of brix, pH, and titratable acidity until harvest.

Treatments were harvested by hand when 95% of the berries were ripe as judged by °Brix and visual measurements and before significant berry drop occurred. In 2016, all treatments were harvested on July 5<sup>th</sup>. In 2017, the control and 35% treatments were harvested on June 27<sup>th</sup> while the 45%, 65%, and 85% treatments were harvested on July 1<sup>st</sup> and 2<sup>nd</sup>. Harvest weight was

recorded for each of the plants and averaged across plots. Subsamples of 300 berries per bush were then removed from each plant harvest for analysis. From this subsample, 200 berries were weighed and water was added to 400 mL and reweighed. Berry volume by displacement was calculated by:

$$400 - [ (\text{weight of 200 berries plus water to 400 mL}) - (\text{weight of 200 berries}) ]$$

The 200 berries were then drained and frozen for further analysis. The 100 remaining berries were weighed and placed in a drying oven at 50°C for at least 96 hours and reweighed to calculate percent dry matter.

Laboratory berry chemical quality measurements in 2017 were conducted with a total of 16 berries per plot. Three berries were used to conduct soluble solid measurements with the pocket refractometer and averaged for berry brix per plot. The remaining 13 berries were combined by treatment, placed in a blender for quick maceration, and squeeze-pressed through a fine metal filter. Juice pH was measured using an Orion 350 PerpHect benchtop meter (Thermo Fisher Scientific, US) with a wine must pH electrode (HI1048, Hanna Instruments, Inc., Woonsocket, RI). Titratable acidity (T.A) was performed in duplicate by taking 6 gram juice samples and adding 50 mL of water. Samples were titrated to a pH of 8.2 with 0.1 N NaOH and calculated as % citric acid. At harvest, 16 berries per plant were taken and 3 were used for final soluble solids per plot. The remaining 13 berries were combined by plot and juiced using previously stated methods and final pH and T.A were measured per plot.

Plant height was measured in May, August, and during dormancy. Leaf area and weight was measured per plant after bloom break in May and after harvest in July by randomly selecting 5 mature leaves from the middle of the stem. Leaf area was measured using a CI-202 Portable Laser Leaf Area Meter. Fresh weight was taken and dry weight was taken after drying the leaves for a minimum of 48 hours at 50° Celsius. Specific leaf weight (SLW) was recorded as average mg dry weight per average cm<sup>2</sup> area of leaf sample.

Powdery mildew and sunscald damage were evaluated from May until August and was rated on a 10-point scale. 0 = no plant damage; 1 = damage detected; 2 = 6-20 leaves damaged, presence of powdery mildew mycelium; 3 = 20+ leaves damaged or infected; 4 = deep leaf browning; 5 = leaf and shoot tip necrosis; 6 = necrosis of old shoots and leaves; 7 = increased

necrosis of all-aged tissue, berry damage noticed; 8 = +50% plant tissue necrosis; 9 = complete plant death.

Experimental design was a randomized complete block with 4 replications. Analysis of variance was performed using JMP Pro (c13, SAS Institute, Cary, NC, USA). Subsamples were averaged across replications before running the analysis. Means were separated using the Tukey-Kramer multiple comparisons test at a significance level of  $\alpha=0.05$ . Parameter means plus or minus standard deviation by treatment and year are given.

## 2.4 Results

### *Yield*

There was a significant year by treatment interaction, so data are reported separately by year. Averaged across all treatments, the yield in 2017 was 1094 grams per bush while the 2016 yield was 694 grams per bush. In 2016, there was no difference in yield amongst any of the treatments, in 2017, the 85% shade treatment had a lower yield than the control (Table 2.1). Averaged across both years, the 65% treatment only reduced yields by 8%.

### *Berry Ripeness*

Berry ripening started on June 7<sup>th</sup> in 2016 and on May 26<sup>th</sup> in 2017. The site averaged 70% veraison on June 28<sup>th</sup> in 2016 and June 21<sup>st</sup> in 2017. Berry harvest began on July 5<sup>th</sup>, 2016 and began on June 23<sup>rd</sup>, 2017. Of the 7 rating dates of visual plant veraison measurements, only one date was non-significant in 2016 (Table 2.2a). Significant differences were measured between the 85% treatment and control for 6 rating dates and significant differences between the 65% treatment and control for 5 rating days. In 2017, of the 7 rating dates of visual plant veraison measurements, 4 rating dates were non-significant. The 85% treatment was different from the control on 4 rating dates while the 65% treatment was different from the control on 3 rating dates.

Berry soluble solids showed no differences among the treatments and control for the initial 3 dates of testing in 2016 and 2017 (Table 2.2b). At harvest in 2016, the °Brix of the control and 35% treatment were higher than the 85% treatment. At the beginning of harvest in 2017, the °Brix of the control was higher than the 65% or the 85% treatments.

### *Berry Physical Properties*

Berry weight was higher in 2016 at 172 grams per 200 berries than in 2017 at 140 grams per 200 berries, however, there were no differences among treatments (Table 2.3). Berry volume was significantly higher in 2016 (166 mL/200 berries) than in 2017 (134 mL/200 berries). There were no differences in berry volume between treatments in 2016. In 2017, all shaded treatments had higher berry volumes than the control. The main effect of treatment was significant for berries per bush. Across both years, the 85% treatment had a significantly lower estimated number of berries per bush than all other treatments.

### *Berry Chemistry*

Harvest berry soluble solids differed by year, by treatment and by the treatment/year interaction. In 2016, the average soluble solids was 12.3 °Brix while in 2017 the average soluble solids was higher at 14.3 °Brix. In 2016, the 85% treatment had lower °Brix than the control and 35% treatment (Table 2.4). In 2017, the control, 45% treatment and 65% treatment all had a higher °Brix than the 85% treatment. The average mean titratable acidity for 2017 was 3.51% and was not different among treatments. The pH also was not different among treatments, with an average of 2.77. Percent berry dry matter varied by treatment. The 85% treatment had significantly lower percent dry matter than the control, 35%, and 45% treatments, while the 65% treatment had significantly lower values than the control and 35% treatment.

### *Leaves*

The year by treatment interaction for leaf weight was significant. In 2016, the control and 45% treatment had higher leaf weights than the 65% and 85% treatments (Table 2.5). In 2017, the control and 35% treatment were significantly higher than the 65% and 85% treatments. Leaf area was higher in the 85% treatment than the control. Specific leaf weight (SLW) decreased in the 45%, 65% and 85% treatments compared to the control.

### *Height*

Plant height differed only by year (Table 2.6). Average plant height in May was significantly greater in 2017 (141 cm) than 2016 (130 cm).



### *Plant Injury Ratings*

Plant powdery mildew and sunscald injury data were only collected in 2017. The average injury rating across dates was lower in the control than the shade treatments (Table 2.6). The 85% shade treatment had significantly higher damage than the remaining treatments except the 45% treatment. Of the 8 dates of plant examination, 4 of the dates showed significant differences among some treatments and the control. Within those dates, the 85% treatment significantly differed from the control 5 times, while the 45% and 65% treatment only differed from the control once.

### *Soil Moisture*

Soil moisture was significantly different between years and treatment but there was no year by treatment interaction. Soil moisture was higher in 2016 (23.5%) than in 2017 (19.3%). In 2016, the mean average across dates was significantly higher in the 65% (25.1%) than the control (22.6%). In 2017, there was no difference in soil moisture between treatments and control when averaged across dates. When averaged across years, shade treatments had an insignificant effect on soil moisture (Table 2.7).

## **2.5 Discussion**

### *Yield*

For the inclusion of woody understory crops in polycultures, the insignificant yield loss found in up to 65% shading proved to be the most exciting result. In both years, only the 85% shade treatment reduced yield compared to the control (Table 2.1). Overall yield in 2016 was lower than 2017. This is most likely due to the 4-year-old plants reaching peak maturity and approaching ceiling yields in 2017. The higher yield in 2017 may also be explained by the addition of a two-year-old variety in the vicinity of the trial that went through flowering and may have served as a pollinizer. Also, warmer temperatures at the end of winter season followed by an extended cool spring may have contributed to increased yields in 2017.

The 65% shade treatment shows the greatest potential with minimal yield reduction in both years. This may be due to increased soil moisture or by the plant maintaining biomass allocation to reproduction immediately after developing shade and into the following year. The low yield in the 85% treatment could be caused both by limited carbon capture under reduced

solar irradiance and by an increase in disease prevalence. Our results are consistent with the yield loss found by Toldam-Andersen and Hansen (1993) in black currants grown under 50% shade conditions who also reported an 8% reduction in yield for shaded plants. Kater et al. (1992) found reduced yield in annuals grown in understory conditions due to an increase in fungal diseases. Indeed, our study showed the highest fungal damage in the 85% treatment (Table 2.8). Additionally, mildew has been shown to reduce shade tolerance in temperate forest species (Valladares and Niinemets 2008) and can additionally decrease the level of irradiance that makes it to the plants leaves due to obstruction and leaf tissue damage (Valladares et al. 2016). In a similar study on blueberries, Kim et al. (2011) found that blueberries performed well up to 60% shading, where heavier shading reduced yield significantly. Overall, our research indicates that black currants in the Midwest can maintain acceptable yields with up to 65% shade, but yields will be significantly reduced at shade levels above 65%.

### *Berry Ripeness*

A clear and consistent ripening process is invaluable to producers who need clear timelines for determining harvest deadlines. The results from our study showed that after the first year, the plants were able to adapt to the shaded environment and maintain an even berry ripening timeline. The percent veraison per bush in 2017 showed less variation than in 2016 yielding a more even ripening process among treatments. In 2016, the ripening process had a more skewed development among treatments. The 2017 results may be attributed to plant adjustment to the shaded environment in the second season. While the variation in ripening was less skewed in 2017, there was still a delay in ripening across treatments which led to the control and 35% treatment reaching harvest time 5 days before the 45%, 65% and 85% treatments. The change in soluble solids across dates were similar for both years, with the overall soluble solids remaining unchanged except for immediately before harvest. In both of these situations, the 85% treatment had the lowest soluble solids, which is typical of a reduction in irradiance and thus a reduction in the available carbon for sugar production.

### *Berry Physical Properties*

Berry weight and volume can be an important determining factor in determining end-use products and harvest methods. Larger berries are easier for hand-harvest and can provide a better

product for fresh-markets, while smaller berries are better suited for machine harvest and processing. Our results showed shading can increase berry volume, while maintaining similar weight. The lack of difference in berry weight among treatments was similar to results found by Toldam-Andersen and Hansen (1993), who found no difference between the 50% shaded black currants fresh berry weight and the control. The berry weights in this research were much larger than reported by Moyer et al. (2002) who found the average berry weight for ‘Consort’ to be only 112 grams per 200 berries when grown in Willamette Valley, Oregon. Berry weight and volume were both highest in the shaded treatments versus control. This is similar to what was found by Bote and Struik (2011) in coffee, where shading produced larger, heavier fruit. Berries were smaller in volume in 2017 than in 2016 which may be due to an increase in yield and plant compensation. Estimated berry counts increased in 2017 over 2016 and the greater number of berries per bush may have contributed to a reduction in overall berry size. Additionally, the lower soil moisture throughout the filling season in 2017 will cause a reduction in berry size. These results suggest that shading can provide a benefit, by increasing berry size, which is an important factor in the fresh berry market and for cultivars with small berry size.

### *Berry Chemistry*

The sugar level and acidity of berries can be a major factor in black currant end-use and for a favorable juice product. Our results were promising, with soluble solids maintained at comparable levels to the control in up to 65% shading and no change in pH or titratable acidity with shading. Berry soluble solids followed similar trends observed by Djordjevik et al. (2014), who found that black currants grown in full sun had the highest soluble solids compared to shaded currants. Soluble solids were much higher in 2017 than in 2016 which may be due to the higher temperatures and dryer growing season, confirming the results reported by Lindard Pedersen (2005). Berry soluble solids were within range of the values reported by Vagiri et al. (2013) in North and South Sweden, but lower than the majority of cultivars tested by Nes et al. (2011) and Heiberg et al. (1992), both in Southeastern Norway. The different harvest dates in 2017 between the control and 35% and the remaining shade treatments should have little impact on berry chemistry parameters. Heiberg et al. (1992) found little difference between berry quality parameters based on 3 separate, 3-day-apart harvests.

Titrateable acidity was within range of the values reported by Nes et al. (2011) and were much lower than the values reported by Vagiri et al. (2013) and Heiberg et al. (1992). Berry pH was very similar (2.78) to the mean pH found by Heiberg et al. (1992) of 2.82. These values represent a good source of sugars with a balanced T.A with the control and intermediate shade treatments showing the best values between the two years, while the 85% treatment had suboptimal values.

Berry dry matter decreased with increasing levels of shade with the highest percent dry matter in the control and lowest in the 85% treatment. This may be due to increased carbon resources with higher levels of light, thus greater biomass allocation towards the berries, or it could also be due to the higher soil moisture in the growing environments allows for “juicier” berries with increased shading.

### *Leaves*

Changes in morphology can serve as indicators for positive plant responses to shading and long-term impacts on plant growth. Under increasing levels of shade, the black currants followed expected morphological shifts, with leaf weight and SLW decreasing and leaf area increasing. Leaf area appeared to adapt to shading in year 2, with 2017 showing no significant differences in leaf area, but leaf weight and SLW followed 2016 trends. This was similar to what was found by Heuvel et al. (2004) in grapes, where leaf area was maintained with increased shading but an immediate effect on weight and leaf density was observed. In olives, Gregorius et al. (2007) found a significant increase in leaf area as the level of shading increased. Leaf plasticity corresponded to expectations for shade tolerant species as outlined by Boardman (1977), Bayala et al. (2015), Roig-Villanova and Martinez-Garcia (2016), and Valladares and Niinemets (2008).

### *Height*

With limited height plasticity under shade conditions being the greatest indicator of a shade species found by Valladares and Niinemets (2008), our results further confirmed the understanding that black currants are a shade species. Shade treatments had an insignificant effect on plant height. This is evidence of black currants shade tolerance, with shade tolerant species reducing apical dominance and thus little height plasticity in shaded environments (Roig-

Villanova and Martinez-Garcia 2016; Valladares and Niinemets 2008). Similar results were found in grapes by Greer et al. (2010), who showed a decrease in apical meristem activity with shading

### *Plant Injury Ratings*

Plant health is critical to plant survival and productivity. Our results indicated that for shaded systems, the injury to plants from disease is a major issue, as light and wind penetration is reduced, resulting in increased plant injury. Sunscald was the first injury noted on plants, quickly followed by powdery mildew. While powdery mildew was present across all plots, it first appeared in the shaded treatments and was most severe in the heaviest shade treatment (Wolske, personal observation). This is most likely due to the increased risk of leaf injury with lower leaf density (Gommers et al. 2013) and the increased humidity and lower light irradiance optimizing the growing conditions of powdery mildew (Valladares et al. 2016). Our results show the importance of selecting for disease resistance in understory crops, as the understory environment increases the overall risk of disease in plants and can be a major contributor to understory crop yield loss.

### *Soil Moisture*

Adequate soil moisture is a major determining factor in the viability of plant growth and productivity, and the results of our study found that there is limited effect of shading across the seasons on soil moisture maintenance, but a slight increase within season at medium to high levels of shading. Soil moisture levels increased with shade, as reported by Valladares et al. 2016. Averages across the years showed adequate soil moisture, with values within the range of recommendations by McCarthy and Stoker (1988). The highest soil moisture in the 65% shade treatment is believed to be caused by the reduced evaporation rate. Research has also shown that the increased air humidity and decreased air temperatures in shade environments can reduce evapotranspiration (Bayala et al. 2015). Additionally, the reduced soil moisture content in the 85% treatment compared to the 65% treatment is most likely caused by a reduction in rainfall penetration through the shade netting, which can reduce precipitation by 10-30% (Valladares et al. 2016). The higher soil moisture content can be a contributing cause to the overall shade tolerance found in this study (Valladares et al. 2016; Bayala et al. 2015), with shade tolerance

and drought tolerance believed to be negatively associated with one another (Valladares and Niinemets 2008). However, it is worth considering the major differences between shade from netting and shade from trees, with a living shaded overstory having an extensive root system that would affect soil moisture levels in ways the artificial shade netting cannot mimic.

## **2.6 Conclusion**

Overall, the results of this study indicate that black currants are an excellent understory crop in light to moderate shade conditions. With a phenotypic plasticity homologous to shade species, currants were able to maintain a substantial yield under shade stress. Further, black currant germplasm could be screened to determine the cultivars having the best shade tolerance and disease resistance. These superior cultivars could then be used in a breeding program to further enhance productivity under shade. Black currants may prove useful in polyculture, providing fruit and nut orchard growers with an additional crop in the system that could increase yield and income without tapping additional land resources.

## 2.7 Tables

**Table 2.1** Total mean yield of black currant (*Ribes nigrum*) by percent shade treatment and percent reduction from the control for the 2016 and 2017 growing season in Urbana, IL in grams per bush  $\pm$  standard deviation. Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of  $\alpha=0.05$  with LSM values shown where significance was found. NS=not significant.

Yield				
	2016		2017	
Treatment	Total (g)	% Reduction	Total (g)	% Reduction
Control	807 $\pm$ 277	-	1294 $\pm$ 256 a	-
35%	638 $\pm$ 197	21	1278 $\pm$ 293 a	1
45%	682 $\pm$ 79	16	1179 $\pm$ 297 a	9
65%	768 $\pm$ 210	5	1158 $\pm$ 275 a	11
85%	577 $\pm$ 98	29	561 $\pm$ 119 b	57
LSM	NS		374.4 ***	

\*,\*\*,\*\*\* Significantly different at the P=0.05, 0.005, or 0.001 probability level, respectively

**Table 2.2a** Change in mean percent veraison (n=4) in black currants grown under different artificial shading rates in Urbana, IL throughout the veraison time period for 2016 and 2017. Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of  $\alpha=0.05$  with Honest Significant Difference (HSD) shown where significance was found. NS=not significant.

Percent veraison throughout berry fill														
	2016							2017						
Treatment	7-Jun	15-Jun	20-Jun	24-Jun	27-Jun	1-Jul	5-Jul	26-May	6-Jun	15-Jun	21-Jun	23-Jun	25-Jun	30-Jun
Control	7	44 a	72 a	89 a	93 a	98 a	100 a	1 a	21	66	93 a	95	95 a	-
35%	2	35 ab	56 ab	84 a	86 ab	95 ab	98 a	0.2 ab	8	53	81 ab	90	92 ab	-
45%	2	19 abc	40 b	58 b	71 bc	88 ab	99 a	0.3 ab	6	39	79 bc	89	90 ab	98
65%	2	15 bc	37 bc	59 b	63 c	81 b	98 a	0.1 b	4	36	71 bc	64	87 b	97
85%	1	3 c	9 c	21 c	28 d	59 c	94 b	0 b	2	37	68 c	83	86 b	97
LSM	NS	27.0 **	27.6 ***	21.2 ***	16.8 ***	14.6 ***	2.7 ***	0.8 *	NS	NS	13.0 **	NS	7.3 *	NS

\*,\*\*,\*\*\* Significantly different at the P=0.05, 0.005, or 0.001 probability level, respectively.



**Table 2.2b** Change in soluble solids of black currants (*Ribes nigrum*) grown under different artificial shading rates in Urbana, IL through veraison measured as mean °Brix (n=4) for 2016 and 2017. Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of  $\alpha=0.05$  with Honest Significant Difference (HSD) shown where significance was found. NS=not significant.

Berry brix throughout veraison									
	2016				2017				
Treatment	20-Jun	28-Jun	30-Jun	5-Jul	19-Jun	21-Jun	23-Jun	25-Jun	30-Jun
control	11.8	14.6	14.7	12.8 a	13.6	13.5	14.0	15.5 a	-
35%	11.3	13.8	14.4	12.7 a	13.0	14.1	14.3	14.8 ab	-
45%	11.7	14.0	13.8	12.3 ab	12.8	13.2	13.2	14.7 ab	16.1
65%	11.1	13.8	14.5	12.3 ab	12.0	13.1	12.7	13.2 b	15.3
85%	10.5	12.7	13.8	11.3 b	12.6	13.2	12.4	13.5 b	15.1
LSM	NS	NS	NS	1.28 *	NS	NS	NS	1.62 **	NS

\*, \*\*, \*\*\* Significantly different at the P=0.05, 0.005, or 0.001 probability level, respectively.

**Table 2.3** Artificial shade treatment effects in 2016 and 2017 on berry weight in grams per 200 berries, berry volume in mL per 200 berries, and estimated number of berries per bush based on yield divided by berry weight of black currants (*Ribes nigrum*) grown in Urbana, IL. Berry weight and estimated berries per bush values are averaged across 2016 and 2017 due to insignificant year and treatment interactions. Values are given plus or minus standard deviation. Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of  $\alpha=0.05$  with Honest Significant Difference (HSD) shown where significance was found. NS=not significant.

Treatment	Berry Weight	Berry Volume		Est. berries per bush
		2016	2017	
Control	150 ± 26	169 ± 8	124.9 ± 8.0 b	789 ± 185 a
35%	156 ± 17	162 ± 9	133.2 ± 10.9 a	729 ± 237 a
45%	157 ± 20	166 ± 10	133.4 ± 5.5 a	706 ± 143 a
65%	161 ± 19	171 ± 10	138.4 ± 4.6 a	760 ± 134 a
85%	157 ± 15	161 ± 12	138.1 ± 8.2 a	449 ± 89 b
LSM	NS	NS	12.7 *	238 **

\*,\*\*,\*\*\* Significantly different at the P=0.05, 0.005, or 0.001 probability level, respectively.

**Table 2.4** Artificial shade treatment effects on black currant (*Ribes nigrum*) grown in Urbana, IL. Berry soluble solids data was recorded and is presented for 2016 and 2017. Berry dry matter was only recorded in 2017 and is presented. Values are given plus or minus standard deviation. Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of  $\alpha=0.05$  with Honest Significant Difference (HSD) shown where significance was found. NS=not significant.

Treatment	Soluble solids (°Brix)		Berry dry matter (%)
	2016	2017	
Control	13 ± 1.4 a	15 ± 1.5 a	24 ± 0.4 a
35%	13 ± 1.1 a	14 ± 1.6 ab	23 ± 0.7 a
45%	12 ± 0.8 ab	15 ± 1.3 a	23 ± 0.5 ab
65%	12 ± 0.9 ab	15 ± 1.3 a	22 ± 0.7 bc
85%	11 ± 0.9 b	13 ± 1.1 b	22 ± 0.7 c
LSM	1.3 *	1.4 **	0.9 ***

\*, \*\*, \*\*\* Significantly different at the P=0.05, 0.005, or 0.001 probability level, respectively.

**Table 2.5** Artificial shade treatment effect on black currant (*Ribes nigrum*) leaf weight, area, and specific leaf weight (SLW) for 2016 and 2017 in Urbana, IL. Leaf area and SLW values are averaged across 2016 and 2017 due to insignificant year and treatment interaction. Values are given plus or minus standard deviation. Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of  $\alpha=0.05$  with Honest Significant Difference (HSD) shown where significance was found. NS=not significant.

Treatments	5 leaf weight (g)		5 leaf area (cm <sup>2</sup> )	SLW (mg/cm <sup>2</sup> )
	2016	2017		
Control	1.5 ± 0.2 a	1.5 ± 0.2 a	278 ± 21 a	5.5 ± 0.3 a
35%	1.3 ± 0.2 ab	1.6 ± 0.3 a	291 ± 41 ab	5.1 ± 0.7 ab
45%	1.5 ± 0.1 a	1.4 ± 0.2 ab	320 ± 25 ab	4.5 ± 0.3 bc
65%	1.3 ± 0.2 b	1.3 ± 0.2 b	309 ± 33 ab	4.2 ± 0.4 cd
85%	1.2 ± 0.2 b	1.2 ± 0.2 b	323 ± 34 b	3.8 ± 0.5 d
LSM	0.17 ***	0.3 **	45 *	0.7 ***

\*, \*\*, \*\*\* Significantly different at the P=0.05, 0.005, or 0.001 probability level, respectively.

**Table 2.6** Artificial shade treatment effects on black currant (*Ribes nigrum*) plant injury for 2017 in Urbana, IL. Higher values are related to increased plant injury on a 0-9 point scale with 0=no injury and 9=plant death. Values are given plus or minus standard deviation. Different letters within a column indicate significant differences as determined by Tukey-Kramer multiple comparison test at a rejection level of  $\alpha=0.05$  with Honest Significant Difference (HSD) shown where significance was found. NS=not significant.

Plant Injury								
2017	26-May	6-Jun	15-Jun	21-Jun	23-Jun	25-Jun	30-Jun	Average
Control	0.8	1.6 b	2.3 b	2.4 b	2.1 b	2.1	2.7	2.0 c
35%	0.9	2.9 ab	3.2 b	3.3 ab	3.4 ab	3.4	3.3	2.9 b
45%	1.1	3.0 ab	3.6 ab	3.5 ab	3.6 a	3.8	3.3	3.1 ab
65%	1.3	2.9 ab	3.4 ab	3.7 ab	3.5 a	3.3	3.3	3.1 b
85%	1.4	3.9 a	4.9 a	4.5 a	4.6 a	4.1	3.8	3.9 a
Average	1.1	2.9	3.5	3.5	3.5	3.3	3.3	3.0
LSM	NS	2.1 *	1.7 *	1.9 *	1.4 **	NS	NS	0.8 ***

\*, \*\*, \*\*\* Significantly different at the P=0.05, 0.005, or 0.001 probability level, respectively.

**Table 2.7** Percent soil moisture available to black currants (*Ribes nigrum*) in Urbana, IL for each artificial shade net treatment averaged across testing dates and the 2016 and 2017 growing season. Values are given plus or minus standard deviation.

Treatment	% Soil Moisture
Control	20.5 ± 2.3
35%	21.1 ± 3.0
45%	21.1 ± 2.7
65%	22.8 ± 2.6
85%	21.4 ± 2.2
LSM	NS

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