7-5-2019

Growth, Flowering, and Powdery Mildew-related Responses of Witchhazels in Tennessee

Lisa W. Alexander
USDA, Agricultural Research Service

Anthony L. Witcher
USDA, Agricultural Research Service

Fulya Baysal-Gurel
Tennessee State University

Growth, Flowering, and Powdery Mildew-related Responses of Witchhazels in Tennessee

Lisa W. Alexander[1], Anthony L. Witcher[2], and Fulya Baysal-Gurel[2,3]

ADDITIONAL INDEX WORDS. ***Hamamelis*, ornamental breeding, cultivar trial, disease evaluation, germplasm evaluation**

SUMMARY. **Witchhazel (*Hamamelis* sp.) cultivars are now available in an array of forms and flower colors, including several native, pollinator-friendly cultivars. However, little is known about response of witchhazel cultivars to powdery mildew (*Podosphaera biuncinata*) or the growth and flowering characteristics of witchhazel cultivars in a nursery field production setting. To provide growth, flowering, and disease incidence data to nursery growers, a cultivar trial including 23 cultivars of witchhazel representing five species was planted Apr. 2016 in McMinnville, TN. Plant growth, flowering density, length of bloom, and foliar disease incidence were evaluated over three growing seasons between May 2016 and Oct. 2018. 'Zuccariniana' japanese witchhazel (*H. japonica*) and 'Sunglow' common witchhazel (*H. virginiana*) showed the greatest height increase during the trial, and 'Sunglow' also added the most width during the trial. Cultivars with negative height or width growth included Sweet Sunshine chinese witchhazel (*H. mollis*) and hybrid witchhazels (*H. ×intermedia*) Aphrodite, Twilight, and Barmstedt Gold. Ten of the 23 cultivars experienced winter injury in the form of stem necrosis. Root crown sprouts were observed for all cultivars at least once during the trial. 'Wisely Supreme' chinese witchhazel had the longest bloom period, followed by 'Westerstede' and 'Twilight' hybrid witchhazels, whereas 'Quasimodo' vernal witchhazel (*H. vernalis*) had the greatest density of flowers. The hybrid witchhazel cultivars Aphrodite, Nina, and Arnold Promise and the common witchhazel cultivars Green Thumb and Sunglow were resistant to powdery mildew under trial conditions in all 3 years. 'Twilight' and 'Barmstedt Gold' hybrid witchhazel, 'Little Suzie' common witchhazel, 'Wisley Supreme' chinese witchhazel, and 'Shibamichi Red' japanese witchhazel were moderately resistant to powdery mildew.**

Witchhazels are represented by about six species distributed across temperate regions of North America and Asia (Leonard, 2006; Wen and Shi, 1999). Although as many as 15 species have been reported (Wiersema, 2017), such as southern witchhazel (*Hamamelis macrophylla*) and mexican witchhazel (*H. mexicana*), morphological and phylogenetic analyses support a monophyletic clade of witchhazels with six species (Li et al., 2000). Witchhazels are large shrubs or small trees bearing characteristically narrow, strap-like flower petals and capsulate fruit that co-occurs with flower buds and flowers. North American species include vernal (or ozark) witchhazel, which is found in the Ozark Mountains of Oklahoma, Missouri, and Arkansas, and in Texas; common witchhazel, which is widely distributed in rich but dry woodlands from southern Canada into the eastern and central United States; and bigleaf witchhazel (*H. ovalis*), a new species represented by a few populations in Mississippi and Alabama (Leonard, 2006). Vernal witchhazel is smaller than common witchhazel and is grown as an ornamental in the U.S. Department of Agriculture (USDA) Hardiness Zones 3 to 8 (U.S. Department of Agriculture, 2012). It flowers December to March and has fragrant, orange–red flowers. Common witchhazel is a medium to large shrub producing lemon–yellow flowers from October to December. Bigleaf witchhazel is a large-leafed, creeping shrub producing orange–red flowers.

Asian witchhazel species include chinese witchhazel and japanese witchhazel. Chinese witchhazel is a small, rounded shrub native to central China, whereas japanese witchhazel is a low, spreading, or vase-shaped shrub distributed throughout Japan. A superior open-pollinated seedling from a chinese witchhazel observed by the Arnold Arboretum (Boston, MA) proved to be a hybrid between chinese and japanese witchhazel, and in 1963 the first hybrid witchhazel, 'Arnold Promise', was registered (Gapinski, 2014). This hybrid combined the dense, yellow blossoms of chinese witchhazel with the cold-hardiness, larger petals, and less winter leaf retention of japanese witchhazel. Due to the variety of form and color, and a longer flowering period, most named witchhazel cultivars are hybrid witchhazel. Of ≈186 named cultivars, 106 are hybrid witchhazel. 'Arnold Promise' hybrid witchhazel remains a garden standard (Dirr, 2009); other notable hybrid witchhazel cultivars include Barmstedt Gold, Jelena, Primavera, and Westerstede (Gapinski, 2014).

Production and adoption of witchhazel often is hampered by production difficulties and a displeasing, irregular, open form of many cultivars in the landscape. Seedling rootstocks are used for bud-grafting of desired cultivars, and rootstock selection is limited by the tendency of witchhazel to produce sprouts from the root collar. Other limitations of witchhazel, especially common witchhazel, include leggy, spreading forms, previous season's foliage retention during flowering, and susceptibility to foliar diseases such as powdery mildew and phyllosticta leaf spot (*Phyllosticta hamamelidis*) in nursery production in the eastern and southeastern United States. Considerable improvement is warranted for quality

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
0.5933	lb/yard^3	kg·m^{-3}	1.6856
0.0254	mil(s)	mm	39.3701
28.3495	oz	g	0.0353
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Table 1. Witchhazel species and cultivars represented in a McMinnville, TN, field trial from 2016 to 2018. All plants were purchased from commercial sources and bud grafted onto rootstock of vernal witchhazel.

Species	Cultivar
Japanese witchhazel	Shibamichi Red
Japanese witchhazel	Zuccariniana
Chinese witchhazel	Sweet Sunshine
Chinese witchhazel	Wisley Supreme
Vernal witchhazel	Amethyst
Vernal witchhazel	Quasimodo
Vernal witchhazel	Red Imp
Common witchhazel	Green Thumb
Common witchhazel	Little Suzie
Common witchhazel	Sunglow
Hybrid witchhazel	Aphrodite
Hybrid witchhazel	Arnold Promise
Hybrid witchhazel	Barmstedt Gold
Hybrid witchhazel	Diane
Hybrid witchhazel	Early Bird
Hybrid witchhazel	Feuerzauber
Hybrid witchhazel	Jelena
Hybrid witchhazel	John
Hybrid witchhazel	Nina
Hybrid witchhazel	Primavera
Hybrid witchhazel	Sunburst
Hybrid witchhazel	Twilight
Hybrid witchhazel	Westerstede

Table 2. Weather variables recorded using a weather station (WatchDog 2700; Spectrum Technologies, Aurora, IL) in a McMinnville, TN, field trial from 2016 to 2018.

Yr	Month	Avg maximum temp (°C)[z]	Avg minimum temp (°C)	Total rainfall (cm)[z]
2016	May	22.9	11.6	3.9
	June	30.3	18.8	19.8
	July	25.1	16.4	13.2
	Aug.	31.3	21.4	11.6
	Sept.	29.7	17.3	4.5
	Oct.	25.3	11.5 (3.4)[y]	1.9
	Nov.	17.0	2.7 (–5.0)[y]	8.7
	Dec.	5.7	–1.8 (–7.2)[y]	21.2
2017	Jan.	12.1	3.4 (–15.0)[y]	12.9
	Feb.	14.4	2.7 (–7.2)[y]	6.6
	Mar.	17.5	4.2 (–6.1)[y]	16.9
	Apr.	24.2	11.6 (2.8)[y]	23.4
	May	25.6	14.8	15.0
	June	28.3	17.7	8.7
	July	30.5	20.7	12.6
	Aug.	28.3	19.0	21.5
	Sept.	25.5	15.2	10.2
	Oct.	22.5	14.9 (–1.7)[y]	13.7
	Nov.	14.8	4.9 (–2.8)[y]	9.1
	Dec.	9.3	–0.9 (–10.0)[y]	12.6
2018	Jan.	4.7	–4.9 (–16.1)[y]	5.4
	Feb.	14.1	4.2 (–7.8)[y]	23.5
	Mar.	13.7	3.2 (–4.4)[y]	16.2
	Apr.	14.1	3.9 (–1.7)[y]	12.8
	May	26.8	16.3	7.3
	June	29.3	19.7	19.7
	July	30.3	20.7	9.4
	Aug.	24.5	16.5	13.3
	Sept.	26.1	15.9	27.9
	Oct.	20.5	10.2	4.9

[z]°C = (°*F* – 32) ÷ 1.8, 1 cm = 0.3937 inch.
[y]The absolute minimum temperature during a given calendar month.

and abundance of flower and the absence of foliage during the flowering period (Dirr, 2009). The objective of this study was to compare growth, flowering, and powdery mildew disease related responses of 23 witchhazel cultivars representing five species for nursery production and landscape value in Tennessee.

Materials and methods

Twenty-three cultivars of witchhazel representing five species were chosen to evaluate and demonstrate the diversity of growth and flowering characteristics of cultivars available in the trade (Table 1). Source plants were purchased from commercial nurseries between 2012 and 2014 and bud-grafted onto vernal witchhazel seedling rootstock. Grafted plants were maintained in 7-gal pots in an unheated coldframe covered in 60% shade at the Otis L. Floyd Nursery Research Center in McMinnville, TN. Growing media consisted of pine bark amended with 6.6 kg·m^{-3} 19N–2.1P–7.4K controlled-release fertilizer (Osmocote Pro; ICL Specialty Fertilizers, Dublin, OH), 0.6 kg·m^{-3} micronutrient fertilizer (Micromax; ICL Specialty Fertilizers), 0.6 kg·m^{-3} iron sulfate, and 0.2 kg·m^{-3} Epsom salts. Plants received additional 70 g of 19N–2.1P–7.4K controlled-release fertilizer in April and July every year until transplanting into the field. Containerized plants were irrigated for 3 min twice per day in June and for 4 min twice per day in July using micro bubbler emitters installed on short stakes.

The cultivar trial was planted 27 Apr. 2016 in a randomized complete block design with three blocks (rows) and one replicate per cultivar per block. Plants were spaced 12 ft within the row and 12 ft between rows. A vegetation free strip (3 ft wide) was maintained within each row with herbicide applications as needed and

Received for publication 15 Mar. 2019. Accepted for publication 21 May 2019.

Published online 5 July 2019.

We acknowledge Adam Blalock, Carrie Witcher, Joseph Davis, Terry Kirby, Terri Simmons, and Benjamin Moore for field support and assistance with plant propagation, data collection, and curation. Two anonymous reviewers provided contributions that greatly improved the manuscript. Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

Mention of trade names of commercial products in the publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture or Tennessee State University.

[1]U.S. Department of Agriculture, Agricultural Research Service, U.S. National Arboretum, Floral and Nursery Plants Research Unit, Otis L. Floyd Nursery Research Center, 472 Cadillac Lane, McMinnville, TN 37110

[2]Tennessee State University, Otis L. Floyd Nursery Research Center, Department of Agricultural and Environmental Sciences, McMinnville, TN 37110

[3]Corresponding author. E-mail: fbaysalg@tnstate.edu.

https://doi.org/10.21273/HORTTECH04349-19

Table 3. Mean plant growth of witchhazel species in a McMinnville, TN, field trial from 2016 to 2018.

Species	Observations (no.)	16 May 2016 Ht (cm)[z]	16 May 2016 Avg width (cm)[y]	22 May 2017 Ht (cm)	22 May 2017 Avg width (cm)	25 Oct. 2017 Ht (cm)	25 Oct. 2017 Avg width (cm)	2 Oct. 2018 Ht (cm)	2 Oct. 2018 Avg width (cm)
		mean + SD							
Hybrid witch hazel	38	139.3 ± 25.5 a[x]	141.5 ± 30.4 a	132.8 ± 24.7 a	138.8 ± 42.6 a	141.6 ± 23.2 a	132.1 ± 44.6 a	164.3 ± 36.8 a	167.9 ± 42.7 a
Japanese witchhazel	6	125.2 ± 28.1 ab	125.3 ± 26.9 a	130.0 ± 11.8 a	118.0 ± 30.2 a	143.2 ± 7.4 a	109.7 ± 32.8 a	171.2 ± 28.9 a	135.3 ± 57.7 a
Chinese witchhazel	5	133.6 ± 21.8 ab	125.7 ± 18.8 a	132.0 ± 20.9 a	134.8 ± 19.6 a	135.6 ± 26.1 a	122.5 ± 13.4 a	155.8 ± 17.6 a	147.5 ± 11.2 a
Vernal witchhazel	9	121.1 ± 24.2 ab	91.8 ± 20.6 b	130.3 ± 23.2 a	110.4 ± 26.0 a	145.3 ± 26.1 a	100.9 ± 15.4 a	158.1 ± 39.1 a	139.8 ± 30.4 a
Common witchhazel	8	104.4 ± 23.8 b	92.3 ± 39.6 b	120.5 ± 16.4 a	111.7 ± 47.6 a	140.3 ± 25.4 a	103.9 ± 37.2 a	153.5 ± 22.1 a	136.5 ± 46.7 a

[z]1 cm = 0.3937 inch.
[y]Average width = (widest width = perpendicular width) ÷ 2.
[x]Treatment means within columns followed by different letters were significantly different ($P \leq 0.05$). One-way analysis of variance was used to partition variance in height and average width to sources attributable to species and error. Means for each cultivar were compared using Fisher's least significant difference test with an $\alpha = 0.05$.

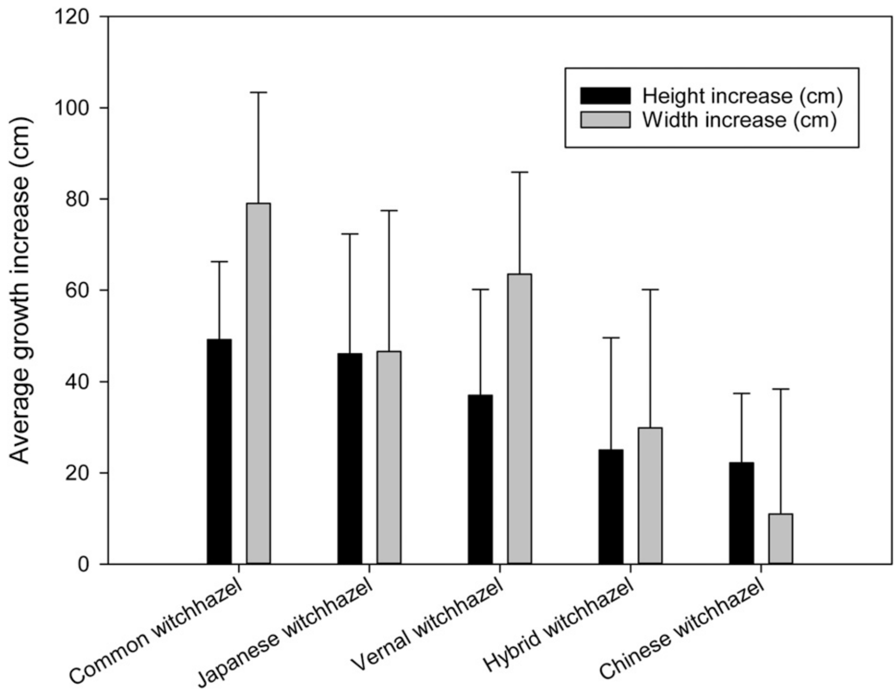

Fig. 1. Growth increase of witchhazel species ordered by decreasing height gain in a McMinnville, TN, field trial from 2016 to 2018. Error bars represent SD; 1 cm = 0.3937 inch.

rows were separated by an 8-ft grass strip. Plants were top-dressed with 72 g of 19N–2.1P–7.4K controlled-release fertilizer in Aug. 2016 and Apr. and Aug. 2017 and 2018. In 2016, plants were irrigated every 2 weeks using drip irrigation (drip tape 5/8 inch diameter, 8 mil thick, 12 inches emitter spacing) during the growing season (May through August) when <1.3 cm rainfall was recorded during the previous 2-week period. Plants did not receive supplemental irrigation in 2017 or 2018.

Plants were measured for growth (height and width) in May 2016, and May and Oct. 2017 and 2018. Shoot height was measured to the tallest node with foliage. Plant width was measured at the widest point and perpendicular to the widest point of each plant. For each measurement date, an average width measurement was calculated as: [(width at widest point + width perpendicular) ÷ 2]. A reduction in height or width between seasons indicates shoot tip dieback. Root crown sprouts present at the base of each plant were counted and removed once in 2017 and once in 2018. Presence or absence of flowers was noted biweekly from 1 Oct. 2016 to 1 May 2017 and from 1 Oct. 2017 to 1 May 2018. One primary, west-facing branch on each plant was marked with flagging tape. Flower number was counted on the flagged branch of each plant biweekly from 1 Oct. 2016 to 1 May 2017. Presence or absence of foliage was recorded 14 Apr. and 21 Nov. 2017 and 18 Apr. 2018.

The severity of powdery mildew was evaluated weekly from 20 Sept. to 4 Oct. 2016; 4 to 22 Sept. 2017; 28 Aug. to 11 Sept. 2018 using a scale of 0% to 100% foliage area affected. The area under the disease progress curve (AUDPC) was calculated according to the formula: $\sum\{[(x_i + x_{i-1})/2](t_i - t_{i-1})\}$ where x_i is the rating at each evaluation time and $(t_i - t_{i-1})$ is the number of days between evaluations.

Maximum and minimum temperatures and rainfall amounts were monitored using a *weather station* (WatchDog 2700; Spectrum Technologies, Aurora, IL) at the Otis L. Floyd Nursery Research Center throughout the trial (Table 2).

Data analysis was performed using SAS software (version 9.4 for Windows; SAS Institute, Cary, NC). The general linear model procedure (PROC GLM) was used to partition variance in height, width, spread, number of root crown sprouts, number of flowers, powdery mildew disease severity, and

Table 4. Mean plant growth of witchhazel cultivars in a McMinnville, TN, field trial from 2016 to 2018.[z]

		16 May 2016		22 May 2017		25 Oct. 2017		2 Oct. 2013	
		Mean ± SD							
Cultivar	Observations (no.)	Ht (cm)[z]	Avg width (cm)[y]	Ht (cm)	Avg width (cm)	Ht (cm)	Avg width (cm)	Ht (cm)	Avg width (cm)
Amethyst	3	152.3 ± 9.3 bc[x]	115.5 ± 5.7 d-g	152.0 ± 16.1 ab	135.3 ± 19.4 b-g	167.7 ± 16.9 ab	113.7 ± 6.5 de	162.7 ± 6.8 a-e	192.5 ± 78.5 ab
Aphrodite	3	133.0 ± 15.9 b-f	172.2 ± 20.6 a	114.7 ± 18.0 de	172.7 ± 26.3 ab	125.0 ± 14.1 dc	164.2 ± 26.8 abc	135.7 ± 8.0 de	113.8 ± 7.6 bc
Arnold Promise	3	126.3 ± 29.2 c-f	117.3 ± 17.3 d-g	118.0 ± 27.7 b-e	116.2 ± 16.3 c-g	126.0 ± 22.6 a-d	110.3 ± 15.8 de	144.0 ± 23.5 b-e	155.8 ± 24.2 bc
Barmstedt Gold	3	164.3 ± 23.2 ab	171.3 ± 2.0 a	150.7 ± 34.4 abc	198.5 ± 5.7 a	157.3 ± 29.7 dc	177.7 ± 6.1 ab	124.3 ± 32.0 e	122.5 ± 6.6 bc
Diane	3	129.3 ± 10.1 c-f	166.3 ± 24.5 a	131.0 ± 12.2 b-e	155.5 ± 17.3 bc	135.0 ± 17.4 bcd	143.5 ± 23.0 bcd	194.7 ± 30.0 ab	175.0 ± 10.9 abc
Early Bird	2	125.5 ± 4.9 c-f	145.3 ± 12.4 a-d	128.0 ± 7.1 b-e	141.8 ± 2.5 b-f	125.0 ± 7.1 dc	124.5 ± 0.7 de	172.0 ± 8.5 a-e	167.5 ± 48.8 abc
Feuerzauber	3	140.7 ± 20.0 bcd	134.5 ± 13.8 b-e	126.3 ± 23.2 b-e	112.2 ± 49.9 c-g	143.0 ± 8.5 bcd	90.3 ± 80.9 de	148.7 ± 40.9 a-e	169.5 ± 79.0 abc
Green Thumb	3	128.3 ± 19.5 c-f	131.5 ± 36.3 b-e	115.3 ± 17.6 de	158.2 ± 40.9 bc	130.0 ± 17.4 bcd	135.8 ± 41.0 dce	153.0 ± 6.6 a-e	182.8 ± 25.7 abc
Jelena	3	115.3 ± 33.2 d-h	136.5 ± 63.4 a-d	118.0 ± 26.2 b-e	143.0 ± 64.5 bcd	128.7 ± 35.5 dc	142.3 ± 49.2 bcd	188.3 ± 33.4 abc	231.8 ± 67.2 a
John	3	143.3 ± 17.1 bcd	96.8 ± 6.2 c-g	146.3 ± 21.2 a-d	95.2 ± 6.9 efg	145.0 ± 17.0 a-d	96.5 ± 18.4 de	199.7 ± 23.5 a	192.8 ± 90.4 ab
Little Suzie	2	92.0 ± 17.0 gh	67.3 ± 0.8 g	116.5 ± 12.0 cde	79.5 ± 39.6 g	137.0 ± 1.4 bcd	84.8 ± 26.5 e	126.0 ± 21.2 e	158.0 ± 65.1 abc
Nina	3	140.3 ± 30.7 bcd	158.5 ± 12.0 ab	140.7 ± 42.9 bcd	162.8 ± 18.1 bc	160.7 ± 29.6 abc	183.3 ± 16.3 a	173.0 ± 36.5 a-e	173.2 ± 36.0 abc
Primavera	3	138.7 ± 11.8 b-e	145.7 ± 7.7 a-d	135.0 ± 15.6 b-e	148.3 ± 18.3 bcd	146.3 ± 9.1 a-d	133.3 ± 14.1 dce	153.3 ± 30.6 a-e	168.8 ± 60.2 abc
Quasimodo	3	104.3 ± 7.0 fgh	85.5 ± 7.2 fg	104.3 ± 5.0 e	87.7 ± 10.8 fg	120.3 ± 25.9 dc	88.7 ± 5.3 e	185.3 ± 49.1 a-d	134.0 ± 35.9 bc
Red Imp	3	106.7 ± 1.5 e-h	74.3 ± 0.5 g	134.7 ± 11.2 b-e	108.2 ± 22.2 d-g	148.0 ± 8.7 a-d	100.3 ± 20.1 de	126.3 ± 31.5 e	139.3 ± 18.8 bc
Shibamichi Red	3	147.3 ± 11.6 bcd	146.0 ± 19.5 a-d	138.3 ± 9.7 b-e	143.7 ± 13.7 b-e	143.3 ± 9.5 bcd	133.7 ± 26.4 dce	151.3 ± 10.7 a-e	164.2 ± 41.7 abc
Sunburst	3	121.7 ± 4.6 c-g	125.5 ± 9.0 b-f	126.7 ± 1.5 b-e	128.3 ± 21.5 c-g	138.3 ± 10.0 bcd	128.7 ± 18.8 dce	175.3 ± 69.0 a-e	186.5 ± 71.8 abc
Sunglow	3	88.7 ± 8.3 h	69.8 ± 0.6 g	128.3 ± 20.4 b-e	86.7 ± 16.1 fg	152.7 ± 39.3 a-d	84.7 ± 18.7 e	172.3 ± 12.7 a-e	168.7 ± 39.4 abc
Sweet Sunshine	2	132.5 ± 24.7 b-f	119.0 ± 10.6 c-g	126.0 ± 22.6 b-e	127.0 ± 8.5 c-g	128.0 ± 41.0 dc	120.8 ± 1.8 de	141.0 ± 1.4 cde	91.0 ± 16.3 c
Twilight	3	188.0 ± 10.1 a	160.2 ± 16.1 abc	178.0 ± 0.0 a	108.8 ± 94.5 b-g	182.0 ± 0.0 a	108.2 ± 93.8 dce	183.3 ± 40.1 a-d	177.7 ± 8.8 abc
Westerstede	3	139.3 ± 28.0 bcd	110.2 ± 14.0 d-g	126.0 ± 22.6 b-e	121.5 ± 17.4 c-g	136.3 ± 29.0 bcd	111.3 ± 23.9 de	146.0 ± 12.5 b-e	191.0 ± 22.5 abc
Wisley Supreme	3	134.3 ± 25.4 b-f	130.2 ± 24.0 b-e	136.0 ± 23.6 b-e	140.0 ± 25.0 b-f	140.7 ± 20.5 bcd	123.7 ± 18.7 de	165.7 ± 16.0 a-e	167.2 ± 36.0 abc
Zuccariniana	3	103.0 ± 19.1 fgh	104.7 ± 12.4 efg	121.7 ± 6.7 b-e	92.3 ± 11.1 efg	143.0 ± 6.9 bcd	85.7 ± 16.4 e	191.0 ± 28.1 abc	179.5 ± 76.6 abc

[z] 1 cm = 0.3937 inch.
[y] Average width = (widest width = perpendicular width) ÷ 2.
[x] Treatment means within columns followed by different letters were significantly different ($P \leq 0.05$). One-way analysis of variance was used to partition variance in height and average width to sources attributable to cultivar and error. Means for each cultivar were compared using Fisher's least significant difference test with an $\alpha = 0.05$.

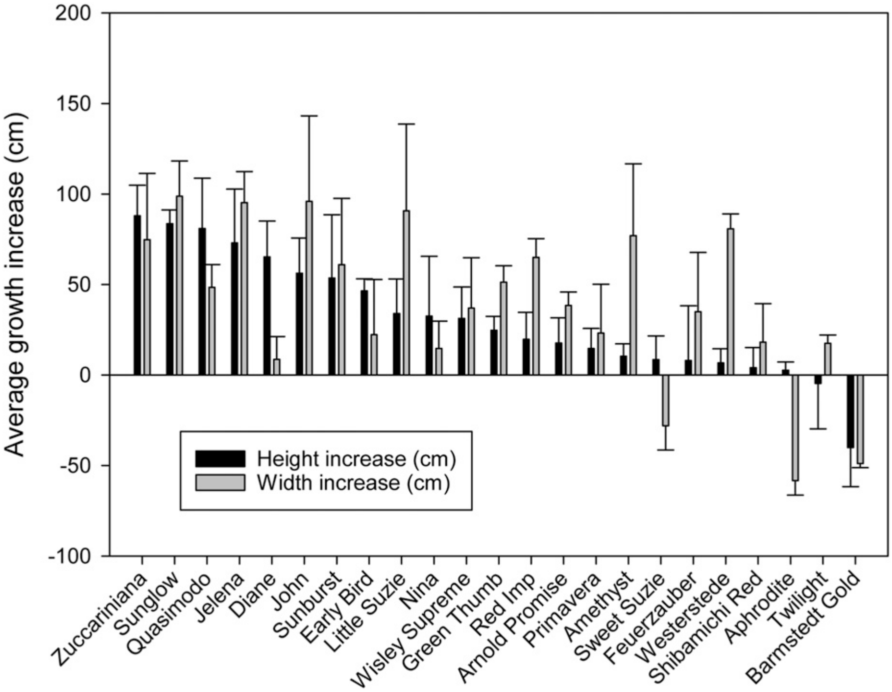

Fig. 2. Growth increase of witchhazel cultivars ordered by decreasing height gain in a McMinnville, TN, field trial from 2016 to 2018. Error bars represent SD; 1 cm = 0.3937 inch.

AUDPC to sources attributable to species or cultivar and error. Constancy of residual variance was checked using the Brown–Forsythe test. All variables satisfied analysis of variance assumption. The error normality assumptions were verified graphically. Means for each cultivar were compared using Fisher's least significant difference test with an $\alpha = 0.05$ significance level.

Results

Initial height for witchhazel species ranged from 139.3 ± 25.5 cm (mean ± SD) for hybrid witchhazel to 104.4 ± 23.8 cm for common witchhazel (Table 3). Similarly, hybrid witchhazel and chinese witchhazel were the widest species, whereas common witchhazel and vernal witchhazel were the narrowest. By the end of the trial, hybrid witchhazel was the widest but there were no significant differences in width among species (Table 3). Common witchhazel showed the largest increase of both height and width growth during the trial, whereas chinese witchhazel had the least height and width increase (Fig. 1).

Initial heights of cultivars varied greatly, from 188.0 ± 10.1 cm for ('Twilight' hybrid witchhazel) to 88.7 ± 8.3 cm ('Sunglow' common witchhazel; Table 4). Ten of the 23 cultivars experienced winter injury in the form of stem necrosis, as reflected in height reduction between May 2016 and 2017. Chinese, japanese, and hybrid witchhazel all had cultivars with winter injury. Cultivars of common and vernal witchhazel were not reduced in height during the same time period (Table 4). By the end of the trial, 'John' and 'Diane' hybrid witchhazels, and 'Zuccariniana' japanese witchhazel were tallest, whereas 'Barmstedt Gold' hybrid witchhazel, 'Red Imp' vernal witchhazel, and 'Little Suzie' common witchhazel were the shortest (Table 4). 'Zuccariniana' japanese witchhazel and 'Sunglow' common witchhazel showed the greatest height increase during the trial. 'Sunglow' also added the most width during the trial (Fig. 2). Cultivars with negative height or width growth included Sweet Sunshine, Aphrodite, Twilight, and Barmstedt Gold (Fig. 2).

Root crown sprouts were observed for all cultivars at least once during the trial (Table 5). Many more sprouts were observed in 2018 than 2017, likely due to the increased establishment of the plants. In 2017, chinese witchhazel cultivars produced significantly more sprouts than any other species. In 2018, common witchhazel had the lowest number of root crown sprouts, with the number of sprouts being 1.5 to 3.2 times less than the other species. (Table 5). Cultivars producing the fewest root crown sprouts were Amethyst vernal witchhazel and Little Suzie common witchhazel, whereas Wisley Supreme chinese witchhazel and Early Bird hybrid witchhazel consistently had the most sprouts (Table 5).

Length of bloom period was shortest for common witchhazel and longest for hybrid witchhazel (Fig. 3). In general, vernal and common witchhazel cultivars had a single bloom period of 6 to 8 weeks in late winter and fall, respectively. Cultivars of chinese witchhazel had a single bloom period of about 16 weeks lasting from January to April. Hybrid witchhazels either had a single short bloom period (e.g., 'John' and 'Primavera'), two short bloom periods (e.g., 'Barmstedt Gold' and 'Nina'), or a single, long bloom period (e.g., 'Twilight' and 'Westerstede'; Fig. 3). Cultivars with two bloom periods often had a more dense floral display in spring compared with fall. The hybrid witchhazels 'Twilight' and 'Westerstede' bloomed continuously from September or October to April or May, with three or four peaks of bloom density. 'Diane' hybrid witchhazel bloomed continuously from Oct. 2016 to May 2017 but only had a single short bloom period from Feb. to Apr. 2018.

Vernal witchhazel cultivars produced the greatest density of flowers during peak bloom. 'Quasimodo' had the greatest density of flowers (with a maximum of 1386 flowers on a single flagged branch observed in Feb. 2017), followed by 'Amethyst' and 'Red Imp' (Fig. 3). 'Little Suzie' common witchhazel and 'Wisley Supreme' hybrid witchhazel also produced a high density of flowers during their respective peak bloom period (Fig. 3).

Powdery mildew appeared naturally and disease pressure was low until late August for all 3 years and then slowly increased due to cool, damp nights followed by warm, dry days. There were significant differences among cultivars in severity of powdery mildew as well as disease progress (AUDPC) in all 3 years (Table 6). 'Green Thumb' and

Table 5. Root crown sprouts of witchhazel species and cultivars in a McMinnville, TN, field trial from 2016 to 2018.

	Observations (no.)	Sprouts (no.) 22 Oct. 2017	Sprouts (no.) 2 Oct. 2018
		mean ± SD	
Species			
Hybrid witchhazel	38	6.3 ± 1.5 b	11.6 ± 15.4 a
Japanese witchhazel	6	3.7 ± 3.7 b	25.2 ± 27.4 a
Chinese witchhazel	5	15.2 ± 4.0 a	19.4 ± 34.7 a
Vernal witchhazel	9	2.7 ± 3.0 b	13.7 ± 22.6 a
Common witchhazel	8	3.6 ± 3.2 b	7.9 ± 9.0 a
Cultivar			
Amethyst	3	0.0 ± 0.0 c	0.7 ± 1.2 b
Aphrodite	3	6.0 ± 6.6 bc	3.7 ± 3.8 b
Arnold Promise	3	3.0 ± 3.0 c	6.7 ± 6.1 b
Barmstedt Gold	3	7.3 ± 4.5 bc	9.7 ± 9.5 ab
Diane	3	0.7 ± 1.2 c	8.0 ± 12.2 ab
Early Bird	2	15.0 ± 21.2 ab	22.5 ± 31.8 ab
Feuerzauber	3	3.5 ± 4.9 c	22.0 ± 22.6 ab
Green Thumb	3	2.0 ± 3.5 c	8.3 ± 7.2 ab
Jelena	3	3.0 ± 5.2 c	8.3 ± 13.6 ab
John	3	19.3 ± 14.4 ab	8.3 ± 3.8 ab
Little Suzie	2	3.5 ± 4.9 c	0.0 ± 0.0 b
Nina	3	0.7 ± 1.2 c	15.0 ± 26.0 ab
Primavera	3	12.3 ± 21.4 ab	8.0 ± 13.9 ab
Quasimodo	3	3.0 ± 5.2 c	21.3 ± 37.0 ab
Red Imp	3	5.0 ± 6.2 be	19.0 ± 17.3 ab
Shibamichi Red	3	3.7 ± 6.4 c	32.7 ± 40.5 a
Sunburst	3	7.0 ± 6.6 bc	23.3 ± 16.5 ab
Sunglow	3	5.3 ± 2.9 bc	12.7 ± 11.7 ab
Sweet Sunshine	2	3.5 ± 4.9 c	5.0 ± 7.1 b
Twilight	3	2.5 ± 3.5 c	1.0 ± 1.7 b
Westerstede	3	1.7 ± 2.9 c	17.7 ± 28.0 ab
Wisley Supreme	3	23.0 ± 18.2 a	29.0 ± 45.1 a
Zuccariniana	3	3.7 ± 6.4 c	17.7 ± 8.3 ab

[z]Treatment means within columns followed by different letters were significantly different ($P \leq 0.05$). One-way analysis of variance was used to partition variance in number of root crown sprouts to sources attributable to species or cultivar and error. Means for each cultivar were compared using Fisher's least significant difference test with an $\alpha = 0.05$.

'Sunglow' common witchhazel and 'Aphrodite', 'Nina', and 'Arnold Promise' hybrid witchhazel were resistant to powdery mildew (showed no powdery mildew symptoms) under trial conditions in all 3 years. A cultivar was considered moderately resistant if it developed the disease, but disease severity was not significantly different from unaffected cultivars. 'Twilight' and 'Barmstedt Gold' hybrid witchhazel, 'Little Suzie' common witchhazel, 'Wisley Supreme' chinese witchhazel, and 'Shibamichi Red' japanese witchhazel were moderately resistant to powdery mildew, with foliar ratings of 0.7%, 4.2%, 1.0%, 1.8%, and 2.0% foliage affected in 2016; with foliar ratings of 0.8%, 3.3%, 1.0%, 1.8%, and 2.3% foliage affected in 2017; with foliar ratings of 2.3%, 2.0%, 1.5%, 1.0%, and 1.8% foliage affected in 2018, respectively. 'Primavera' hybrid witchhazel was moderately resistant to powdery mildew with a foliar rating of 4.2% in 2016, but the powdery mildew severity slightly increased, with foliar rating of 11.7% in 2017 and 2018. Season-long disease progress (AUDPC) was greatest in 'Westerstede' hybrid witchhazel in 2016, 2017, and 2018 and 'Quasimodo' vernal witchhazel only in 2016.

Discussion

In general, witchhazels are a slow-growing group of plants that are not widely available in the United States. Nursery producers are reluctant to grow witchhazel because they require a long-term investment in production space. Identifying witchhazel cultivars that grow faster, have a longer bloom period, and have fewer pest issues could have a positive impact on availability and landscape use. This trial was conducted in the nursery production center of Tennessee, USDA Hardiness Zone 6b/7a transition area, where plants often experience both cold-damage during winter and experience the disease/insect pressures associated with warm summers. Growth of popular and long-flowering chinese and hybrid witchhazel cultivars was hampered by cold injury manifested as stem necrosis. Common witchhazel showed the largest increase of both height and width growth during the trial, whereas chinese witchhazel grew the least. This is unsurprising, as chinese witchhazel is the smallest of the witchhazel species and considered the least cold-hardy (Gapinski, 2014); its slow growth likely reflects both its natural smaller size and reduced fitness due to cold injury in this trial.

'Zuccariniana' japanese witchhazel and 'Sunglow' common witchhazel showed the greatest height increase during the trial; 'Sunglow' also added the most width during the trial. Cultivars with negative height or

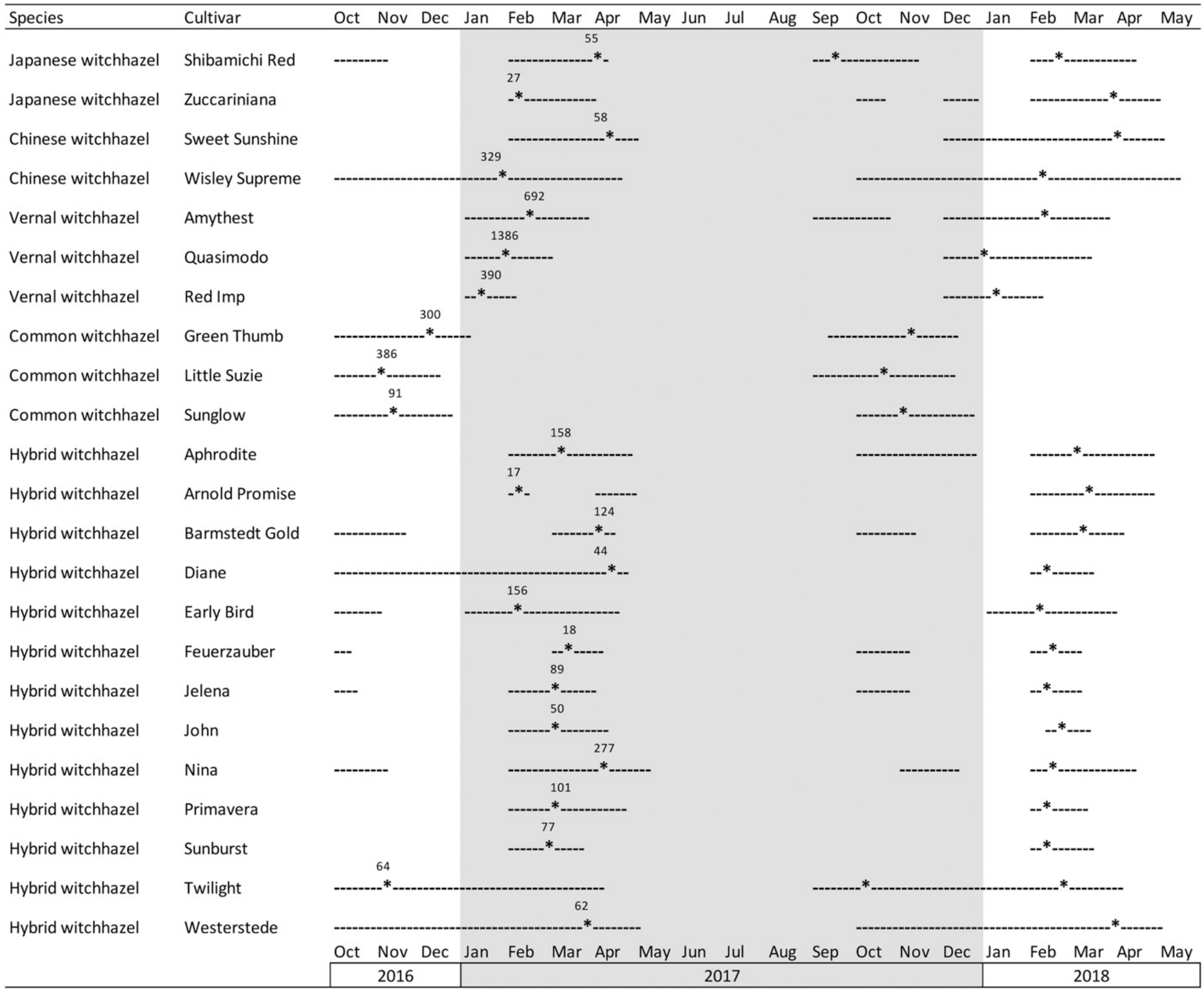

Fig. 3. Flowering period of witchhazel cultivars in a McMinnville, TN, cultivar trial. Asterisks (*) represent peak flowering based on flower counts from one flagged branch of three replicates per cultivar. The mean maximal number of flowers counted in 2016 for each cultivar is displayed above the asterisk. Calendar year 2017 is shaded gray for clarity.

width growth included Sweet Sunshine, Aphrodite, Twilight, and Barmstedt Gold. 'Barmstedt Gold' showed negative growth for both height and width. Interestingly, 'Barmstedt Gold' began the trial as a larger plant, but cold injury and poor growth significantly reduced its size. On the basis of the results of this trial, Red Imp and Little Suzie appear to be true semidwarf cultivars.

There was large variation in bloom period, especially among cultivars of chinese and hybrid witchhazel. In general, vernal and common witchhazel cultivars had a single bloom period of 6 to 8 weeks in spring and fall, respectively. One cultivar of chinese witchhazel bloomed continuously from October to May, whereas the other chinese witchhazel cultivar bloomed in spring only. All cultivars of hybrid witchhazel bloomed in spring; some also bloomed in fall and some such as Twilight and Westerstede bloomed continuously from September or October to April or May, with three or four peaks of bloom density. 'Diane' hybrid witchhazel displayed this continuous bloom pattern from Oct. 2016 to May 2017, but only had a single short bloom period from Feb. to Apr. 2018. Variation in bloom in the hybrid cultivars may result from various amounts of influence of the chinese witchhazel parent relative to the japanese witchhazel parent, or it could be that all cultivars could have a continuous bloom under favorable environmental conditions.

Cultivars of vernal witchhazel had the densest floral display of all witchhazel species. However, the flowers of 'Quasimodo', which averaged more than 1300 per flagged branch, were small, appressed and not particularly colorful or attractive. Similarly, the flowers of 'Red Imp' were appressed, muted in color, and lacking in ornamental display. Aside from vernal witchhazel cultivars, Little Suzie common witchhazel and Wisley Supreme chinese witchhazel produced the densest floral displays. All common witchhazel cultivars dropped foliage before peak bloom and all vernal witchhazel cutlivars

Table 6. Response of witchhazel cultivars to powdery mildew disease and disease progress in a McMinnville, TN, field trial from 2016 to 2018.

	Powdery mildew (mean ± SE)					
	2016		2017		2018	
Cultivar	Final disease severity (%)[z]	AUDPC[z]	Final disease severity (%)	AUDPC	Final disease severity (%)	AUDPC
Amethyst	11.7 ± 1.6 b-e[y]	148.8 ± 22.0 b-e	33.3 ± 1.6 a	449.2 ± 23.3 a	22.5 ± 1.4 c	236.3 ± 22.0 c
Aphrodite	0.0 ± 0.0 h	0.0 ± 0.0 i	0.0 ± 0.0 i	0.0 ± 0.0 h	0.0 ± 0.0 h	0.0 ± 0.0 g
Arnold Promise	0.0 ± 0.0 h	0.0 ± 0.0 i	0.0 ± 0.0 i	0.0 ± 0.0 h	0.0 ± 0.0 h	0.0 ± 0.0 g
Barmstedt Gold	4.2 ± 0.8 fgh	49.6 ± 11.6 f-i	3.3 ± 0.8 f-i	18.7 ± 2.9 gh	2.0 ± 6.4 gh	21.6 ± 6.4 fg
Diane	15.0 ± 0.0 bc	198.3 ± 5.8 bc	28.3 ± 3.3 ab	297.5 ± 26.7 b	15.0 ± 0.0 d	169.2 ± 15.4 d
Early Bird	16.7 ± 4.4 b	221.7 ± 64.9 b	8.3 ± 0.8 def	72.9 ± 2.9 fgh	12.5 ± 2.5 d	134.2 ± 29.1 de
Feuerzauber	9.2 ± 0.8 def	105.0 ± 17.5 def	13.3 ± 3.3 d	169.2 ± 46.6 de	20.8 ± 2.2 c	233.3 ± 23.8 c
Green Thumb	0.0 ± 0.0 h	0.0 ± 0.0 i	0.0 ± 0.0 i	0.0 ± 0.0 h	0.0 ± 0.0 h	0.0 ± 0.0 g
Jelena	6.7 ± 1.6 efg	87.5 ± 22.0 e-h	6.7 ± 0.8 e-h	58.9 ± 6.5 fgh	13.3 ± 2.2 d	151.7 ± 24.9 d
John	10.0 ± 2.8 cde	131.3 ± 38.1 cde	11.7 ± 1.6 de	122.5 ± 10.1 ef	6.7 ± 1.6 f	53.1 ± 12.8 fg
Little Suzie	1.0 ± 0.0 gh	8.8 ± 1.7 i	1.0 ± 0.0 i	12.3 ± 1.0 h	1.5 ± 0.5 h	15.8 ± 5.3 g
Nina	0.0 ± 0.0 h	0.0 ± 0.0 i	0.0 ± 0.0 i	0.0 ± 0.0 h	0.0 ± 0.0 h	0.0 ± 0.0 g
Primavera	4.2 ± 0.8 fgh	51.3 ± 9.0 f-i	11.7 ± 1.6 de	128.3 ± 15.4 ef	11.7 ± 3.0 de	125.4 ± 39.2 de
Quasimodo	35.0 ± 5.0 a	460.8 ± 64.9 a	21.7 ± 1.6 c	215.8 ± 5.8 cd	33.3 ± 1.6 b	373.3 ± 23.3 b
Red Imp	11.7 ± 10.9 b-e	92.8 ± 10.9 d-h	13.3 ± 1.6 d	163.3 ± 29.1 de	13.3 ± 0.8 d	137.1 ± 5.8 d
Shibamichi Red	2.0 ± 0.5 gh	26.8 ± 6.4 ghi	2.3 ± 1.3 ghi	32.7 ± 18.6 gh	1.8 ± 0.4 gh	20.4 ± 4.7 fg
Sunburst	9.2 ± 0.8 def	102.1 ± 2.9 d-g	7.5 ± 1.4 efg	70.0 ± 5.0 fgh	8.3 ± 1.6 ef	78.2 ± 18.7 ef
Sunglow	0.0 ± 0.0 h	0.0 ± 0.0 i	0.0 ± 0.0 i	0.0 ± 0.0 h	0.0 ± 0.0 h	0.0 ± 0.0 g
Sweet Sunshine	9.2 ± 3.0 def	110.8 ± 41.1 def	8.3 ± 1.6 def	88.7 ± 25.5 fg	15.0 ± 2.8 d	169.2 ± 47.7 d
Twilight	0.7 ± 0.1 h	3.5 ± 1.7 i	0.8 ± 0.1 i	5.3 ± 1.0 h	2.3 ± 0.1 gh	21.0 ± 4.4 fg
Westerstede	38.3 ± 4.4 a	490.0 ± 50.5 a	26.7 ± 6.6 bc	280.0 ± 97.4 bc	61.7 ± 1.6 a	740.8 ± 40.8 a
Wisley Supreme	1.8 ± 0.6 gh	22.8 ± 10.5 hi	1.8 ± 0.4 hi	18.1 ± 4.5 gh	1.0 ± 0.0 h	8.8 ± 1.7 g
Zuccariniana	13.3 ± 1.6 bcd	166.3 ± 26.2 bcd	9.2 ± 0.8 de	71.8 ± 3.6 fgh	5.8 ± 0.8 fg	47.3 ± 8.7 fg
F	25.67	24.96	25.06	20.91	95.17	67.77
df	22	22	22	22	22	22
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[z]Disease ratings and area under the disease progress curve (AUDPC) were based on percentage of foliage area affected.
[y]Treatment means within columns followed by different letters were significantly different ($P \leq 0.05$). One-way analysis of variance was used to partition variance in AUDPC to sources attributable to cultivar and error. Means for each cultivar were compared using Fisher's least significant difference test with an $\alpha = 0.05$.

reached peak bloom before spring leaf out. Foliage and flowers comingled during peak bloom period of the other species.

This 3-year field trial is the first long-term experiment designed to assess powdery mildew severity of witchhazel cultivars. Powdery mildew infection resulted in a reduction in aesthetic value, including the production of fewer flowers of poorer quality, and reduced plant growth. Several notable hybrid cultivars, including Diane, Jelena, John, and Westerstede, grew well in the trial but developed severe powdery mildew infection. All five species in the trial had at least one cultivar that was completely resistant (remained powdery mildew disease-free) or moderately resistant (relatively low disease severity) to powdery mildew disease, indicating that resistance is not species-dependent. Of the five cultivars that remained disease-free, Sunglow showed the largest growth increase during this field trial followed by Nina, Green Thumb, and Arnold Promise. Five other cultivars with moderate resistance were identified, including Nina and Little Suzie, which both had positive growth during the trial. 'Aphrodite', 'Barmstedt Gold', and 'Twilight' hybrid witchhazels were completely or moderately resistant to powdery mildew but displayed negative growth values, indicating cold damage. These cultivars may be promising for growth in Zone 7 and warmer, where powdery mildew disease is often a problem but winter injury is less probable. Currently, little is known about the nature of resistance of witchhazel cultivars to powdery mildew. Several factors, including cuticle thickness (Heintz and Blaich, 1989), tissue maturity (Salzman et al., 1998), host defense mechanisms (Develey-Riviere and Galiana, 2007), and pathogen factors could play a role in resistance and could be investigated in the future.

The nursery industry in Tennessee and in the surrounding region is valued at over $310 million, has a $3.9 billion green industry impact, and is ranked sixth in the nation for nursery stock sold (US Department of Agriculture, 2014). Uses of witchhazels are varied and numerous, including essential oils, an ornamental plant, astringent, and winter flowers. It is a food source in early spring for pollinators and a source of winter food for wildlife. These attributes make it an attractive value-added crop for nursery producers in the southeast. Witchhazel recommendations for Tennessee nursery producers based on growth rate, resistance, and susceptibility of witchhazel cultivars to powdery mildew, and flowering include Sunglow, common witchhazel, Little Suzie common witchhazel (semidwarf habit), Wisely Supreme chinese witchhazel, and Nina hybrid witchhazel. Sunglow has the added benefit of rooting well from cuttings, indicating that it could be grown as a cultivar on its own roots rather than grafted (Alexander et al., 2018). Witchhazel cultivars with resistance to powdery mildew disease but poor growth in this trial may have production potential in Southeastern growers in the U.S. Department of Agriculture Hardiness Zone 7 and warmer. Research regarding production timelines and practices is ongoing. These results should aid in the adoption and production of witchhazel by southeastern nursery producers.

Literature cited

Alexander, L.W., A. Witcher, and M.A. Arnold. 2018. 'Sunglow' american witchhazel. HortScience 53:575–577.

Develey-Riviere, M. and E. Galiana. 2007. Resistance to pathogens and host developmental stage: A multifaceted relationship within the plant kingdom. New Phytol. 175:405–416.

Dirr, M.A. 2009. Manual of woody landscape plants: Their identification, ornamental characteristics, culture, propagation and uses. Stipes, Champaign, IL.

Gapinski, A. 2014. Hamamelidaceae, part 1: Exploring the witchhazels of the Arnold Arboretum. Arnoldia 72:2–17.

Heintz, C. and R. Blaich. 1989. Structural characters of epidermal cell walls and resistance to powdery mildew of different grapevine cultivars. Vitis 28:153–160.

Leonard, S.W. 2006. A new species of witch-hazel (*Hamamelis*: Hamamelidaceae) apparently endemic to southern Missouri. SIDA Contrib. Bot. 22:849–856.

Li, J.H., A.L. Bogle, A.S. Klein, and M.J. Donoghue. 2000. Phylogeny and biogeography of *Hamamelis* (Hamamelidaceae). Harv. Pap. Bot. 5:171–178.

Salzman, R.A., I. Tikhonova, B.P. Bordelon, P.M. Hasegawa, and R.A. Bressan. 1998. Coordinate accumulation of antifungal proteins and hexoses constitutes a developmentally controlled defense response during fruit ripening in grape. Plant Physiol. 117:465–472.

US Department of Agriculture. 2012. USDA plant hardiness zone map. 7 Dec. 2018. <http://planthardiness.ars.usda.gov>.

US Department of Agriculture. 2014. Census of agriculture. 14 Nov. 2018. <http://www.agcensus.usda.gov/Publications/2014>.

Wen, J. and S.H. Shi. 1999. A phylogenetic and biogeographic study of *Hamamelis* (Hamamelidaceae), an eastern Asian and eastern North American disjunct genus. Biochem. Syst. Ecol. 27:55–66.

Wiersema, J.H. 2017. GRIN taxonomy. 13 Oct. 2018. <https://npgsweb.ars-grin.gov/gringlobal/taxon/taxonomysimple.aspx>.