VEGETATIVE GROWTH AND FRUITING CHARACTERISTICS OF BLACK WALNUT

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By

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The undersigned, appointed by the dean of the Graduate School,

have examined the Thesis entitled

VEGETATIVE GROWTH AND FRUITING CHARACTERISTICS OF BLACK WALNUT

Presented by Andrew Biggs

A candidate for the degree of

Master of Science

And hereby certify that, in their opinion, it is worthy of acceptance.

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ABSTRACT

Three studies were conducted to evaluate sequential vegetative and fruiting characteristics of black walnut. ‘Sparrow’ vegetative shoots or those with one fruit were smaller in diameter than shoots with three fruits in 2009. Also, 2009 vegetative shoots were most likely to remain non-bearing in 2010. However, 2009 bearing shoots were equally likely to produce 0, 1, 2, or 3 nuts in 2010.

When crop yields for 15 cultivars were evaluated from 2008 to 2010, ‘Bowser’ and ‘Elmer/Myer’ produced low (≤ 378 nuts/tree), but consistent annual yields. In contrast, ‘Emma K’, ‘Kwik Krop’, and ‘Sparrow’ had high cumulative yields (≥ 3000 nuts/tree). Two cultivars exhibited a biennial bearing habit, while five cultivars had two consecutive low production years followed by high yields the third year. Also, ‘Davidson’, ‘Emma K’, ‘Kwik Krop’, ‘Sparks 127’, ‘Sparrow’, and ‘Tomboy’ were more yield efficient than ‘Bowser’ and ‘Elmer/Myer’ from 2008 to 2010. The incidence of ambers was similar among black walnut cultivars and averaged ≤ 7% per tree.

CHAPTER 1:
INTRODUCTION

Between 11.4 and 13.6 million kg of black walnuts (*Juglans nigra* L.) are harvested annually from 15 states, resulting in 680 to 910 thousand kg of marketable walnut kernels in the United States (Hammons, 2009). Hammons Products Company of Stockton, MO has historically purchased 4,500 to 15,900 t of hulled black walnuts annually (Coggeshall, 2011). Due to the erratic bearing habit of black walnut trees, the supply of black walnuts is limited in some years. For example, a 'Schessler' tree growing in New Franklin, MO produced 1143, 641, and 3789 nuts in 2008, 2009, and 2010 respectively (M. V. Coggeshall, unpublished data).The majority of the nuts sold commercially are harvested from wild trees, which may have a lifespan of ≈250 years of age (Woodroof, 1979; Zarger, 1969).

Black walnut trees are monecious, with flowers visible in mid April to early May (Reid et al., 2009). Staminate flowers (e.g., catkins) occur on previous season's growth above leaf scars. Pistillate flowers occur in clusters of one to four at the distal ends of current season's shoots (Manning, 1938; Schaffer et al., 1996; Sparks, 2003; Van Sambeek and Rink, 1981). Most black walnut cultivars are protogynous (Coggeshall, 2011; Reid et al., 2004).

Fruits are harvested during the months of September and October. In orchard settings with large-scale nut production, tree shakers are used to remove the crop from the trees and a Nut Wizard or Savage harvester (Savage Equipment, Inc.; Madill, OK) is used to collect the fruits from the ground. For small-scale nut production, fruits are picked up by hand or with Nut Wizards after they fall from the trees.

The average wild black walnut weighs 17 g (after hulling and air-drying) and is 17% kernel by weight (Duke, 2001; Reid et al., 2004; Zarger, 1969). In contrast, selected cultivars can produce nuts with up to 34% kernel by weight, after hulling and air-drying (Reid et al., 2004). High quality nuts have thin shells and have large, light-colored kernels that remain in large pieces after cracking (Stoke, 1941; Warmund et al., 2009; Woodroof, 1979). Kernel color is influenced by the time of harvest and by the time of hull removal from the nut after harvest (Brawner, 2007; Warmund, 2008). Warmund (2008) found that the kernels from ‘Emma K’, ‘Kwik Krop’, and ‘Sparrow’ nuts were darker with later harvest dates. Brawner (2007) demonstrated that nuts of ’Emma K’, ‘Kwik Krop’, and ‘Football’ hulled two weeks after harvest had darker kernels than those hulled immediately after harvest.

Frequently, black walnuts have kernels that exhibit ambers. These nuts have thin, brittle shells, kernels that are necrotic and shriveled, and hulls with no visible symptoms of damage. Affected kernels also have an altered chemical composition (Mangoff, 1980). Ambers is currently undetectable until nuts are harvested, hulled, dried, and cracked. Thus, growers incur production costs for a crop that may have unmarketable kernels. In a 2007 preliminary study, up to 68% of the nuts sampled from selected cultivars had ambered kernels at a commercial orchard with 35 year old trees near Windsor, MO (M. Warmund, unpublished data). However, the causative agent of ambers has not been elucidated but it may be related to vegetative and fruiting shoot characteristics or crop load. It has been speculated that ambers is symptomatic of a cotyledon development abnormality, fungal infection, insect damage, or environmental factors (Funk, 1979; Gibson and Kearby, 1976; Kintzel, 1968; Stoke, 1941).

To better understand fruiting patterns and the occurrence of ambers, a study was conducted to determine vegetative and fruiting characteristics of 'Sparrow' black walnut shoots over a 2 year period. Also, fruiting on shoots of 4 black walnut cultivars with 2 nuts per shoot was evaluated over a 2 year period. Additionally, the occurrence of ambered nuts was evaluated among fifteen black walnut cultivars.

CHAPTER 2:
LITERATURE REVIEW

Black walnut trees are monecious and have a heterodichogamous flowering habit (Beineke and Masters, 1977; Coggeshall, 2011). Most black walnut cultivars are protogynous, resulting in a shortage of pollinator cultivars early in the season (Coggeshall, 2011). Protandrous cultivars include ‘Cranz’, ‘Knuvean’, ‘Mintel’, ‘South Fork’, and ‘Wiard’ (Warmund and Coggeshall, 2010).

Pistillate flowers differentiate in dormant buds produced proximally on current season’s growth. In mid April to early May, flowering and leafing occur concurrently (Funk, 1979; Michler et al., 2007). Pistillate flowers usually occur in groups of one to four per cluster, but four flowers are rarely pollinated (Manning, 1938; Schaffer et al., 1996; Sparks, 2003). Female flowers are approximately 0.6 cm long, with two feathery stigmata that are red, orange, or green (Reid et al., 2009). Additionally, ovaries in pistillate flowers usually have two carpels, but occasionally have three (Manning, 1940). Carbohydrate or nitrogen deficiencies may lead to pistillate flower abscission (Van Sambeek, 1998).

In the spring, catkins emerge from buds on the previous season’s wood above the leaf scars during the period of rapid shoot elongation (Manning, 1938; Schaffer et al., 1996; Warmund and Coggeshall, 2010). A staminate flower includes a bract, two bracteoles, and four sepals, or a bract and six sepals. Bracteoles and sepals form a calyx-like circle around the stamens (Manning, 1948). Each catkin has 20 to 30 sessile stamens. Catkins may grow to a length of 51 to 102 mm before dehiscing (Beineke and Masters, 1977).

Black walnut trees are wind pollinated. Pollen develops slowly at cooler temperatures but it matures rapidly with warm temperatures (Beineke and Masters, 1977). Overtree irrigation may be used on black walnut to delay pollen maturation, presumably by evaporative cooling (Beineke and Hunley, 1979). Cross pollination increases the likelihood of fertilization occurring, but some flowers are self-fertile (Reid et al., 2009).

Fertilization of black walnut occurs two to five days after pollination, followed by a period of rapid expansion of the fruit, and then shell hardening in early July (Funk, 1979; Van Sambeek and Rink, 1981). As the ovary matures, the involucre and sepal tissue form the hull around the ovary wall (Schaffer et al., 1996; Sparks, 2003). In late July, the embryo and cotyledons enlarge and utilize most of the liquid endosperm. Kernel development begins adjacent to the testa and continues inward until the exocarp is filled (Nast, 1941; Van Sambeek and Rink, 1981). Factors that influence kernel fill include tree nutritional status, overall tree health, the previous and current year's crop load, and environmental conditions, especially summer drought (Crane, 1949). Fruits generally attain full size by August and kernel fill is completed by late September or October (Brawner, 2007; Funk, 1979).

Black walnut trees are often alternate bearing, with fluctuating annual nut production (Monselise and Goldschmidt, 1982). In low production years, few pistillate flowers are produced or biotic or abiotic factors decrease fruiting (Sparks, 2003). Alternate bearing of black walnut trees is presumably influenced by a variety of factors including cultivar, age, climactic conditions, carbohydrate reserves in trees, or growth-promoting or inhibiting hormones (Monselise and Goldschmidt, 1982; Van Sambeek, 1998).

High-quality kernels are large with light-colored pellicles (Stoke, 1941; Warmund et al., 2009; Woodroof, 1979). However, maximum kernel size and the occurrence of light-colored kernels may not coincide for some cultivars (Warmund, 2008; Warmund et al., 2009). Poor quality nuts lack completely filled kernels and have dark colored pellicles. Pellicle color is cultivar dependent, but is also affected by the harvest date and time of subsequent hull removal (Brawner, 2007). At later harvest dates, kernels become darker and duller in color (Warmund, 2008). After harvest, kernels turn dark brown when hulling is delayed by as little as two weeks (Brawner, 2007). Dark-colored kernels have more intense burnt, musty/dusty, oily, woody, astringent, and sour flavors than light-colored ones (Warmund et al., 2009). Additionally, dark-color of kernels of ‘Emma K’ and ‘Sparks 127’ has been associated with acrid, rancid, and bitter flavors (Warmund et al., 2009).

The term “ambers” is commonly used to describe poor quality, dark-colored kernels in nuts with thin, brittle shells that are inside hulls with no visible external damage. These kernels have an altered chemical composition with less stearic and oleic acid than high quality, non-ambered kernels (Mangoff, 1980). Ambered kernels also have more protein, crude fiber, ash, potassium, phosphorous, calcium, magnesium, linoleic, and linolenic acid per gram than non-ambered kernels (Mangoff, 1980; Stoke, 1941). In a 2007 preliminary study, up to 68% of the nuts sampled from selected cultivars had ambered kernels at a commercial orchard with 35 year old trees near Windsor, MO (M. Warmund, unpublished data). Gibson and Kearby (1976) investigated the relationship between walnut husk maggot (*Rhagoletis suavis* [Loew]) larvae and ambered black walnut kernels. They found walnut husk maggot larvae present in the hulls of up to 84% of fruits sampled, but few kernels were ambered. Ambers has also been attributed to anthracnose, lack of moisture, low light, or nutrient deficiency (Funk, 1979; Kintzel, 1968; Stoke, 1941). However, the development and expression of symptoms has not been investigated extensively and thus, the cause of ambers remains unknown.

Similar to black walnut ambers, English walnut (*Juglans regia* L.) trees may also produce dark, shriveled kernels, with low oil content, and are known as “oilless nuts” (Grant et al., 1985; Haas and Batchelor, 1928). Oilless nuts have higher carbohydrate and lower lipid content than non-affected nuts (Grant et al., 1985). Cultivars such as ‘Ashley’, ‘Serr’, and ‘Chico’ produce oilless nuts more frequently than other cultivars (Sibbett, 1999). Unlike black walnut nuts with ambers, oilless nuts most typically occur on shaded, interior portions of the trees. Also, hulls of the fruits with oilless nuts often split and fruits abscise from the trees before non-affected ones (Grant et al., 1985).

Kernel necrosis is a disorder of pecan (*Carya illinoinensis* [Wangenh.] C. Koch.) kernels (Smith et al., 2007). Symptoms include necrotic tissue on more than one third of the kernel. Like black walnut ambers, the cause of this disorder in pecans remains unknown.

CHAPTER 3:
STUDY 1

Methods

Sequential vegetative and fruiting terminal shoot characteristics of 'Sparrow' black walnut trees were evaluated in this study. Trees were grafted onto 'Thomas' seedling rootstock in 1996 and were planted in a Menfro silt loam (fine-silty, mixed, superactive, mesic typic hapludalfs) soil at the Horticulture and Agroforestry Research Center (HARC) near New Franklin, MO. Tree spacing was 15.2 x 15.2 m apart. Each year, 67 $kg{\cdot}ha^{-1}$ and 45 $kg{\cdot}ha^{-1}$ of pelletized ammonium nitrate (34N-0P-0K) were applied in late April and late October, respectively. In Aug. 2009, 8 terminal shoots each with 0, 1, 2, or 3 fruits were selected and labeled from all four quadrants of the crown on limbs located 1 to 5 m above the soil surface on each of four trees. Netting (Bird-X, Inc.; Chicago, IL) was placed over the fruits in early August to ensure their retention at harvest. Number of leaves per shoot was recorded in mid August. Shoot diameter (measured at the proximal end of the current season's growth) and length were recorded on 22 Sept. 2009.

In 2010, fertilization rates were increased to 90 $kg{\cdot}ha^{-1}$ and 78 $kg{\cdot}ha^{-1}$ of ammonium nitrate in late April and late October, respectively. All shoots produced from those labeled in 2009 were measured on 15 Sept. 2010 as previously described. Additionally, number of nuts on each labeled shoot was recorded. Shoots labeled in 2009 that branched into multiple shoots the following year were treated as a single shoot when analyzing 2010 growth data. Thus, numbers of leaves, lengths of the shoots, and numbers of nuts on 2010 branched shoots were summed. Additionally, diameters of the branched shoots were averaged for statistical analysis.

Data were analyzed by year as a randomized complete block design using individual trees as blocks. Number of leaves per shoot, shoot diameter, and shoot length for both years and nuts per shoot in 2010 were subjected to analysis of variance (ANOVA) using the PROC GLM procedure in SAS (Version 9.2; SAS Institute; Cary, NC) and means were separated by Fisher's protected least significant difference (LSD) test ($P \leq .05$). The stepwise regression procedure of PROC REG in SAS was used to model 2010 nuts per shoot. First, leaf number per shoot, shoot diameter, shoot length, and number of nuts per shoot for 2009 were included in the model. Next, variables were omitted to determine when the R^2 value was significantly reduced. Following this procedure, an equation was generated to predict number of nuts produced in 2010 from the 2009 measurements.

Odds were calculated to estimate the probability that a 2009-labeled shoot type would produce a new shoot with 0, 1, 2, or 3 nuts the following year. For this analysis, the maximum nut number per shoot (even when branched in 2010) was considered to be three. Data were subjected to the GLIMMIX procedure in SAS with a link=logit function and dist=bin for a binomial distribution. Random and fixed effects were tree and 2009 nut number per shoot, respectively. Mean differences among logits for shoot types were determined using the LSMEANS statement. Odds were calculated from the antilog of the logit value and back-transformed [% shoot type = odds/(1+odds)] to estimate percentage of each shoot type in 2010.

Results

In 2009, leaf number per shoot and shoot lengths among shoot types were similar (Table 1). Although not statistically different, vegetative shoots (i.e., zero nuts per shoot) had relatively fewer leaves per shoot and averaged 20 to 30 mm longer shoots than nut bearing ones. Also, vegetative shoots had smaller diameters than those with two or three nuts.

Table 1. Vegetative growth characteristics of 'Sparrow' shoots with 0, 1, 2, or 3 nuts in 2009.[z]

Nuts/shoot in 2009	Leaf number/ shoot	Shoot diameter (mm)	Shoot length (mm)
0	9.5	6.1 c	108
1	9.8	6.9 bc	76
2	10.3	7.4 ab	87
3	10.5	7.9 a	82

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means followed by different letters are significantly different by Fisher's LSD ($P \leq .05$).

In 2010, all vegetative characteristics measured, as well as nut number per shoot, were similar among shoot types (Table 2). Results from 2010 were similar to those in 2009 where vegetative shoots generally had fewer leaves and smaller diameters than nut-bearing shoots. In contrast to 2009, vegetative shoots were 3 to 26 mm shorter than nut-bearing shoots in 2010.

Table 2. 2010 Vegetative growth characteristics of 'Sparrow' shoots with 0, 1, 2, or 3 nuts in 2009.[z]

Nuts/shoot in 2009[y]	Leaf no./ shoot	Shoot diameter (mm)	Shoot length (mm)	Nuts/ Shoot
0	7.1	4.2	56	1.1
1	9.1	5.0	77	1.2
2	7.8	4.7	59	1.0
3	9.6	4.5	82	1.4

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher's LSD ($P \leq .05$).
[y] Shoots had 0, 1, 2, or 3 nuts in 2009 and current season's growth was measured on these same shoots in 2010.

When step-wise linear regression was performed using all 2009 variables to predict nut number per shoot in 2010. The model was significant ($P \leq .001$), but R^2 values were low (Table 3). The model that included all four variables had a similar R^2 value (0.15) to that for the combination of shoot diameter, shoot length, and nut number per shoot. When two or less variables were used in the model, the R^2 values decreased. However, when only one variable was used, shoot diameter was the most reliable predictor of 2010 nut number, with $R^2 =$ 0.12. Because the strongest model included three variables, the following equation best predicts 2010 nut production based upon the data collected

$$\text{2010 nuts/shoot} = 0.433(\text{2009 shoot diameter}) – 0.005(\text{2009 shoot length}) – 0.233(\text{2009 nuts/shoot}) – 1.212$$

Table 3. Prediction values for characteristics of 2009-labeled ‘Sparrow’ shoots determining number of nuts per shoot in 2010.

Variables in model[z]	R^2 value
DIA	0.12
LEAF	0.05
LEN	0.02
NUT	0.00
DIA, NUT	0.13
DIA, LEN	0.12
DIA, LEAF	0.12
LEAF, NUT	0.05
LEAF, LEN	0.05
LEN, NUT	0.02
DIA, LEN, NUT	0.15
DIA, LEAF, NUT	0.13
DIA, LEAF, LEN	0.12
LEAF, LEN, NUT	0.05
DIA, LEAF, LEN, NUT	0.15

[z] DIA= 2009 shoot diameter; LEAF= 2009 number of leaves per shoot; LEN= 2009 shoot length; NUT= 2009 number of nuts per shoot

When odds were calculated, shoots that were vegetative in 2009 were most likely to be vegetative again in 2010 ($P \leq .07$) (Table 4). Also, 17 to 25% of the 2009-labeled vegetative shoots were likely to produce one or more fruits in 2010. All other 2009-labeled shoot types with 1, 2, or 3 nuts had statistically equal odds of becoming a non-bearing shoot or bearing 1, 2, or 3 nuts in 2010 (Tables 5, 6, 7).

Table 4. Odds and percentages of 2009-labeled 'Sparrow' shoots with 0 nuts in 2009 producing 0, 1, 2, or 3 nuts/shoot in 2010.[z]

Nuts/shoot in 2009	Nuts/shoot in 2010	Odds	% shoot types in 2010
0	0	1.13	53a
0	1	0.20	17b
0	2	0.26	21b
0	3	0.33	25b

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means followed by different letters are significantly different by Fisher's LSD ($P \leq .07$).

Table 5. Odds and percentages of 2009-labeled 'Sparrow' shoots with 1 nut in 2009 producing 0, 1, 2, or 3 nuts/shoot in 2010.[z]

Nuts/shoot in 2009	Nuts/shoot in 2010	Odds	% shoot types in 2010
1	0	0.78	44
1	1	0.46	31
1	2	0.50	33
1	3	0.46	31

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher's LSD ($P \leq .05$).

Table 6. Odds and percentages of 2009-labeled 'Sparrow' shoots with 2 nuts in 2009 producing 0, 1, 2, or 3 nuts/shoot in 2010.[z]

Nuts/shoot in 2009	Nuts/shoot in 2010	Odds	% shoot types in 2010
2	0	0.91	48
2	1	0.23	19
2	2	0.63	39
2	3	0.52	34

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher's LSD ($P \leq .05$).

Table 7. Odds and percentages of 2009-labeled 'Sparrow' shoots with 3 nuts in 2009 producing 0, 1, 2, or 3 nuts/shoot in 2010.[z]

Nuts/shoot in 2009	Nuts/shoot in 2010	Odds	% shoot types in 2010
3	0	0.60	38
3	1	0.50	33
3	2	0.26	21
3	3	0.27	22

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher's LSD ($P \leq .05$).

CHAPTER 4:
STUDY 2

Methods

This study evaluated the sequential vegetative and fruiting characteristics of four black walnut cultivars with two fruits per shoot. Trees were grafted, planted, and fertilized as described in study 1. In Aug. 2009, 8 terminal shoots with two fruits were labeled on each of 4 trees per cultivar. Fruits were enclosed in netting (Bird-X, Inc.; Chicago, Ill) to ensure their retention at harvest. On 7, 15, 15, 22 Sept. 2009 fruits were harvested from ‘Surprise’, ‘Emma K’, ‘Kwik Krop’, and ‘Sparrow’, respectively. All shoot measurements were recorded and data was statistically analyzed as described in the first study.

In 2010, nitrogen fertilizer was applied as described in study 1. All 2010 shoot measurements were recorded for those produced from 2009-labeled shoots. On 11, 11, 15, 15 Sept. 2010, fruits were harvested from ‘Emma K’, ‘Surprise’, ‘Kwik Krop’, and ‘Sparrow’, respectively. Total number of nuts on each labeled shoot was recorded. Data were statistically analyzed as described in study 1.

Results

In 2009, ‘Sparrow’, ‘Surprise’, ‘Kwik Krop’, and ‘Emma K’ had similar numbers of leaves per shoot, shoot diameters, and shoot lengths (Table 8). Although not statistically significant, ‘Emma K’ had relatively fewer leaves, smaller shoot diameters, and shorter shoot lengths than the other cultivars.

‘Surprise’ generally had the largest mean number of leaves per shoot, while ‘Kwik Krop’ had relatively larger shoot diameters and shoot lengths than the other cultivars.

Table 8. Vegetative characteristics of four black walnut cultivars with two nuts per shoot in 2009.[z]

Cultivar	Leaf number/ shoot	Shoot diameter (mm)	Shoot length (mm)
‘Sparrow’	10.3	7.4	87
‘Surprise’	10.7	7.6	85
‘Kwik Krop’	10.1	7.9	92
‘Emma K’	9.4	6.7	69

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher’s LSD ($P \leq .05$).

In 2010, there were no significant differences among cultivars for any of the vegetative and fruiting characteristics measured (Table 9). Also, the number of nuts per shoot were similar among cultivars even though only one ‘Emma K’ shoot produced 2 nuts, while all other ‘Emma K’ shoots were vegetative.

Table 9. 2010 Characteristics of four black walnut cultivars with two nuts per shoot in 2009.[z]

Cultivar	Leaf no./ shoot	Shoot diameter (mm)	Shoot length (mm)	Nuts/ shoot
‘Sparrow’	7.8	4.5	59	1.0
‘Surprise’	12.8	5.7	98	0.8
‘Kwik Krop’	14.5	5.5	136	1.3
‘Emma K’	11.1	4.1	106	0.1

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher’s LSD ($P \leq .05$).

Logit analyses revealed that 2009-labeled shoots of ‘Sparrow’, ‘Surprise’, and ‘Kwik Krop’ were all equally likely to produce 0, 1, 2, or 3 nuts on a shoot in 2010 (Tables 10, 11, 12). For ‘Emma K’, 2009-labeled shoots failed to produce new shoots bearing one or three nuts in 2010 (Table 13). Thus, an estimated 82% of 2009-labeled shoots were vegetative and very few (5%) had two nuts in 2010.

Table 10. Odds and percentages of 2009-labeled ‘Sparrow’ shoots with 2 fruits producing shoots with 0, 1, 2, or 3 fruits in 2010.[z]

2010 nut number	Odds	% of shoots in 2010
0	0.91	48
1	0.23	19
2	0.63	39
3	0.52	34

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher’s LSD ($P \leq .05$).

Table 11. Odds and percentages of 2009-labeled 'Surprise' shoots with 2 fruits producing shoots with 0, 1, 2, or 3 fruits in 2010.[z]

2010 nut number	Odds	% of shoots in 2010
0	1.91	66
1	1.08	52
2	0.31	23
3	0.57	36

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher's LSD ($P \leq .05$).

Table 12. Odds and percentages of 2009-labeled 'Kwik Krop' shoots with 2 fruits producing shoots with 0, 1, 2, or 3 fruits in 2010.[z]

2010 nut number	Odds	% of shoots in 2010
0	0.54	35
1	0.30	23
2	0.23	19
3	0.31	24

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher's LSD ($P \leq .05$).

Table 13. Odds and percentages of 2009-labeled 'Emma K' shoots with 2 fruits producing shoots with 0, 1, 2, or 3 fruits in 2010.[z]

2010 nut number	Odds	% of shoots in 2010
0	4.49	82
1	---[y]	---[y]
2	0.05	5
3	---[y]	---[y]

[z] Values represent means of 8 shoots/tree from each of 4 trees. Means were not statistically different by Fisher's LSD ($P \leq .05$).
[y] No nuts were produced on these shoots in 2010, therefore odds could not be calculated.

CHAPTER 5:
STUDY 3

Methods

The purpose of this study was to evaluate the number of ambered and non-ambered nuts per tree, as well as crop efficiency of 15 black walnut cultivars. Trees were maintained at HARC as described in study 1. Fruits were harvested from four trees each of ‘Davidson’, ‘Elmer/Myer’, ‘Emma K’, ‘Hare’, ‘Kwik Krop’, ‘Mystry’, ‘Sauber #1’, ‘Schessler’, ‘Sparrow’, ‘Surprise’, ‘Thomas’, and ‘Thomas/Myer’, and from three trees each of ‘Bowser’, ‘Sparks 127’, and ‘Tomboy’, in early Oct. 2009 and 2010. After harvest, fruits were hulled, nuts were washed, and the total number of fruits per tree was recorded. Fifty fruits per tree were randomly sampled then cross sectioned with a band saw and kernels were evaluated for ambers. Kernels were considered ambered when >25% of the kernel within a nut was shriveled and/or the testa was dark-brown or black. To evaluate crop efficiency, number of nuts per tree, and trunk diameter at 10 cm above the graft union were recorded in 2008, 2009, and 2010. Trunk cross-sectional area (TCA) was then calculated and used to determine crop efficiency (total nut number/TCA).

Nut data were subjected to ANOVA using the PROC GLM procedure of SAS, and means were separated by Fisher’s LSD ($P \leq .05$). Odds were calculated to estimate the probability of ambered nuts for each cultivar in 2009 and 2010. Data were subjected to the GLIMMIX procedure in SAS with a logit link function as described in Study 1. Random and fixed effects were tree and cultivar, respectively. Odds were back-transformed as previously described to estimate the percentage of ambered nuts per tree for each black walnut cultivar.

Results

In 2008, 2009, and 2010 number of nuts per tree varied among cultivars (Table 14). ‘Sparrow’ yielded more nuts in 2008 than all other cultivars except for ‘Schessler’ and ‘Sparks 127’. In 2009, ‘Emma K’ produced more nuts than any other cultivar. ‘Thomas/Myer’ trees also had a higher yield than those of ‘Bowser’, ‘Elmer/Myer’, ‘Hare’, ‘Kwik Krop’, and ‘Sparks 127’. In 2010, ‘Davidson’, ‘Kwik Krop’, ‘Sauber #1’, ‘Sparrow’, and ‘Tomboy’ produced more nuts than ‘Bowser’ and ‘Elmer/Myer’.

Few ambered nuts were found in 2009 and 2010 at HARC (Table 14). In 2009 and 2010, cultivars averaged 4 and 6 ambered nuts per 50 nut sample, respectively. Thus, odds of trees producing ambered nuts were low and differences among cultivars were not detected.

Cultivars were similar for cumulative nuts per tree from 2008 to 2010 (Table 14). ‘Bowser’ and ‘Elmer/Myer’ produced ≤ 733 nuts per tree from 2008 to 2010 whereas ‘Emma K’ and ‘Sparrow’ had 3388 and 3705 nuts per tree, respectively. Cultivars differed for cumulative crop efficiency. ‘Emma K’, ‘Sparks 127’, and ‘Sparrow’ had higher cumulative crop efficiencies than ‘Bowser’, ‘Elmer/Myer’, ‘Hare’, ‘Mystry’, ‘Surprise’, and ‘Thomas’.

Table 14. Nuts per tree, ambered nuts, cumulative nuts per tree, and cumulative crop efficiency of 15 black walnut cultivars in 2008, 2009, and 2010.[z]

				2009		2010		Cumulative	
Cultivar	2008 nuts/tree	2009 nuts/tree	2010 nuts/tree	Ambered nuts odds	% ambered nuts	Ambered nuts odds	% ambered nuts	Nuts/tree[y]	Crop efficiency (nuts/cm^2)[x]
Bowser	78 c[w]	277 c	378 e	0.04	4	0.02	2	733	2.0 cd
Davidson	290 c	519 bc	1635 abcd	0.04	4	0.04	3	2443	6.4 ab
Elmer/Myer	77 c	246 c	355 e	0.03	3	0.04	4	678	1.7 d
Emma K	354 bc	2577 a	609 d	0.03	2	0.13	12	3388	7.5 a
Hare	332 bc	239 c	1054 cd	0.05	5	0.04	4	1362	2.8 bcd
Kwik Krop	154 c	143 c	2768 a	0.04	3	0.04	3	3064	5.7 ab
Mystry	177 c	426 bc	1300 bcd	0.05	4	0.07	6	1903	3.8 bcd
Sauber #1	201 c	529 bc	1566 abcd	0.03	3	0.09	8	2296	5.4 abcd
Schessler	424 abc	573 bc	1415 bcd	0.04	4	0.09	8	2412	5.7 abc
Sparks 127	810 ab	237 c	1423 bcd	0.04	3	0.06	6	2469	8.1 a
Sparrow	903 a	853 bc	1949 abc	0.02	1	0.04	3	3705	7.9 a
Surprise	387 bc	429 bc	1302 bcd	0.08	7	0.10	9	2117	3.7 bcd
Thomas	102 c	539 bc	625 cd	0.06	5	0.06	6	1393	3.5 bcd
Thomas/Myer	348 bc	1065 b	631 cd	0.02	2	0.04	4	2139	5.5 abc
Tomboy	15 c	482 bc	2445 ab	0.06	5	0.11	10	2943	6.3 ab

[z] Fifty nuts per tree were randomly sampled from 4 trees for ambers evaluation in 2009 and 2010.
[y] Cumulative nuts/tree [(2008 nuts/tree)+(2009 nuts/tree)+(2010 nuts/tree)]
[x] Cumulative crop efficiency [(2008 nuts/tree)+(2009 nuts/tree)+(2010 nuts/tree)]/trunk cross sectional area (cm^2) as measured at 10 cm above the graft union.
[w] Means followed by different letters are significantly different by Fisher's LSD ($P \leq .05$).

CHAPTER 6:
DISCUSSION

Results from this study demonstrated that annual fruiting varied among black walnut cultivars. When individual shoots were examined, about half of the ‘Sparrow’ vegetative shoots labeled in 2009 produced a fruit-bearing shoot the following year (Table 4). In contrast, all other 2009-labeled shoot types were equally likely to produce a shoot with 0, 1, 2, or 3 fruits in 2010 (Tables 5, 6, 7). The combination of vegetative characteristics that best predicted 2010 nut number for ‘Sparrow’ trees was 2009 shoot diameter and length, as well as nuts per shoot. The model revealed that greater 2009 shoot diameter resulted in greater 2010 nut number, but greater 2009 shoot length or nut number resulted in reduced 2010 nut number.

While some of the characteristics measured in the present study were associated with nut number per shoot the following year, only 15% of the variation was explained (Table 3). Other researchers reported that light distribution within a tree influences nut production (Arreola-Avila et al., 2006; Hall, 1998). Ryugo (1986) reported that shading within the lower canopy of ‘Serr’ English walnut trees resulted in 65 to 98% pistillate flower abscission. Also, sun-exposed chestnut shoots with large diameters produced greater nut yield than weaker, shaded shoots (Hall, 1998). In the present study, terminal shoots in the lower portion of the tree canopy were examined which likely had less light exposure than those in the upper part of the tree. While light measurements were not recorded in this study, the addition of this variable in the regression model of predicted 2010 nut number may have explained additional variation.

In addition to light exposure, moisture stress also influences nut number (Buchner et al., 2008; Reid et al., 2009). From April to August, monthly rainfall at the study site ranged from 91 to 212 mm in 2009 and from 101 to 331 mm in 2010. During the months with the highest temperatures (June, July, and August), rainfall occurred at least once per week in both years. Thus, drought did not occur during the growing season and likely did not adversely offset fruit growth or yield.

The number of nuts harvested per tree fluctuated among cultivars and production years (Table 14). ‘Bowser’ and ‘Elmer/Myer’ produced ≤ 378 nuts each year of the study and were consistently low-yielding. In contrast, ‘Emma K’ and ‘Thomas/Myer’ had few nuts in 2008 (an “off” year), followed by an “on” year with 2577 and 1065 nuts per tree, respectively, and then an “off” year in 2010. Other cultivars, including ‘Davidson’, ‘Hare’, ‘Kwik Krop’, ‘Sparrow’, ‘Surprise’, and ‘Tomboy’ had low nut numbers per tree in 2008 and 2009, but produced a large crop in 2010. While these results are limited to a three year period, different types of fruiting cycles were recorded with several cultivars exhibiting two years of low nut production followed by a year of high production. Sparks (1974) reported that crop yields of pecan trees generally increase annually up to 10 years of age, but the trees bear irregularly as they mature. However, it is unknown if this cyclic production is typical of young black walnut trees such as those used in this study, as well as mature trees. Presumably, black walnut curculio, *Conotrachelus retentus* (Say), which causes major fruit loss, and anthracnose, which causes premature defoliation, would interrupt the “normal” fruiting cycle (Worley, 1979).

Irregular bearing has been reported for many fruit and nut crops including black walnut, English walnut, pecan, heartnut (*Juglans ailantifolia* Carr.), and hazelnut (*Corylus avellana* L.) (Campbell, 2001). However, some cultivars of these crops tend to bear on a biennial cycle (Campbell, 2001). Monselise and Goldschmidt (1982) developed an alternate bearing index equation to quantify the tendency to bear irregularly. An index value near 0 indicates stable annual crop yields, while a value near 1 indicates a biennial bearing cycle. However, the alternate bearing index does not reflect crop yield of a tree. For example, an alternate bearing index of 0 only indicates that a tree bears consistently, but does not reveal high or low cropping. Similarly, it is impossible to distinguish if a tree was “off, off, on” or “on, on, off” (i.e., 0.5 alternate bearing index) without the corresponding yield data. Thus, alternate bearing index has limited usefulness for black walnut cultivars that are not annual or biennial bearers.

Another method used to characterize fruiting of tree crops is cumulative yield efficiency (Westwood, 1993). Because trunk cross-sectional area is related to canopy volume (Bartelink, 1997), crop efficiency can be used to evaluate nut production per unit trunk area (Table 14). Thus, this study revealed that relatively young trees of ‘Davidson’, ‘Emma K’, ‘Kwik Krop’, ‘Sparks 127’, ‘Sparrow’, and ‘Tomboy’ were more efficient than ‘Bowser’ and ‘Elmer/Myer’. Van Sambeek (1988) reported that competition among black walnut trees occurs when the crown competition factor ranges from 80 to 100. However, crown competition factor within the plantings at HARC was only 17 in 2010, thus trees were not competing for resources (M. Coggeshall, personal communication; Schlesinger, 1988). While data were limited to three production years, these results indicated that cultivars with higher cumulative crop efficiencies may be planted at closer spacings to increase nut yield per hectare than those with lower crop efficiencies.

Black walnut cultivars can be classified by their bearing habit (Reid et al., 2004). Terminal bearing trees fruit distally on primary branches. Spur-bearing trees fruit distally on branches, as well as on spurs. Spurs are 200 to 300 mm-long shoots that arise along primary branches. Thus, when fruits are produced on terminal branches and on spurs, fruiting potential may be increased (Reid et al., 2009). Five spur-bearing cultivars, ‘Davidson’, ‘Emma K’, ‘Kwik Krop’, ‘Sparks 127’, and ‘Surprise’, were included in the current study. Four of these spur-bearing cultivars generally had high cumulative nuts per tree and crop efficiencies relative to several other cultivars. However, ‘Surprise’ had a similar crop efficiency value to that of ‘Bowser’ and ‘Elmer/Myer’, which were the least efficient cultivars.

Results from this study also demonstrated that ambers was not a major factor influencing fruiting of any of the cultivars evaluated at HARC (Table 14). Because the incidence of ambered kernels was a rare event, differences in the number of ambered kernels among cultivars were not detected. This finding differed from 2007 results for 35 year-old trees at a commercial orchard near Windsor, MO in which 68, 37, and 16% of the nuts sampled from ‘Sparrow’, ‘Emma K’, and ‘Kwik Krop’, respectively, had ambered kernels (M. Warmund, unpublished data). The reason for differing results may be related to tree age or other factors. Suggested causes of ambers include anthracnose, lack of light, moisture, or nutrients (Funk, 1979; Kintzel, 1968; Stoke, 1941). Gibson and Kearby (1976) found that walnut husk fly feeding was not associated with ambers. Thus, the causative agent of ambers remains unknown.

CHAPTER 7:
SUMMARY AND CONCLUSIONS

Three studies were conducted to evaluate sequential vegetative and fruiting characteristics of black walnut. In the first study, diameters of ‘Sparrow’ vegetative shoots or those with one fruit were smaller than shoots with three fruits in 2009. Also, 2009 vegetative shoots were most likely to remain non-bearing in 2010. However, 2009 bearing shoots were equally likely to produce 0, 1, 2, or 3 nuts in 2010. Step-wise regression revealed that greater 2009 shoot diameter resulted in greater 2010 nut number. However, greater 2009 shoot length or nut number resulted in reduced 2010 nut number.

In another study, sequential fruiting of 2009-labeled ‘Sparrow’, ‘Surprise’, ‘Kwik Krop’, and ‘Emma K’ shoots with two fruits each was evaluated. All cultivars had similar odds of producing 0, 1, 2, or 3 fruits the following year except ‘Emma K’. All but one 2009-labeled ‘Emma K’ shoots were vegetative in 2010.

When crop yields for 15 cultivars were evaluated from 2008 to 2010, ‘Bowser’ and ‘Elmer/Myer’ produced low (≤ 378 nuts/tree), but consistent annual yields. In contrast, ‘Emma K’, ‘Kwik Krop’, and ‘Sparrow’ had high cumulative yields (≥ 3000 nuts/tree). ‘Emma K’ and ‘Thomas/Myer’ exhibited a biennial bearing habit, while ‘Davidson’, ‘Hare’, ‘Kwik Krop’, ‘Sparrow’, ‘Surprise’, and ‘Tomboy’ had two consecutive low production years followed by high yields the third year. Also, ‘Davidson’, ‘Emma K’, ‘Kwik Krop’, ‘Sparks 127’, ‘Sparrow’, and ‘Tomboy’ were more yield efficient than ‘Bowser’ and ‘Elmer/Myer’ from 2008 to

2010. The incidence of ambers was similar among black walnut cultivars and averaged ≤ 7% per cultivar.

LITERATURE CITED

Arreola-Avila, J., E. Herrara-Aguirre, R. Trejo-Calzada, A. Flores-Hernández, R. Parra-Quezada, and A. Borja-de la Rosa. 2006. Sunlight availability and nut production after thinning of pecan trees (*Carya illinoensis* K. Koch). Revista Chapingo Serie Horticultura 12(2):117-181.

Bartelink, H.H. 1997. Allometric relationships for biomass and leaf area of beech (*Fagus sylvatica* L.). Ann. Sci. For. 54:39-50.

Beineke, W.F. and J.L. Hunley. 1979. Delay of floral and leaf development by overtree irrigation in black walnut. Can. J. For. Res. 9:379-382.

Beineke, W.F. and C.J. Masters. 1977. Pollen maturation and extraction in black walnut. Tree Planter's Notes 28:7-9.

Brawner, S.A. 2007. Husk softening and kernel characteristics of eastern black walnut (*Juglans nigra* L.) cultivars at successive harvest dates. Univ. of MO., Columbia, M.S. Thesis.

Buchner, R.P., B.D. Lampinen, T.L. Prichard, and L.J. Schwankl. 2008. Effects of regulated deficit irrigation on walnut grafted on 'Northern California Black' or 'Paradox' rootstock. Acta Hort. 792:141-146.

Campbell, R.D. 2001. Alternate or sometimes bearing of nut trees. Northern Nut Growers Assn. Annu. Rpt. 92:79-80.

Coggeshall, M.V. 2011. Black walnut: a nut crop for the midwestern United States. HortScience 46(3):340-342.

Crane, H.L. 1949. The development and filling of nuts. Northern Nut Growers Assn. Annu. Rpt. 39:130-139.

Duke, J.A. 2001. *Juglans nigra* L. (juglandaceae)- eastern black walnut, p. 190-193. In: Handbook of nuts. CRC Press, Boca Raton, FL.

Funk, D.T. 1979. Black walnuts for nuts and timber, p. 51-73. In: R.A. Jaynes (ed.). Nut tree culture in North America. Northern Nut Growers Assn., Hamden, CT.

Gibson, K.E. and W.H. Kearby. 1976. Black walnut nutmeat quality in relation to the presence of husk fly maggots in the husks. Northern Nut Growers Assn. Annu. Rpt. 67:109-113.

Grant, J., G.S. Sibbett, and J. Labavitch. 1985. Oilless nut biology and composition. Oilless nut biology and composition- walnut research reports. 26 Aug. 2011. <http://walnutresearch.ucdavis.edu/1985/1985_37.pdf>.

Haas, A.R.C. and L.D. Batchelor. 1928. Relation of phosphorus content to shriveling of walnut kernels. Bot. Gaz. 86(4):448-455.

Hall, P. 1998. Physiological and ecological characteristics of chestnuts. Proc. Chestnut Pruning and Grafting Conf., Wkshp. and Farm Walk. Beechworth, Victoria, Australia, 29-30 Aug. 1998.

Hammons, B. 2009. The importance of black walnuts. MO. Dept. Agr. 5 Aug. 2011. <http://mda.mo.gov/plants/pdf/tc_brianhammons.pdf>.

Kintzel, F. 1968. The filling of black walnuts. Northern Nut Growers Assn. Annu. Rpt. 59:100-101.

Mangoff, R.N. 1980. Nutrient content of light and amber black walnut kernels. Univ. of MO., Columbia. M.S. Thesis.

Manning, W.E. 1938. The morphology of the flowers of the Juglandaceae. I. The inflorescence. Amer. J. Bot. 25(6):407-419.

Manning, W.E. 1940. The morphology of the flowers of the Juglandaceae. II. The pistillate flowers and fruit. Amer. J. Bot. 27(10):839-852.

Manning, W.E. 1948. The morphology of the flowers of the Juglandaceae. III. The staminate flowers. Amer. J. Bot. 35(9):606-621.

Michler, C.H., K.E. Woeste, and P.M. Pijut. 2007. Black Walnut, p. 189-198. In: C. Kole (ed.). Genome mapping and molecular breeding in plants, Vol. 7. Springer, Berlin, Germany.

Monselise, S.P. and E.E. Goldschmidt. 1982. Alternate bearing in fruit trees, p. 128-173. In: J. Janick (ed.). Hort. Rev. Vol. 4. AVI Publishing, Westport, CT.

Nast, C.G. 1941. The embryogeny seedling morphology of *Juglans regia* L. Lilloa 6:163-205.

Reid, W., M.V. Coggeshall, K.L. Hunt. 2004. Cultivar evaluation and development for black walnut orchards. Proc. 6th Walnut Council Res. Symp., Lafayette, Indiana, 25-28 July. p. 18-24.

Reid, W., M. Coggeshall, H.E. Garrett, and J. Van Sambeek. 2009. Growing Black Walnut for Nut Production. Ctr. Agroforestry Univ. MO. 2 Nov. 2011. <http://extension.missouri.edu/explorepdf/agguides/agroforestry/af1011.pdf>.

Ryugo, K. 1986. Promotion and inhibition of flower initiation and fruit set by plant manipulation and hormones, a review. Acta Hort. 179:301-307.

Schaffer, K.L., M.F. George, M. Peleg, H.E. Garrett, and R.A. Cecich. 1996. Pistillate flower development in eastern black walnut. Can. J. For. Res. 26:1514-1519.

Schlesinger, R.C. 1988. First thinning, p. 1-2. In: E.L. Burde (ed.). Walnut notes. U.S. Dept. Agr., For. Serv., North Central Expt. Sta., St. Paul, MN.

Sibbett, S. 1999. There will be some “oilless” nuts this year. UCCE Tulare County, In-A-Nutshell (July 1999). 26 Aug. 2011. <http://ucce.ucdavis.edu/counties/ceulare/pub/nut0799.htm>.

Smith, M.W., B.S. Cheary, and B.L. Carroll. 2007. The occurrence of pecan kernel necrosis. HortScience 42(6):1351-1356.

Sparks, D. 1974. The alternate fruit bearing problem in pecans. Northern Nut Growers Assn. Annu. Rpt. 65:145-158.

Sparks, D. 2003. Growth, flowering, and fruiting, p. 273-290. In: D.W. Fulbright (ed.). A guide to nut tree culture in North America. Vol. 1. McNaughton and Gunn, Saline, MI.

Stoke, H.F. 1941. Factors influencing the color and quality of black walnut kernels. Northern Nut Growers Assn. Annu. Rpt. 32:37-42.

Van Sambeek, J.W. and G. Rink. 1981. Physiology and silviculture of black walnut for combined timber and nut production. Northern Nut Growers Assn. Annu. Rpt. 72:100-107.

Van Sambeek, J.W. 1998. Carbohydrate assimilation, translocation, and utilization, p. 73-78. In: J.E. Jones, R. Mueller, and J.W. Van Sambeek (eds.). Nut production handbook for eastern black walnut. Southwest MO. Resources, Conservation, and Dev., Inc., Republic, MO.

Van Sambeek, J.W. 1988. Nut production, p. 1-2. In: E.L. Burde (ed.). Walnut notes. U.S. Dept. Agr., For. Serv., North Central Expt. Sta., St. Paul, MN.

Warmund, M.R. 2008. Kernel color of three black walnut cultivars after delayed hulling at five successive harvest dates. HortScience 43(7):2256-2258.

Warmund, M.R. and M.V. Coggeshall. 2010. Flowering and fruit characteristics of black walnut cultivars at the University of Missouri repository. Acta Hort. 861:177-181.

Warmund, M.R., J.R. Elmore, K. Adhikari, and S. McGraw. 2009. Descriptive sensory analysis of light, medium, and dark colored kernels of black walnut cultivars. J. Sci. Food Agr. 89:1969-1972.

Westwood, M.N. 1993. Plant efficiency: growth and yield. p. 275-299. In: Temperate-zone pomology. 3rd edition. Timber Press, Portland, OR.

Woodroof, J.G. 1979. Black walnuts, p. 604-615. In: Tree nuts: production processing products. 2nd edition. AVI Publishing, Westport, CT.

Worley, R.E. 1979. Fall defoliation date and seasonal carbohydrate concentration of pecan wood tissue. J. Amer. Soc. Hort. Sci. 104(2):195-199.

Zarger, T.G. 1969. Black walnuts-as nut trees, p. 203-211. In: R.A. Jaynes (ed.). Handbook of North American nut trees. W.F. Humphrey Press, Geneva, NY.