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The Kentucky Pawpaw Regional Variety Trial

Kirk W. Pomper[1], Sheri B. Crabtree[2], Desmond R. Layne[3], R. Neal Peterson[4], Joseph Masabni[5], and Dwight Wolfe[6]

Abstract

The North American pawpaw [*Asimina triloba* (L.) Dunal] is in the initial stages of commercial production. Two pawpaw variety trial orchards were established in Kentucky to evaluate the suitability of various varieties for this region. The first orchard was planted in the fall of 1995 in Princeton, at the University of Kentucky Research and Education Center (UKREC). A second orchard was planted in the spring of 1998 at the Kentucky State University (KSU) Research Farm in Frankfort. A randomized complete block design was used in both plantings with 8 replicates of 28 grafted cultivars and advanced selections. Cultivars being evaluated included 'Middletown', 'Mitchell', 'NC-1', 'Overleese', 'PA-Golden', 'Sunflower', 'Taylor', 'Taytwo', 'Wells', and 'Wilson'. The other 18 clones were selections from the PawPaw Foundation (PPF) breeding effort. Trunk cross-sectional area, number of fruit per tree, fruit weight, cumulative yield, cumulative yield efficiency, number of fruit per cluster, growing degree days required for ripening, harvest peak, harvest duration (days), and biennial bearing index all varied significantly among cultivars and advanced selections 7 to 9 years after planting at both planting sites. Fruit weight varied greatly, with some clones averaging less than 100 g per fruit ('Middletown', 'Wilson', and 'Rappahannock') and others averaging over 170 g per fruit ('Overleese', 8-20, 'NC-1', 'Susquehanna', 'Wabash', 5-5, and 'Potomac'). 'PA-Golden' and 2-10 were early ripening clones while 'Middletown' and 9-47 were late ripening clones. Cumulative yield varied greatly, with some cultivars and advanced selections exceeding 30 kg/tree. Cumulative yield efficiency ranged from 0.38 to 0.91 kg/cm^2 TCA. Based on fruit size yield, and availability, 'Potomac', 'Susquehanna', 'Wabash', 'Overleese', 'Shenandoah', 'NC-1', and 'Sunflower' can be recommended for production in this region. Additional PPF advanced selections that show promise are 10-35, 9-58, 2-10, 8-20, 5-5, and 1-68.

The North American pawpaw [*Asimina triloba* (L.) Dunal] is in the initial stages of commercial production in the United States (10, 21). Pawpaws can be grown successfully in USDA plant hardiness zones 5 (minimum of -29°C) through 8 (minimum of -7°C) (8). The pawpaw fruit has both fresh market and processing potential, with an intense flavor that resembles a combination of banana, mango, and pineapple.

Pawpaws have dark maroon blossoms that occur singly on the previous year's wood and produce one to nine carpels or one to nine fruited clusters (8, 21). Flowers are strongly protogynous and are likely self-incompatible (23). Pollination is performed by flies (Diptera) (23) and beetles (Nitidulidae) (8). Fruit set in the wild is usually low, possibly due to pollinator or resource limitations (9, 23). When ripe, the fruit softens and has a powerful aroma (11, 22). In some cultivars, there is a skin color change from green to green-yellow when the fruit ripens (e.g., 'PA-Golden #1'). Flesh color of ripe fruit ranges from creamy white through bright yellow to shades of orange. In the fruit, there are two rows of seeds (12 to 20 seeds) that are brown and bean-shaped and may be up to 3 cm long.

Efforts to cultivate the pawpaw began early in the 20th century (17, 24). Elite pawpaw

[1] Principal Investigator of Horticulture and Curator, USDA Clonal Germplasm Repository for *Asimina* species, Atwood Research Facility, Kentucky State University, Frankfort, KY 40601-2355. To whom reprint requests should be addressed.
[2] Co-Investigator of Horticulture, Atwood Research Facility, Kentucky State University, Frankfort, KY 40601-2355.
[3] Associate Professor of Pomology and Extension Fruit Specialist, Dept. of Horticulture, Box 340375, Clemson Univ., Clemson, SC 29634-0375
[4] Peterson Pawpaws, P.O. Box 1011, Harpers Ferry, WV 25425
[5] Assistant Professor, Fruit and Vegetable Specialist, Department of Horticulture, University of Kentucky, Research & Education Ctr., P.O. Box 469, 1205 Hopkinsville Street, Princeton, KY 42445
[6] Horticulture Research Specialist, Department of Horticulture, University of Kentucky, Research & Education Ctr., P.O. Box 469, 1205 Hopkinsville Street, Princeton, KY 42445

selections from the wild were assembled in extensive collections by various enthusiasts and scientists, including Benjamin Buckman (Farmington, Illinois, circa 1900 to 1920), George Zimmerman (Linglestown, Pennsylvania, 1918 to 1941), and Orland White (Blandy Experimental Farm, Boyce, Virginia, 1926 to 1955) (16, 17, 18, 24). From about 1900 to 1960, at least 56 clones of pawpaw were selected and named. Fewer than 20 of these cultivars remain, with many being lost from cultivation through neglect, abandonment of collections, and loss of records necessary for identification (17). Since 1960, additional pawpaw cultivars have been selected from the wild or developed as a result of breeding efforts of hobbyists. More than 40 clones are currently available (7). The loss of cultivars over the last century may have led to erosion in the genetic base of current pawpaw cultivars (6). Urban encroachment and the resulting destruction of native pawpaw patches may also be leading to a reduction in genetic diversity in the wild.

In 1981, R. Neal Peterson and Harry Swartz began a long-term breeding project to develop improved pawpaw cultivars (16, 17, 18). A collection of about 1500 accessions of open-pollinated seedlings was assembled at the University of Maryland Experiment Stations at Queenstown and Keedysville, Maryland. The seed for this germplasm collection was obtained from pawpaw trees that remained at the sites of the historic collections of Buckman, Zimmerman, and the Blandy Experimental Farm, as well as those of Hershey (Dowington, Pennsylvania), Allard (Arlington, Virginia), Ray Schlaanstine (West Chester, Pennsylvania), and open-pollinated seed from some modern cultivars.

In 1993, the Pawpaw Foundation (PPF) and Kentucky State University (KSU) embarked on a joint venture to test 10 commercially available pawpaw cultivars and 18 of PPF's advanced selections from the Maryland orchards in a Pawpaw Regional Variety Trial (PRVT), which was established on the properties of 13 universities or private cooperators (10, 19, 20). The PRVT was established in Princeton, KY in 1995 and the Frankfort, KY planting was established in 1998. The objective of the PRVT plantings was to evaluate commercially available named pawpaw varieties and PPF's advanced selections within and outside of the pawpaw's native range. Here we report on the performance of the PRVT in Kentucky for mature trees at the Frankfort and Princeton sites.

Materials and Methods

The 28 grafted scion varieties (Table 1) were propagated on seedling rootstock produced from open-pollinated half-sibling trees as described by Pomper et al. (20). At both Kentucky PRVT sites, eight replicate trees of each of clone (Table 2) were planted in a randomized complete block design with eight complete blocks (block = 4 rows x 7 trees) at an in-row spacing of 2 m and between-row spacing of 5.5 m. Rows were placed in north-south orientation. During the trial, some advanced selections were named and released; in this case, the cultivar name and advanced selection number are both included in Table 1.

For the Frankfort location trees were planted in late March, 1998. A total of 224 grafted trees (eight trees of each selection) and 75 Kentucky seedlings serving as border row trees were planted in a Lowell silt loam soil (pH 6.9) at the KSU Research and Demonstration Farm in Frankfort, Ky. Trees were fertigated with Peters 20-20-20 (20N-8.7P-16.6K) water-soluble fertilizer (Scotts Co., Marysville, Ohio) once in May, June, July, and August each year for a total of 12.1 kg/ha of nitrogen (N). Corrective pruning was implemented in late spring by removing only the lower limbs below a height of about one meter. Additional irrigation was provided as needed by drip irrigation; each tree had two emitters per tree (5.7 liters/hour each).

For the Princeton planting, 224 grafted trees (eight trees of each selection) and 75 Kentucky seedling trees as border row trees were planted in Oct. 1995, in a Crider silt loam

Table 1. Genetic background of pawpaw (*Asimina triloba*) selections[z] included in the Kentucky Pawpaw Regional Variety Trials (PRVT) and tree survival in the Frankfort and Princeton, Kentucky plantings after 9 and 12 years respectively.

Clone[z]	Genetic background	Surviving trees in Frankfort KY, (%)	Surviving trees in Princeton KY, (%)
Middletown	Wild seedling from Middletown, Ohio	100	50
Mitchell	Wild seedling from Iuka, Illinois	100	50
NC-1	Davis× Overleese	100	75
Overleese	Cultivated (open-pollinated) seedling from Rushville, Ind.	88	63
PA-Golden	Second-generation seedling from G.A. Zimmerman collection	100	50
Potomac (4-2)	Open-pollinated seedling of BEF-53	100	50
Rappahannock (8-58)	Open-pollinated seedling of BEF-30	100	75
Shenandoah (1-7-1)	Open-pollinated seedling of Overleese	100	75
Sunflower	Wild seedling from Chanute, Kansas	100	88
Susquehanna (11-5)	Open-pollinated seedling of BEF-53	88	13
Taylor	Wild seedling from Eaton Rapids, Mich.	75	38
Taytwo	Wild seedling from Eaton Rapids, Mich.	100	50
Wabash (1-7-2)	Open-pollinated seeding from BEF-30[y]	100	63
Wells	Cultivated (open-pollinated) seedling from Salem, Ind.	88	75
Wilson	Wild seedling from Cumberland, Ky.	75	88
1-23	Open-pollinated seedling of Taylor	100	50
1-68	Open-pollinated seedling of Overleese	100	63
2-10	Open-pollinated seedling of BEF-30	75	63
2-54	Open-pollinated seedling of GAZ-VA[x]	100	50
3-11	Open-pollinated seedling of BEF-33	88	75
3-21	Open-pollinated seedling of BEF-43	100	50
5-5	Open-pollinated seedling of BEF-54	88	38
7-90	Open-pollinated seedling of RS-2[w]	100	50
8-20	Open-pollinated seedling of Sunflower	100	50
9-47	Open-pollinated seedling of BEF-49	100	88
9-58	Open-pollinated seedling of BEF-50	100	38
10-35	Open-pollinated seedling of BEF-49	100	88
11-13	Open-pollinated seedling of BEF-53	100	50
Total (± SE)		95±9	59±18

[z] Numbered selections from the PawPaw Foundation orchards; numerous wild selections from the remnant collections of H.A. Allard (Arlington, Va.), Blandy Experimental Farm (Boyce, Va.), B. Buckman (Farmington, Ill.), J. Hershey (Dowington, Pa.), R. Schlaanstine (West Chester, Pa.), and G. Zimmerman (Linglestown, Pa.), plus some from truly wild trees and some from named varieties that were assembled by R. N. Peterson and H. J. Swartz at the Univ. of Maryland Experiment Stations in Keedysville and Queenstown, Md.

[y] BEF = Blandy Experimental Farm collection (Boyce, Va.); numerous wild seedlings plus portions of Zimmerman's collection, donated posthumously; assembled by Orland E. White and staff at Boyce, Va., from 1926 to 1955.

[x] GAZ = George A. Zimmerman collection containing most, if not all of the named varieties of the time plus numerous wild selections and interspecific hybrids; assembled by George A. Zimmerman of Linglestown, Pa., from 1920 to 1940.

[w] RS = Ray Schlaanstine collection, material descending from Zimmerman's collection via John Hershey; assembled by Ray Schlaanstine of West Chester, Pa., date uncertain, circa 1960.

(pH 6.9) at the University of Kentucky (UK) Research and Education Center in Princeton, Ky. Trees were fertilized with 28.0 kg /ha of N broadcast distribution of granular fertilizer (34-0-0) in early March. Trees at the Princeton planting were not irrigated. The graft union of trees was about 15 cm at both the Frankfort and Princeton sites.

At both locations, the number of clusters and number of fruit per cluster on each tree were counted in late July each year following the normal fruit drop period. Fruit were harvested on Mondays, Wednesdays, and Fridays during the harvest season (mid August to late September). Average fruit weight was based on the weights of 10 or more fruit per tree. Trunk diameters were measured at 30 cm from the soil surface annually in March. For the Frankfort planting, growing degree days (GDDs) were calculated using a base temperature of 10°C (University of Kentucky Agricultural Weather Center calculator, http://wwwagwx.ca.uky.edu/calculators.html). Temperature data were obtained from the University of Kentucky Agricultural Weather Center's monthly climate summary (http://wwwagwx.ca.uky.edu/cgi-public/climsum2.ehtml), with temperatures recorded at their Lexington station, approximately 25 miles from Frankfort.

For each site, data for trunk cross-sectional area [TCA (cm^2)], number of fruit per tree, fruit weight (g), cumulative yield (total kg), cumulative yield efficiency [CYE, (total kg yield/ cm^2 TCA)], average number of fruit per cluster, GDDs required for ripening, harvest peak (month/day), harvest duration (days), and biennial bearing index (BBI) were subjected to GLM analysis of variance and Least Significant Difference (LSD) means separation, using the statistical program Costat (CoHort Software, Monterey, Calif.). Treatment means were separated based on a significance level of $P < 0.05$. The BBI was calculated on the basis of the Pearce and Debusek-Urbank formula (14):

$$BBI = 1 / (n-1) \text{ X } \{|(a_2 - a_1)| / (a_2 + a_1) + |(a_3 - a_2)| / (a_3 + a_2) \ldots + |(a_{(n)} - a_{(n-1)})| / (a_{(n)} + a_{(n-1)})\}$$

where n = number of years, and a_1, a_2, …, $a_{(n-1)}$, a_n = yield of corresponding years. The BBI is a measure of a cultivar's tendency to produce alternating high and low yields; ranges are from 0 to 1, with 0 = no alternation and 1 = complete alternation. Biennial bearing index was calculated based on three years of data from each site.

Results

Frankfort, KY trial. At the Frankfort planting, 95% of the trees survived (Table 1). Most of the trees that died were lost during the first summer after planting. 'Wilson' and 'Taylor', and the advanced selection 2-10, had the poorest survival rate (75%). All other cultivars and advanced selections had survival rates of 88% or higher (Table 1).

Vigor and yield of trees were evaluated annually from 2002 to 2006. In 2003, a frost event destroyed almost the entire pawpaw crop; therefore, only vigor and fruiting characteristics from 2004, 2005, and 2006 are reported in Table 2, but yield for each year is presented (Table 3). The variables TCA, number of fruit per tree, fruit weight, cumulative yield, cumulative yield efficiency, number of fruit per cluster, GDDs required for ripening, harvest peak, harvest duration (days), and biennial bearing index all varied significantly among cultivars and advanced selections ($P < 0.001$) 7, 8, and 9 years after planting.

Based on TCA recorded in 2006, most clones displayed excellent vigor, ranging from 32.8 to 78.6 cm^2 , especially 'Wabash', 'Wilson', 7-90, and 10-35, although some clones lacked vigor (e.g., 'Wells', 'Middletown', and 3-21; Table 2). 'PA-Golden', 'Wilson', and 10-35 averaged more than 100 fruit per tree, whereas 'Susquehanna' and 5-5 averaged fewer than 40 fruit per tree. Variability in number of fruit per tree was high (LSD=31). Fruit weight also varied greatly among cultivars and advanced selections, with some clones having an average fruit weight of 170 g or more per fruit ('Overleese', 8-20, 'NC-1', 'Susquehanna', 'Wabash', 5-5, and 'Potomac'), and some under 100 g ('Middletown', 'Wilson', and 'Rappahannock').

Table 2. Tree vigor, yield, fruit ripening and harvest characteristics for 28 cultivars and PawPaw Foundation advanced selections in the PawPaw Regional Variety Trial in 2004, 2005, and 2006 in Frankfort, Kentucky.

Clone	Truck cross sectional area (2006) (cm^2)	Average no. of fruit per tree	Average fruit weight (g)	Cumulative yield (kg)	Cum. yield efficiency (kg/cm^2 TCA)	No. of fruit per cluster	GDDs required for ripening	Harvest peak (mo./day)	Harvest duration (days)
Middletown	36.6 klm	74 def	75 n	16.3 k	0.43 fgh	2.6 bcdefgh	2,823 ab	9/13 a	22 bcdef
Mitchell	46.4 hijkl	58 fghi	112 jkl	19.2 ijk	0.43 fgh	1.9 l	2,736 cdef	9/8 cde	20 efgh
NC-1	60.5 bcdef	44 ghi	179 bc	22.9 fghijk	0.39 h	2.6 bcdefghi	2,620 klm	9/4 ijk	19 fgh
Overleese	52.0 defghij	54 fghi	170 bcd	24.8 efghijk	0.48 defgh	2.6 bcdefghi	2,637 jkl	9/4 hij	20 defgh
PA-Golden	59.6 bcdefg	118 ab	108 jklm	38.7 abc	0.66 bcd	2.2 ghijkl	2,499 o	8/29 m	25 bc
Potomac	64.3 bcd	44 ghi	235 a	29.1 cdefghi	0.43 fgh	2.9 bc	2,720 def	9/8 cde	22 bcdefgh
Rappahannock	46.9 ghijkl	96 bcd	96 lm	27.2 defghij	0.59 bcdef	2.2 ijkl	2,586 lm	9/1 kl	18 h
Shenandoah	49.7 efghijk	78 def	156 def	34.8 bcde	0.71 bc	2.3 efghijkl	2,697 efghij	9/7 defg	26 ab
Sunflower	48.3 fghijk	74 def	155 def	34.5 bcde	0.72 b	2.2 hijkl	2,737 cdef	9/8 cde	22 bcdef
Susquehanna	45.5 hijklm	39 i	184 b	20.2 hijk	0.46 fgh	2.5 cdefghij	2,703 efghi	9/7 defgh	22 bcdefg
Taylor	44.2 ijklm	68 efg	106 jklm	22.9 fghijk	0.49 defgh	2.8 bcdef	2,676 fghijk	9/5 fghi	20 defgh
Taytwo	44.6 hijklm	73 def	121 hijk	25.9 efghijk	0.57 bcdefg	2.5 cdefghij	2,648 ijk	9/4 hij	22 bcdefgh
Wabash	66.6 abc	65 fg	185 b	36.8 abcd	0.56 bcdefg	2.0 kl	2,572 mn	9/2 jk	21 defgh
Wells	32.8 m	64 fgh	104 klm	18.8 jk	0.53 cdefgh	2.8 bcde	2,751 cde	9/9 bcd	18 gh
Wilson	68.1 abc	128 a	89 mn	34.7 bcde	0.52 cdefgh	3.1 b	2,710 defghi	9/7 defgh	24 bcde
1-23	53.7 defghij	90 cde	126 ghij	30.6 cdefg	0.57 bcdefg	2.7 bcdef	2,690 fghij	9/6 efgh	22 cdefgh
1-68	52.6 defghij	90 cde	167 bcd	46.6 a	0.91 a	2.4 defghijk	2,660 ghijk	9/5 ghi	22 bcdefgh
2-10	44.6 hijklm	52 fghi	160 cde	24.5 efghijk	0.56 bcdefgh	2.0 jkl	2,512 no	8/30 lm	24 bcdef
2-54	54.6 cdefghij	73 def	121 hijk	26.7 efghij	0.48 efgh	2.6 bcdefghi	2,715 defgh	9/7 defgh	22 bcdefgh
3-11	57.5 cdefgh	68 ef	137 efgh	27.3 defghij	0.43 fgh	2.8 bcdef	2,655 hijk	9/5 ghij	21 defgh
3-21	35.0 lm	60 fghi	115 ijkl	19.4 hijk	0.55 bcdefgh	2.7 bcdef	2,566 mn	9/1 klm	21 cdefgh
5-5	41.8 jklm	39 hi	188 b	22.9 fghijk	0.55 bcdefgh	2.2 ghijkl	2,775 bcd	9/11 abc	23 bcdef
7-90	78.6 a	74 def	135 fghi	29.2 cdefgh	0.38 h	2.6 bcdefghi	2,793 abc	9/11ab	24 bcd
8-20	58.8 bcdefgh	59 fghi	170 bcd	28.2 defghij	0.48 efgh	2.3 fghijkl	2,753 cde	9/9 bcd	21 cdefgh
9-47	53.3 defghij	74 def	100 lm	20.9 ghijk	0.40 gh	2.7 bcdefg	2,842 a	9/13 a	23 bcdef
9-58	62.3 bcde	79 def	146 efg	31.6 cdef	0.52 cdefgh	2.8 bcde	2,718 defg	9/8 cdef	19 fgh
10-35	71.6 ab	105 abc	145 efg	43.6 ab	0.64 bcde	2.9 bcd	2,679 fghijk	9/6 efghi	25 bcd
11-13	55.2 cdefghi	75 def	124 hij	27.3 defghij	0.49 defgh	3.7 a	2,707 efghi	9/7 defgh	30 a
significance	***	***	***	***	***	***	***	***	***
LSD	16.2	30.6	25.3	12.6	0.22	0.6	76.4	3.4	5.3
mean	53.2	72	139	28.1	0.53	2.6	2688	9/6	22
block effect	**	NS	NS	*	NS	NS	NS	NS	**

Table 3. Yield (kg per tree) of pawpaw (*Asimina triloba)* selections from 2002-2006 for the Frankfort, Kentucky pawpaw regional variety trial.[z]

Clone	2002	2004	2005	2006	Biennial bearing index (2004-2006)[y]
Middletown	3.7 abc	7.1 f	3.5 ghij	6.2 hi	0.56 abcd
Mitchell	0.5 fg	8.1 def	2.9 ij	7.1 ghi	0.56 abcd
NC-1	1.4 cdefg	8.3 def	3.7 ghij	11.3 defgh	0.62 ab
Overleese	1.7 cdefg	6.6 f	4.9 defghij	10.1 efghi	0.56 abcd
PA-Golden	5.7 a	14.4 abcde	8.8 ab	17.2 ab	0.25 fg
Potomac	1.8 cdefg	12.8 bcdef	5.7 cdefghi	12.8 bcdef	0.54 abcd
Rappahannock	1.9 cdefg	14.0 abcdef	4.3 fghij	11.5 cdefgh	0.29 efg
Shenandoah	2.9 bcdef	17.0 ab	4.3 efghij	13.1 abcdef	0.49 abcde
Sunflower	3.8 abc	11.8 bcdef	3.8 ghij	16.7 abc	0.22 g
Susquehanna	1.0 defg	8.2 def	5.1 defgh	8.8 efghi	0.46 abcde
Taylor	2.0 bcdefg	9.6 cdef	3.5 ghij	7.9 fghi	0.46 abcde
Taytwo	1.5 cdefg	9.1 def	6.7 bcdef	10.2 efgh	0.43 abcdef
Wabash	2.3 bcdefg	11.0 bcdef	8.0 abc	13.4 abcde	0.40 cdefg
Wells	2.5 bcdefg	7.9 def	4.9 defghij	5.0 i	0.42 bcdefg
Wilson	1.5 cdefg	10.5 bcdef	6.0 bcdefgh	13.0 abcdef	0.58 abc
1-23	3.5 abcd	13.3 abcdef	4.1 ghij	12.0 bcdefg	0.56 abcd
1-68	3.2 abcde	14.4 abcd	5.6 cdefghi	16.6 abc	0.32 efg
2-10	1.8 cdefg	8.4 def	6.4 bcdefg	11.7 bcdefgh	0.29 efg
2-54	0.9 efg	7.5 ef	3.1 hij	12.8 bcdef	0.40 bcdefg
3-11	2.0 bcdefg	10.7 bcdef	2.5 j	15.9 abcd	0.32 efg
3-21	0.4 g	6.1 f	4.7 efghij	8.4 efghi	0.55 abcd
5-5	0.4 g	9.5 cdef	6.6 bcdefg	8.8 efghi	0.35 defg
7-90	1.2 defg	12.4 bcdef	7.8 abcd	13.6 abcde	0.63 a
8-20	3.1 bcde	16.3 abc	2.9 ij	12.5 bcdef	0.28 efg
9-47	1.0 defg	11.1 bcdef	5.8 cdefgh	9.0 efghi	0.41 bcdefg
9-58	1.6 cdefg	7.9 ef	4.7 efghij	15.9 abcd	0.35 defg
10-35	4.5 ab	19.7 a	9.6 a	18.2 a	0.25 fg
11-13	2.6 bcdefg	14.5 abcd	7.1 abcde	9.2 efghi	0.60 abc
significance	***	**	***	***	***
LSD	2.5	9.2	3.5	6.6	0.25
mean	2.2	11.0	5.2	11.8	0.44
block effect	***	NS	NS	**	*

[z] A freeze event in 2003 killed all developing fruit, therefore data was not recorded in this year.

[y] The Biennial bearing index (BBI) was calculated on the basis of the Pearce and Debusek-Urbank formula (14):
BBI = 1 / (n-1) X {|(a2 – a1)| / (a2 + a1) + |(a3 – a2)| / (a3 + a2) … + |(a(n) – a(n-1))| / (a(n) + a(n-1))} where n = number of years, and a1, a2, …, a(n-1), an = yield of corresponding years.

Cumulative yield varied greatly among cultivars and advanced selections (Table 2). A number of clones exceeded 30 kg/tree from 2004-2006 (1-23, 9-58, 'Sunflower', 'Wilson', 'Shenandoah', 'Wabash', 'PA-Golden', 10-35, and 1-68); however, some clones yielded less than 20 kg per tree over the same period ('Middletown', 'Wells', 'Mitchell', and 3-21). CYE also varied greatly (0.38 to 0.91 kg/TCA cm^2); no clones had a CYE over 1.0 and a number of clones had a CYE between 0.60 and 0.91 (e.g., 10-35, 'PA-Golden', 'Shenandoah', 'Sunflower', and 1-68). Only 'Mitchell' averaged fewer than two fruit per cluster, and two clones, 11-13 and 'Wilson', averaged more than three fruit per cluster.

'PA-Golden' and 2-10 had the earliest peak ripening dates (August 29 and August 30, respectively) and the fewest GDDs required for ripening (2499 and 2512, respectively). There was a trend for 'Middletown' (September 13 and 2823 GDD) and 9-47 (September 13 and 2842 GDD) to display the latest peak ripening dates and required the most GDDs to ripen. 'Wells' and 'Rappahannock' tended to have the most concentrated harvest period at 18 days and 'PA-Golden', 10-35, 'Shenandoah', and 11-13 the longest (25 and 30 days).

Yields varied year to year with most cultivars and advanced selections, likely as a result of a frost event in 2003 that destroyed the entire pawpaw crop (Table 3). Biennial BBI values over 0.6 indicate that a selection has a strong tendency towards biennial bearing (14). The BBI varied from 0.22 to 0.63 for the clones examined with 11-13, NC-1, and 7-90 having values greater than 0.60.

Correlations between TCA, number of fruit per tree and cumulative yield were examined. There was no relationship between TCA and the number of fruit per tree, but TCA was linearly related to cumulative yield ($r = 0.60$, $P<0.001$).

Princeton, KY trial. In the Princeton planting, 59% of trees survived in 2004 (Table 1). Most of the trees that died were lost during the first summer after planting. 'Susquehanna' (13%), 'Taylor' (38%), 5-5 (38%), and 9-58 (38%) had the lowest survival rates. This was likely due to the lack of irrigation at the Princeton planting. Vigor and yield of the trees at Princeton were evaluated at 7, 8, and 9 years after planting (in 2002, 2003, and 2004). TCA, number of fruit per tree, average fruit weight, cumulative yield, CYE , and number of fruit per cluster all varied significantly ($P < 0.001$) among cultivars and advanced selections over the three year period (Table 4). Since only one 'Susquehanna' tree survived, this selection was excluded from statistical analysis. Based on TCA taken in 2004, most clones displayed excellent vigor, ranging from 24 to 54.6 cm^2 in 2004, especially 'PA-Golden', 'Wilson', and 9-58, although some clones lacked vigor (e.g., 'Overleese' and 5-5). 'PA-Golden' and 'Wilson' had more than 80 fruit per tree and 'Potomac' and 5-5 had 18 fruit per tree or less (Table 4). Fruit weight also varied greatly, with some clones averaging under 100 g per fruit ('Middletown', 'Wells', 'Wilson', 9-47, and 'Rappahannock') and others over 170 g per fruit (1-68, 5-5, 'Sunflower', 'Wabash', and 'Potomac').

Cumulative yield varied greatly among cultivars and advanced selections, with only 'Sunflower' exceeding 30 kg/tree from 2002 to 2004 (Table 4). A number of clones yielded less than 20 kg per tree over the same period (5-5, 'Overleese', 'Wells', 'Middletown', 2-54, 9-47, 'Mitchell', 'NC-1', 'Potomac', and 3-21). CYE varied greatly among the cultivars and advanced selections (0.37 to 1.00 kg/TCA cm^2) with 'Sunflower' having the highest cumulative yield efficiency of 1.0 kg/TCA cm^2. Only three clones had fewer than two fruit per cluster, 5-5, 'Mitchell', and 'PA-Golden', and no clones averaged more than three fruit per cluster. The BBI was not significantly different among clones, and varied between 0.18 and 0.58, suggesting that there was little tendency towards biennial bearing (Table 5).

Correlations between TCA, number of fruit per tree, and cumulative yield were also examined for the Princeton trial. There were significant linear relationships between TCA and the number of fruit per tree ($r = 0.55$; $P<0.001$), and between TCA and cumulative yield ($r = 0.60$; $P<0.05$).

Table 4. Tree vigor, yield, fruit ripening and harvest characteristics for 28 cultivars and PawPaw Foundation advanced selections in the Pawpaw Regional in 2002, 2003, and 2004 in Princeton, KY.

Clone	Trunk cross sectional area (2004)	Number of fruit per tree	Fruit weight (g)	Cumulative yield (kg)	Cumulative yield efficiency	Number of fruit per cluster
Middletown	33.3 def	64 abcde	66 m	12.6 defg	0.37 d	2.4 abcd
Mitchell	36.7 bcdef	36 defgh	112 hi	15.5 cdefg	0.45 cd	1.8 ef
NC-1	36.0 cdef	27 gh	155 cd	15.6 cdefg	0.44 cd	2.1 cdef
Overleese	24.7 f	26 gh	143 def	11.2 fg	0.51 cd	2.6 ab
PA-Golden	51.1 abc	81 ab	111 hi	29.7 ab	0.62 bcd	1.9 def
Potomac	39.2 abcdef	18 h	252 a	16.1 cdefg	0.70 bc	2.1 cdef
Rappahannock	33.1 def	55 bcdef	94 jk	20.2 bcdef	0.64 bcd	2.0 def
Shenandoah	35.0 def	43 cdefgh	157 cd	23.2 abcd	0.82 ab	2.2 bcde
Sunflower	29.4 ef	52 cdefg	175 b	30.0 a	1.00 a	2.0 def
Taylor	38.4 abcdef	69 abc	105 ij	22.8 abcde	0.61 bcd	2.5 abc
Taytwo	38.4 abcdef	69 abc	107 ij	24.7 abc	0.65 bcd	2.5 abc
Wabash	35.3 cdef	37 defgh	181 b	23.0 abcd	0.69 bc	2.0 def
Wells	35.0 def	51 cdefg	79 lm	12.2 efg	0.50 cd	2.2 bcde
Wilson	54.6 a	84 a	87 kl	24.8 abc	0.47 cd	2.5 ab
1-23	38.0 bcdef	65 abcd	114 hi	25.0 abc	0.64 bcd	2.5 abc
1-68	31.0 def	32 fgh	172 b	20.0 bcdefg	0.71 bc	2.3 bcde
2-10	40.5 abcdef	43 cdefgh	146 de	22.8 abcd	0.56 bcd	2.0 def
2-54	38.3 bcdef	41 cdefgh	112 hi	15.0 cdefg	0.41 cd	2.0 def
3-11	45.8 abcd	42 cdefgh	138 efg	21.7 abcde	0.49 cd	2.3 abcd
3-21	41.5 abcdef	35 efgh	128 fgh	16.8 cdefg	0.47 cd	2.2 bcdef
5-5	23.7 f	15 h	172 bc	9.4 g	0.39 cd	1.7 f
7-90	46.8 abcd	44 cdefgh	133 efg	20.2 bcdefg	0.46 cd	2.1 cdef
8-20	36.2 bcdef	40 cdefgh	156 cd	21.6 abcde	0.59 bcd	2.2 bcde
9-47	34.5 def	50 cdefg	94 jk	15.3 cdefg	0.46 cd	2.1 cdef
9-58	54.3 ab	57 abcdef	145 def	29.8 ab	0.55 bcd	2.4 abcd
10-35	41.6 abcde	57 abcde	140 efg	28.3 ab	0.69 bc	2.7 a
11-13	37.5 bcdef	52 bcdefg	125 gh	23.2 abcd	0.61 bcd	2.8 a
significance	*	***	***	***	**	***
LSD	20.0	34.3	19.7	12.4	0.36	0.55
mean	38.1	48	132	20.6	0.59	2.2
block effect	**	ns	***	ns	**	ns

Table 5. Yield and biennial bearing index of pawpaw (*Asimina triloba*) selections from 2002-2004 for the Princeton, Kentucky pawpaw regional variety trial.

Clone	Yield (kg) / tree 2002	2003	2004	Biennial bearing index [z] 2002-2004
Middletown	4.1	5.2 bcd	3.3 h	0.28
Mitchell	1.2	2.9 d	8.4 cdefgh	0.47
NC-1	1.6	4.1 cd	7.2 defgh	0.40
Overleese	2.1	3.4 d	4.6 efgh	0.34
PA-Golden	6.8	8.6 ab	12.1 abcd	0.18
Potomac	2.5	2.9 d	9.7 abcdef	0.53
Rappahannock	1.5	4.8 bcd	10.0 abcde	0.52
Shenandoah	4.2	7.5 abc	8.8 bcdefg	0.50
Sunflower	6.5	5.9 bcd	15.1 a	0.35
Taylor	4.0	5.0 bcd	12.0 abcd	0.23
Taytwo	3.6	10.1 a	6.6 defgh	0.20
Wabash	3.9	5.5 bcd	4.5 fgh	0.42
Wells	4.5	7.2 abc	10.0 abcde	0.46
1-23	4.3	6.8 abcd	10.8 abcd	0.45
1-68	2.8	4.0 cd	7.9 cdefgh	0.23
2-10	3.1	5.6 bcd	11.5 abcd	0.48
2-54	2.8	2.9 d	7.7 cdefgh	0.42
3-11	2.5	2.8 d	12.1 abc	0.28
3-21	2.4	3.8 cd	9.7 abcdef	0.42
5-5	1.4	3.8 cd	3.4 h	0.33
7-90	3.2	4.4 bcd	10.0 abcde	0.41
8-20	4.0	2.4 d	12.7 abc	0.58
9-47	3.5	6.3 bcd	4.4 gh	0.34
9-58	3.6	5.6 bcd	15.8 a	0.34
10-35	3.8	6.0 bcd	14.2 ab	0.31
11-13	3.1	5.8 bcd	10.9 abcd	0.33
P-value	NS	* ***	NS	
LSD	7.2	8.5	6.7	0.33
mean	3.5	5.3	9.3	0.38
block	**	NS	NS	NS

[z] The Biennial bearing index (BBI) was calculated on the basis of the Pearce and Debusek-Urbank formula (14):
BBI = 1 / (n-1) X $\{|(a_2 - a_1)| / (a_2 + a_1) + |(a_3 - a_2)| / (a_3 + a_2) \ldots + |(a_{(n)} - a_{(n-1)})| / (a_{(n)} + a_{(n-1)})\}$
where n = number of years, and a1, a2, …, a(n-1), an = yield of corresponding years.

When examining cultivar and advanced selection relationships, significant correlations were noted between TCA (r = 0.49; $P<0.01$), number of fruit per tree (r = 0.79; $P<0.001$), and cumulative yield (r = 0.66; $P<0.001$) for cultivars and advanced selections in both plantings.

Discussion

Some differences were observed between the two Kentucky pawpaw trials in terms of vigor and yield of selections, but generally clones performed similarly in comparison to each other at the two locations. TCA, number of fruit per tree, and cumulative yield for cul-

tivars and advanced selections were correlated between the two plantings. Tree survival was likely greater at the Frankfort planting than at the Princeton planting due to trees being irrigated at the Frankfort planting but not at Princeton. Additionally, trees were fall planted at the Princeton site and spring planted at the Frankfort site; pawpaws often have a lower establishment rate with fall planting. During the 7th, 8 th, and 9 th years after planting, trees in the Frankfort trial displayed greater vigor than those in the Princeton trial. The greater vigor at Frankfort was likely due to supplemental irrigation there. More vigorous clones had larger cumulative yield per tree, but not a greater number of fruit per tree. Most clones had average fruit weights over 100 g which would be desirable for growers and consumers. Most cultivars and advanced selections averaged about two fruit per cluster, which is also desirable. Single fruit clusters are most desirable, since harvesting the fruit by cutting the peduncle would not leave the open scar that accompanies pulling fruit from a cluster. Cumulative yield efficiency for the pawpaw clones examined was lower than reported for many apple cultivars (2), with no pawpaw clones having cumulative yield efficiency greater than 1.0. 'PA-Golden' and 2-10 required around 2500 GDDs for fruit to ripen and would be desirable for production in northern climates. No pawpaw clones displayed concentrated ripening periods. Biennial bearing was observed with some clones in the Frankfort planting, likely the result of a devastating frost event in 2003, because biennial bearing was not observed in any of these same selections at Princeton.

Pawpaw yields are lower than would be expected for most other tree fruits (17). Bartholomew (1) reported obtaining 4 kg of fruit and Ourecky and Slate (13) obtained 11.5 and 23 kg/year from superior pawpaw trees. Selections in this study did not exceed yields for superior pawpaw trees previously reported (13). Although PPF advanced selections failed to show greater yields than previously available cultivars in this study, some PPF selections may have higher quality fruit. Duffrin and Pomper (3) developed a descriptive language for frozen pawpaw fruit puree where panelists generated 13 visual, 17 flavor, and 12 texture puree descriptors. Using these descriptors with fruit collected from non-cultivated native sites in southeast Ohio and two PPF advanced selections, collected from the Frankfort trial (1-23 and 10-35), panelists identified positive characteristics of stronger melon and fresh flavors compared to puree from native Ohio fruit. These advanced selections both performed well in terms of fruit size and yield in the Princeton and Frankfort trials. Fruit quality of all PRVT cultivars and advanced selections will be examined in future studies.

Cherimoya (*Annona cherimola*), sweetsop or sugar apple (*A. squamosa*), soursop (*A. muricata*), and atemoya (*A. squamosa* × *A. cherimola*), are tropical relatives of the pawpaw and also have low yields due to low rates of natural pollination (5, 15, 17). In commercial plantings, these tropical pawpaw relatives are hand-pollinated to increase yields (15, 17). Low rates (<5%) of fruit set have also been noted in wild pawpaw patches (9, 23). Native pawpaw patches common in the forest understory are often root suckers of a single clone that will not self-pollinate. In addition, sunlight levels are very low in the shaded understory. Further, pollinators may be limited in this setting (23). At the KSU site, pawpaw genotypes are in close proximity to goat herds at the same farm about 150 m from the pawpaw orchards. Flies are abundant, therefore, pollinator limitation and opportunities for cross-pollination are not likely limiting in the KSU orchards. It has been suggested by some hobbyists that 'Sunflower' may be self-fruitful, but this has not been experimentally documented. 'Sunflower' did not produce the greatest number of fruit per tree in this study, suggesting that if it is self-fruitful, pollinator limitation was not a factor. Pollinizer relationships between pawpaw cultivars and advanced selections have not been examined and could be valuable for growers who may not plant a diverse group of pawpaw cultivars.

The trees in the Frankfort trial had some disease and pest problems. Pawpaw leaves can exhibit leaf spot, principally a complex of *Mycocentrospora asiminae* Ellis & Kellerm., *Rhopaloconidium asiminae* Ellis & Morg., and *Phyllosticta asiminae* Ellis & Kellerm (4, 17). Some trees in the Frankfort planting exhibited *M. asiminae* growth on the leaves and fruit. The advanced selection 7-90 exhibited very little leaf and fruit spot and appears to be resistant to this fungal complex. The pawpaw peduncle borer (*Talponia plummeriana* Busck) is a moth larva that burrows into the fleshy tissues of the flower causing the flower to wither and drop (17). Pawpaw peduncle borer damage was observed in the Frankfort orchards in 2005 and 2006. Japanese beetles (*Popillia japonica* Newman) damaged young leaves on pawpaw trees in the planting each year, but damage was very limited. The larvae of the leafroller (*Choristoneura parallela* Robinson) (12) also damaged pawpaw leaves in the orchard. The zebra swallowtail butterfly (*Eurytides marcellus*), whose larvae feed exclusively on young pawpaw foliage, will damage leaves, but this damage has been negligible at the two sites. Deer will not generally eat the leaves or twigs, but they will eat fruit that has dropped on the ground and male deer will sometimes rub their antlers on younger trees causing significant damage to or killing the tree.

Conclusion

Based on fruit size, yield, and tree availability, the cultivars 'Potomac', 'Susquehanna', 'Wabash', 'Overleese', 'Shenandoah', 'NC-1', and 'Sunflower' can be recommended for production in Kentucky. Some additional PPF advanced selections that show promise are 10-35, 9-58, 2-10, 8-20, 5-5, and 1-68. Orchard performance will continue to be examined at each site in terms of pests, yield, year-to-year consistency, tree decline, and fruit quality characteristics in the coming years at the PRVT plantings. Pawpaw trees generally reach full production by their 7th year, therefore trees at both sites are in full production.

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Literature Cited

1. Bartholomew, E.A.1962. Possibilities of the pawpaw. Northern Nut Growers Assn. Annu. Rpt. 53:71-74.
2. Crassweller, R., R. McNew, D. Greene, S. Miller, J. Cline, A. Azarenko, B. Barritt, L. Berkett, S. Brown, W. Cowgill, E. Fallahi, B. Fallahi, E. Garcia, C. Hampson, T. Lindstrom, I. Merwin, J.D. Obermiller, M. Stasiak and G. Greene. 2007. Performance of apple cultivars in the 1999 NE-183 regional project planting. I. Growth and yield characteristics. J. Amer. Pomol. Soc. 61:84-96.
3. Duffrin M.W. and K.W. Pomper. 2006. Development of flavor descriptors for pawpaw fruit puree: a step toward the establishment of a native tree fruit industry. Family and Consumer Sciences Research Journal. 35:118-130.
4. Farr, D.F., G.F. Bills, G.P. Chamuris and A.Y. Rossmoan. 1989. Fungi on plants and plant products in the United States. APS Press, St. Paul, Minn.
5. George, A.P., R.J. Nissen and J.A. Campbell. 1992. Pollination and selection in *Annona* species (cherimoya, atemoya, and sugar apple). Acta Hort. 321:178-185.
6. Huang, H., D.R. Layne and R.N. Peterson. 1997. Using isozyme polymorphisms for identifying and assessing genetic variation in cultivated pawpaw [*Asimina triloba* (L.) Dunal]. J. Amer. Soc. Hort. Sci. 122:504–511.
7. Jones, S.C, R.N. Peterson, T. Turner, K.W. Pomper and D.R. Layne. 1998. Pawpaw planting guide: Cultivars and nursery sources. Kentucky State University Pawpaw Ext. Bull. 002. 8 pp.
8. Kral, R. 1960. A revision of *Asimina* and *Deeringothamnus* (Annonaceae). Brittonia 12:233–278.
9. Lagrange, R.L. and E.J. Tramer. 1985. Geographic variation in size and reproductive success in the paw paw (*Asimina triloba*). Ohio J. Sci. 85:40-45.
10. Layne, D.R. 1996. The pawpaw [*Asimina triloba* (L.) Dunal]: a new fruit crop for Kentucky and the United States. HortScience 31:777–784.

11. McGrath, M.J. and C. Karahadian. 1994. Evaluation of physical, chemical, and sensory properties of pawpaw fruit (*Asimina triloba*) as indicators of ripeness. J. Agr. Food Chem. 42:968-974.
12. Norman, E.M., K. Rice and S. Cochran. 1992. Reproductive biology of *Asimina parviflora* (Annonaceae). Bull. Torrey Bot. Club 119:1-5.
13. Ourecky, D.K. and G.L. Slate. 1975. Evaluation system for pawpaw fruit. Northern Nut Growers Assn. Annu. Rpt. 65:57-58.
14. Pearce, S.C. and S. Debusek-Urbanc. 1967. The measurement of irregularity in growth and cropping. J. Hort. Sci. 42:295-305.
15. Pena, J.E., A. Castineiras, R. Bartelt and R. Duncan. 1999. Effect of pheromone for sap beetles (Coleoptera: Nitidulidae) on *Annona* spp. fruit set. Fla. Entomol. 82:475-480.
16. Peterson, R.N. 1986. Research on the pawpaw (*Asimina triloba*) at the University of Maryland. Northern Nut Growers Assn. Annu. Rpt. 77:73-78.
17. Peterson, R.N. 1991. Pawpaw (*Asimina*). Acta Hort. 290:567-600.
18. Peterson, R.N. 2003. Pawpaw variety development: a history and future prospects. HortTechnology 13: 449-454.
19. Pomper, K.W., D.R. Layne and R.N. Peterson. 1999. The pawpaw regional variety trial. Pp. 353-357. In: J. Janick (ed). Perspectives on new crops and new uses. ASHS Press, Alexandria, Va.
20. Pomper, K.W., D.R. Layne, R.N. Peterson and D. Wolfe. 2003. The pawpaw regional variety trial: background and early data. HortTechnology 13: 412-417.
21. Pomper, K.W. and D.R. Layne. 2005. The North American pawpaw: botany and horticulture. Hort. Rev.31:351-384.
22. Shiota, H. 1991. Volatile components of pawpaw fruit (*Asimina triloba* Dunal). J. Agr. Food Chem. 39:1631-1635.
23. Willson, M.F. and D.W. Schemske. 1980. Pollinator limitation, fruit production, and floral display in pawpaw (*Asimina triloba*). Bull. Torrey Bot. Club. 107:401–408.
24. Zimmerman, G.A. 1941. Hybrids of the American pawpaw. J. Heredity 32:83-91.