

**Combating an Invasive Boxwood Pathogen – *Calonectria pseudonaviculata* – in the United States by Shifting Production to Less Susceptible Cultivars**

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**Abstract**

Boxwood Blight (BB) caused by *Calonectria pseudonaviculata* (*Cps*) is an economically devastating disease affecting the entire boxwood supply chain from growers to gardeners, since it was first officially documented in the United States in 2011. This disease has taken a heavy toll on boxwood, an iconic landscape plant and the number one evergreen nursery crop. The objective

of this study was to examine the adoption of one sustainable management strategy available to growers: shifting boxwood production from highly susceptible to less susceptible cultivars. We investigated the ongoing shift by comparing boxwood sales of 17 selected nurseries from seven states across the country in 2011, 2016 and 2021. Results revealed that from 2021 to 2016, sales of cultivars highly susceptible to BB were reduced by over 35% while less sales of less susceptible boxwood cultivars increased 55%. Increased boxwood sales have been seen for ‘Winter Gem’, ‘Wintergreen’, ‘SB 300’ (Freedom®), ‘SB 108’ (Independence®), and ‘Little Missy’, all of which have been rated less susceptible than *B. sempervirens* ‘Suffruticosa’ in numerous trials. The potential for long-term positive impact on sustainable boxwood production and plantings in the U.S. through the use of such less susceptible cultivars is discussed. Better boxwood cultivar choices will build crop health into new plantings and sustain customer demand for boxwood. This is a case study for how sustainable crop protection strategy helps to maintain production of a crop under serious pressure from an invasive pathogen.

Index words: Sustainable production, horticultural sales, agricultural trade, woody plant, cultivar resistance, plant disease

## **Introduction**

### **Boxwood, a plant of historical importance in the United States**

Based on contemporary classification, the Buxaceae (boxwood) family is comprised of seven accepted genera: *Buxus*, *Didymeles*, *Haptanthus*, *Notobuxus*, *Pachysandra*, *Sarcococca* and *Styloceras* (USDA, National Plant Germplasm System website, GRIN). The genus *Buxus* has about 117 accepted species and botanical varieties (Batdorf 2021; Van Laere et al. 2011; Batdorf 2004) with two of the most common, *B. sempervirens* and *B. microphylla*, grown as shrubs with worldwide distribution in both tropical and temperate climates. Under various common names such as boxwood, box, boxtree, buis, and buxbom, plants in the *Buxus* genus are native to Central

and South America (45 native species), Africa (10), Europe (2) and Asia (34) (Köhler and Brückner 1989; Batdorf 2004) but have become globally recognized for various uses in the landscape industry. Boxwood plants are choice ornamental plants in landscape designs for homes, historic gardens and parks in northern temperate climates; they accentuate garden entryways, give structure to garden designs, edge garden beds, divide courtyards, designate parking areas, fill window boxes, and create labyrinths.

Boxwood has become popular in the U.S. green industry since its first introduction in the 1600s (Fig. 1) and is consistently ranked as the top selling evergreen shrub for landscaping. For example, in 2009 alone, 13 million boxwood plants from 1,952 operations valued at \$103 million accounted for 12.9% of the total sales of 113 million broadleaf evergreens worth \$793 million of the U.S. broadleaf evergreen industry (USDA-NASS 2007). The preference for boxwood includes factors such as ease of maintenance, deer resistance, and drought and cold tolerance. Evolving global challenges facing agricultural production, particularly the invasion of pests and pathogens, have impacted boxwood production and necessitated improvements through boxwood cultivar development efforts over the centuries (Fig. 1).

While certain boxwood cultivars, such as the American and English, quickly became favorite choices among nursery growers and homeowners in the U.S., major threats from pests and diseases hampered their production. The ‘English’ and ‘American’ cultivars are particularly susceptible to leafminer, psyllid, webworm, mite, mealybug, and moth pests (Relf et al. 1989; Cory and Craham 1930; Matsiakh et al. 2018). Also, wounded foliage and twigs are particularly susceptible to diseases caused by *Pseudonectria* spp. and *Dothiorella candollei* and roots and stems to Phytophthora root rot; these plants also exhibit boxwood decline and nematode-induced injuries (d'Eustachio and Raupp 2001; Wiesner et al. 2021; Lopez-Nicora et al. 2012).

These diseases and pests require various remedies such as chemical controls and cultural practices in order to maintain boxwood production (Bosmans et al. 2009). However, more sustainable disease and pest management has been achieved with the replacement of highly susceptible cultivars such as ‘English’ with more disease resistant cultivars. An outstanding example is ‘Vardar Valley’, one of Edgar Anderson’s boxwood selections while he served as Director of the Missouri Botanical Garden and staff member at the Arnold Arboretum (Fig. 1).

‘Vardar Valley’ got its initial reputation for remarkable winter hardiness and mounded growth habit; however, as it became popular among nursery growers by the 1970s and 1980s, the important trait of broad pest and disease resistance was observed. ‘Vardar Valley’ showed resistance to the boxwood decline disease, which for a time was the most dreaded of all boxwood diseases across eastern North America (Del Tredici 2007). The Arnold Arboretum, privately owned nurseries such as Sheridan Nurseries in Canada, Saunders Genetics LLC, and institutions such as the U.S. National Arboretum and American Boxwood Society have been at the forefront of boxwood selection efforts (Fig. 1).

In 2011, Boxwood blight (BB), caused by the ascomycete fungus *Calonectria pseudonaviculata*, became the most challenging disease of boxwood in the U.S., having devastating economic impact on boxwood production and plantings that affected the entire green sector. Before the first official report of boxwood blight in the U.S. in the fall of 2011 (Ivors et al. 2012), BB had been reported in the United Kingdom in the 1990s and had spread throughout

Europe in the late 1990s and early 2000s (Crous et al. 2002; Henricot and Culham 2002) (Fig. 1).

Over the years, BB has also been reported in Asia (Gasich et al. 2013), Iran (Mirabolfathy et al. 2013), and Turkey (Akilli et al. 2012). In the U.S., the initial report of boxwood blight in eight states in 2011 (Ivors et al. 2012) increased progressively to 25 states in 2018 (Malapi-Wight et al. 2014; Blomquist et al. 2018) and to 30 states by 2020 (Hall et al. 2021). The first detection instances led to the loss of 10,000 containerized ‘American’ boxwood plants in North Carolina and 150,000 ‘English’ boxwood in Connecticut a few weeks later. Hall et al. (2021) reported what may turn out to be a lasting structural shift in boxwood production across the U.S. due to the BB disease (Hall et al. 2021). An important parallel shift that has not been documented is growers’ production inventory changing from highly-susceptible to less-susceptible cultivars — a cultivar selection approach to achieve sustainable crop production.

### **Cultivar selection as a tool in sustainable plant disease management**

A boxwood cultivar may initially be marketed for various reasons such as its adaptability across different hardiness zones, form, size, plant color, propensity to grow, and other morphological preferences (Niemiera 2018). However, there have been conscious research efforts to assess

cultivars for their level of susceptibility to the contemporary pest and disease issues of the time (Fig. 1). These efforts dovetail into the development of cultivars that eventually are made available to growers.

In the case of boxwood decline in the U.S., selection efforts led to a shift to less susceptible cultivars such as ‘Green Velvet’, ‘Green Beauty’, and ‘Green Mountain’ (Saunders 2021). With the raging epidemics of the boxwood leafminer came the industry’s embrace of cultivars such as ‘Pyramidalis,’ ‘Handsworthiensis’, ‘Franklin’s Gem’, ‘Green Pillow’, ‘Grace Hendrick Phillips’, ‘Richard’ and ‘Nana’ that showed some resistance to leafminer as evidenced by lower oviposition scars and larval development (d'Eustachio and Raupp 2001; Kaur and Dale 2020). Although there are references attesting to research studies conducted to identify less susceptible cultivars to major boxwood diseases, there is no proper documentation of the actual shift to the less susceptible cultivars as witnessed among growers.

The attempt to understand resistance of boxwood cultivars to BB has involved different groups across the U.S. (Ganci 2014; Ganci et al. 2013; LaMondia 2015; LaMondia and Shishkoff 2017; Kramer et al. 2020) and Belgium alike (Van Laere et al. 2019; Luypaert et al. 2016). Most of these efforts classified boxwood cultivars in terms of their susceptibility to the causal fungus after challenging different cultivars with sufficient pathogen inoculum to cause disease. Two years after the first detection of BB in the U.S., Ganci et al. (2013) shared results of evaluating thirtytwo boxwood cultivars challenged with the blight pathogen through splash dispersal from infected “inoculum-reservoir” plants. The study reported ‘Aurea Pendula’ as the most susceptible, and ‘Green Beauty’ as the least susceptible (LS) of all the cultivars evaluated (Niemiera 2018; Ganci et al. 2013; Ganci 2014). ‘Suffruticosa’ showed equally high susceptibility to BB and cultivars such as ‘Green Velvet’ and ‘Wintergreen’ generally were among the least susceptible, showing low leaf drop or defoliation (Ganci et al. 2013). More studies have carefully evaluated the susceptibility of U.S.-grown boxwood cultivars to blight, some studies evaluating more cultivars than others (Shishkoff et al. 2015; Kramer et al. 2020; LaMondia and Shishkoff 2017). Despite differences in the plant part used for assessment, inoculation methods, and environmental factors, boxwood cultivars fairly consistently show low, moderate or high susceptibility to blight disease; the widely grown ‘English boxwood’ cultivar consistently shows high susceptibility. However, since the publication of recent plant performance findings that have allowed classification of

cultivar susceptibility into these three categories, the adoption of the LS cultivars among nursery growers has not been carefully analyzed and documented. This makes the impact of cultivar resistance in managing the BB disease difficult to assess.

The primary objective of this study was to analyze the changes in boxwood plants sold in the U.S. in terms of their susceptibility to boxwood blight since 2011, when this disease was first discovered in North America. This study was intended to document and call attention to this inventory shift and get all of the nation's boxwood production and planting on a fast track to sustainability by helping growers and gardeners to make the best possible decisions about which boxwood to grow for landscape ornamental uses.

## **Methodology**

### **Data sources and collection**

Seventeen nurseries were surveyed across seven major boxwood-producing states in the U.S. to understand how they might have utilized the latest cultivar evaluation research data to gradually shift their inventories to boxwood cultivars more resistant to BB. The states included in the survey were California, Connecticut, Georgia, North Carolina, Ohio, Oregon and Virginia (Fig. 2). BB had previously been reported in these states at different time points as shown on the map, although the positive detections were mostly from plants in landscape settings, and none were in the nurseries included in this survey. Nine of the 17 nurseries surveyed were in Virginia, two nurseries were in Oregon, and there was one nursery each in California, Connecticut, Georgia, North Carolina, and Ohio (Supplementary Table 1). The first report of boxwood blight differs across these locations; all nurseries were in active boxwood production from 2011-2021.

The data collected were mostly boxwood sales and they are referred to as 'boxwood plant sales' or 'plants shipped' hereafter. Data collection began with requesting copies of boxwood propagation, production, or sales inventories, with the first call in September 2021. In the request email sent out, nursery growers were requested to share their boxwood inventories of 2011, 2016 and 2021 by cultivar to support this study. As expected, most nurseries had detailed records of plant sales data which were easily downloaded from their computer systems. In contrast, few had detailed records of propagation or production data; for those who did, their records may not be in

electronic format, so these details difficult to track down and locate. As a result, the vast majority of the nurseries opted to share their monthly boxwood sales data and they sent to the authors at the end of September or October their annual sales data for 2011 and 2016 and the first 9- or 10-month data for 2021. These data are confidential, as are the names of supporting nurseries. They are protected per the protocol approved by Virginia Tech's Institutional Review Board.

The quantity of boxwood plant sales or plants shipped per month in 2011, 2016 and 2021 was extracted from the inventories provided and classified based on cultivar name. These years were selected because they represent key points in the history of BB in the U.S. 2011 was the year four of the states under consideration first reported BB (Fig. 2), while 2016 was five years into BB invasion in the U.S. During these five years and beyond, studies evaluating different boxwood species, varieties and cultivars for their resistance to BB were conducted in lab and field settings, and the results of these research studies were immediately made available to the horticultural industry and the public (Ganci et al. 2013; Kramer et al. 2020; LaMondia 2015; LaMondia and Shishkoff 2017; Guo et al. 2016). 2021 represents the tenth year since BB was introduced to the U.S. Now that there has been a decade of experience with boxwood blight in the U.S, it appears timely to assess how growers may have used the latest research to make informed cultivar selections for boxwood propagation and production in response to this fairly new disease.

Boxwood are slow-growing plants, and it takes several years from propagation to ready for-sale (Batdorf 2004). Thus, the sales inventories of individual nurseries might be slightly different from their actual cultivar number and plant quantity counts in production. They were the best approximations available for the production inventories. The sales inventory data also have several advantages over the propagation and production data – being the most accurate in cultivar number and plant quantity counts, in addition to being most readily available and the easiest to access, download and share. Therefore, sales inventory and production inventory are used interchangeably in this study.

Raw data were received by cultivar common names, including some invalid names. Using “Boxwood: An Illustrated Encyclopedia” (Batdorf 2004) and the “International Checklist of Cultivated *Buxus* L.” (Batdorf 2021) as guides, cultivar names were combined into valid cultivar

synonyms. The raw data received were also in different plant and container sizes, and different types of production categories. Sizes were combined for simplified analyses.

Overall, the total number of boxwood plants shipped from the 17 nurseries surveyed was 1.3 million in 2011, 1.2 million in 2016 and 1.5 million in 2021 (Supplementary Figure 1). According to the latest USDA-NASS Census of Agriculture report (USDA-NASS 2020), the national total of boxwood plants sold in 2019 was 124.1 million with 66.2 million or 53.4% from the seven states surveyed in this study. Approximately, the number of boxwood plants shipped from the 17 nurseries in this study was about 10% of the national total in each of the three years (Supplementary Figure 1). Thus, the nurseries and states surveyed are a good representation of the national boxwood production and sales and the survey data could be analyzed to draw data-based inferences on cultivar changes at the national level.

## **Classification based on susceptibility to blight disease**

Determination of the susceptibility class used in this study was based upon a previously published meta-analysis of six resistance screening studies of 131 cultivars grown in the U.S. (Kramer et al. 2020). In the reference study, Kramer et al. (2020) allotted Susceptibility Estimates (SE) between -3.96 and 3.10 to each cultivar. The current study has 40 cultivars with known SE based on this reference (Kramer et al. 2020). In order to have well-defined susceptibility classes in the current study, SE between -3.96 and 3.10 were divided into three classes. The division was based on the division of the mean rank of 131 boxwood cultivars used in the reference study (Kramer et al. 2020). The first one-third of the mean ranking (i.e 1.03-43.80) fell in the susceptibility estimates of -3.96 and -0.35. The second one-third of the mean ranking (44.70-87.50) fell within SE of -0.34 to 0.68. The third one-third of the mean ranking (88.77-131) fell within the 0.70 to 3.10 SE.

Therefore, in the current study, boxwood cultivars with SE from 0.70 to 3.10 are called “highly susceptible” (HS), the cultivars with SE from -0.34 to 0.68 are regarded as “moderately susceptible” (MS), and the cultivars with SE from -3.96 and -0.35 are considered the “least susceptible” (LS) cultivars, showing little or no susceptibility to BB (Kramer et al. 2020). The susceptibility class of 19 cultivars in the survey that are not found in the reference publication was determined using other BB resistance screening studies conducted by (Yoder et al. 2022) local



nurseries and a long-term study conducted in Germany (Brand et al. 2022). In addition, the classification for Vardar Valley was determined to be MS based on field studies conducted in 2021 by the authors that negated its classification as a LS cultivar. Also, of special concern in the classification assignment is the cultivar ‘Dee Runk’, which falls in the HS category based on researchers’ trials but is often considered a moderately blight resistant cultivar by the landscape trade. Consistent with the literature, some cultivars in the least susceptible category may be called low in susceptibility, less susceptible, or more resistant (Kramer et al. 2020; LaMondia and Shishkoff 2017): these words are used interchangeably in this study and publication. The susceptibility classes assigned to each cultivar were used in follow-up analyses to determine which cultivar susceptibility class showed the highest sales by year.

### **Data summary and analysis**

All analyses were conducted using statistical analysis software v9.4 (SAS Institute, Cary, North Carolina, USA), and visualization was done using Microsoft Excel and Tableau Public. Before visualization of relevant results, data was subjected to Proc UNIVARIATE, Proc NPAR1WAY, and Proc ANOVA. Analysis was first conducted on the combined data across all three years, all seven states, and all cultivars. Effect of main factors of year, location and cultivar was thus determined. Separate analysis was then conducted on data from each year and the effect of states (location) and cultivars was observed within each year. Separate analysis was then conducted on boxwood sales across the three susceptibility classes (HS, MS, and LS) of the cultivars to capture the effect (inventory shifts) of susceptibility classes within each year.

Separately, the effect of location on cultivar susceptibility classes within each year was tested. To achieve this, the seven states where surveys of boxwood sales were conducted (locations of the seventeen nurseries) were divided into two location classes (Virginia and non-Virginia). We grouped the states into two categories to understand how nurseries in Virginia or outside Virginia were adopting LS cultivars over the years. Nine Virginia nurseries were elected to stand together in this part of the analysis and eight nurseries across the six other states were grouped as non-Virginia. By using this grouping, the performance of cultivars in Virginia nurseries (and likewise the non-Virginia nurseries) in sales across the three susceptibility categories over the years could clearly be reported.

Additional comparisons were performed between the 2016 and 2021 sales data to further assess the inventory shifts made by growers informed by the latest research that evaluated boxwood cultivars for their susceptibility to the blight during the first few years (Ganci et al. 2013; Kramer et al. 2020; LaMondia 2015; LaMondia and Shishkoff 2017; Guo et al. 2016). Time point selection considers factors such as the increasing disease pressure with time and the time required from propagation to ready-for-sale boxwood plants. Also evaluated were how the top-ten sellers may have been shifted to LS cultivars over the same period.

All results are presented as sum, counts, and percentages for clearer understanding of observed differences.

## Results

### Boxwood production/sales across all nurseries and years surveyed

A total of fifty-nine different cultivars were included in boxwood sales across all seventeen nurseries. The total number of boxwood cultivars across the nurseries was forty-four in 2011 and fifty in both 2016 and 2021 (Table 1).

Total quantity of boxwood plants sold was not significantly different among the three years ( $P=0.7699$ ) but was significant among three susceptibility classes ( $P=0.0006$ ), seven locations (states) ( $P=0.0001$ ) and cultivars ( $P=0.0001$ ). However, for each year, the differences in the number (count) of boxwood cultivars sold were not statistically significant among the three susceptibility classes; neither was the quantity of any of the susceptibility classes for the three years ( $P>0.7699$ ).

Overall, ‘Winter Gem’ had the highest sale quantity across the three years, accounting for 33%, 23% and 26% of the total boxwood plant sales in 2011, 2016 and 2021, respectively. This was closely followed by ‘Green Velvet’ which accounted for 21%, 24% and 17% of the total boxwood plant sales in 2011, 2016 and 2021, respectively. In third place was ‘Green Mountain’ with 14%, 13% and 13% of the total boxwood plant sales. For cultivars in fourth place, there was variation across the three years with ‘Green Beauty’ for 2011, ‘Suffruticosa’ for 2016, and ‘SB 108’ (Independence®) for 2021 (Table 1).

### 273 **Boxwood production/sales inventory shift to LS cultivars between 2011 and 2021**

274 The first sign of a boxwood sales inventory shift was the increase in the number of LS cultivars  
 275 available for sale, which became evident in 2016. In 2011, LS cultivars accounted for 17 of the 44  
 276 total cultivars offered for sale. This increased to 22 of the 50 in 2016 and 24 of the 50 (or 48%) in  
 277 2021. Meanwhile, the number of HS cultivars in the sales inventories of nurseries decreased from  
 278 17 in 2011 to 16 in 2016 and 14 in 2021 (Fig. 3a). The second measurement of boxwood sales  
 279 inventory shift was the quantity of LS plants sold and this shift became obvious in 2021 (Fig. 3a).  
 280 LS plant sales accounted for 45.48% of the total boxwood sales in 2011 and 38.58% in 2016; but  
 281 this percentage increased to 60.04% in 2021. Comparatively, the HS plant sales dropped to 37.60%  
 282 of the total boxwood sales in 2021 from 58.59% in 2016 (Fig. 3b).

### 283 **Top-ten seller boxwood shifted to LS cultivars between 2011 and 2021**

284 In addition to increased overall LS boxwood sales observed above (Fig. 3; Table 1), the top-ten  
 285 sellers shifted to LS cultivars over the 10-year period surveyed (Fig. 4). In 2011, there were only  
 286 three LS cultivars among the top-ten sellers. This number increased to four in 2016 and further  
 287 increased to 7 LS cultivars in 2021. A total of nine LS cultivars were among the top-ten sellers at  
 288 least one year over the three years surveyed, with ‘Winter Gem’ consistently being the top-selling  
 289 LS cultivar, accounting for 22.74 to 32.56% of the total sales of these years (Fig. 4). ‘Green  
 290 Beauty’ was the second top-selling LS cultivar in 2011 and 2016, accounting for 6.41% and 5.02%  
 291 of the total sales of respective years; its rank, however, dropped to the fourth top-selling LS cultivar  
 292 in 2021. The most significant additions to the 2021 top-ten seller list were two NewGen Boxwood  
 293 cultivars ‘SB 300’ (Freedom®) and ‘SB 108’ (Independence®) and also ‘Little Missy’. The  
 294 NewGen boxwood cultivars entered the market with limited availability in late 2019 (McClellan  
 295 2019). Within two years, ‘SB 300’ (Freedom®) and ‘SB 108’ (Independence®) emerged as the  
 296 second and third top-selling LS cultivars, accounting for 8.88% and 6.49% of the 2021 total  
 297 boxwood sales, respectively. The other five LS cultivars that made it to the top-ten seller rank were  
 298 ‘Green Gem’, ‘Little Missy’, ‘Winter Green’, ‘Faulkner’, and ‘Franklin’s Gem’.

Accompanying increased LS boxwood sales were reductions in the plant inventory and sales of HS cultivars. For example, the percentage of ‘Suffruticosa’ sales in total annual sales drastically reduced from 9.1% in 2016 to 0.97% in 2021. Also, the percentage of ‘Green Velvet’ sales in the annual total reduced from 20.5% in 2011 to 17.2% in 2021. Likewise, the percentage of ‘Green Mountain’ sale in the annual total reduced from 14.2 in 2011 to 13.05% in 2021. Similarly, ‘Justin Brouwers’ reduced from 3.9% in 2016 to 0.1% in 2021 (Fig. 4).

### **LS cultivar shift: Virginia vs. non-Virginia nurseries**

A greater rate of LS cultivar shift from 2016 to 2021 was seen in Virginia than in non-Virginia nurseries. This is reflected in both LS plant sales and cultivar number. For example, LS plant sales in Virginia nurseries increased from 33% in 2016 to 64% in 2021, while those in non-Virginia nurseries increased from 40.3% to 58.3% during the same period (Fig. 5). More LS cultivars were observed in the 2021 production/sales inventory of Virginia than non-Virginia nurseries (21 vs. 17), Table 2). Accompanying these LS plant increases were corresponding levels of HS boxwood sales reduction in both Virginia (62.65 to 34.10%) and non-Virginia nurseries (57.35 to 39.15%) from 2016 to 2021 (Fig. 5).

A total of 456,086 boxwood plants from 41 cultivars were sold at the Virginia nurseries while 1,024,361 plants from 28 cultivars were sold at the non-Virginia nurseries in 2021 (Table 2; Supplementary Fig. 2). Five major LS cultivars with >10,000 plant sales seen in both Virginia and non-Virginia nurseries were ‘Winter Gem’, ‘Green Beauty’, NewGen ‘SB 300’ (Freedom®), ‘SB 108’ (Independence®), and ‘Little Missy’. ‘Franklin’s Gem’ and ‘Green Gem’ were the two other LS cultivars in the same rank with the former only seen in the Virginia nurseries and the latter only in the non-Virginia nurseries. Two major HS cultivars observed in both Virginia and non-Virginia nurseries were ‘Green Mountain’ and ‘Green Velvet’. ‘Monrue’, ‘Suffruticosa’, and ‘Variegata’ were the other three HS cultivars in the same rank with ‘Dee Runk’ in the Virginia nurseries and in non-Virginia nurseries. One of the most significant boxwood cultivars has long been

‘Suffruticosa’, commonly used as the susceptible boxwood standard in cultivar evaluation studies. In 2021, a total of 14,282 plants of this cultivar was still sold in the non-Virginia nurseries, representing 1.39% of its total sales. Likewise, 11,597 ‘Variegata’ plants were sold from the same nurseries in 2021 (Table 2; Supplementary Tables 2 and 3).

**Top-ten seller boxwood shift to LS cultivars: Virginia vs. non-Virginia nurseries**

A total of nine LS cultivars were on the top-ten seller list either in both 2016 and 2021. These cultivars were ‘Winter Gem’, ‘Green Beauty’, ‘Green Gem’, ‘Franklin’s Gem’, ‘Faulkner’, ‘Wintergreen’, SB 300 (Freedom®) and ‘SB 108’ (Independence®), and ‘Little Missy’. There were several variations in LS cultivar shift from 2016 to 2021 between Virginia and non-Virginia nurseries. First, seven LS cultivars were among the top-ten sellers in 2021 in the Virginia nurseries while only six LS cultivars were on the top-ten sellers list in non-Virginia nurseries (Table 2). Both lists had two more LS cultivars compared to the corresponding 2016 lists. Second, while five cultivars - ‘Winter Gem’, ‘Green Beauty’, ‘SB 300’ (Freedom®) and ‘SB 108’ (Independence®), and ‘Little Missy’ - made both lists, ‘Franklin’s Gem’ and ‘Wintergreen’ only made it onto the Virginia nurseries’ list and ‘Green Gem’ only made it onto the non-Virginia nurseries’ list. Third, with the surge of three new LS cultivar additions – ‘Little Missy’, SB 300 (Freedom®) and ‘SB 108’ (Independence®) in the 2021 sales, ‘Faulkner’ lost its place in the non-Virginia nurseries’ top-ten seller list although it was in the 2016 list. Likewise, ‘Wintergreen’ lost its place in the 2021 Virginia nurseries’ top-seller list although it was on the 2016 list. Third, there were some other cultivar-dependent variations in the LS shift from 2016 to 2021 between the Virginia and non-Virginia nurseries. For instance, ‘Little Missy’ accounted for 10% of Virginia nurseries’ sales but only 1.7% of those in the non-Virginia nurseries. ‘Freedom’ accounted for 8.5% of Virginia nurseries’ sales and 9.1% of sales in the non-Virginia nurseries (Fig. 6). ‘Glencoe’, a moderately susceptible cultivar, was one of the top-ten sellers in the non-Virginia nurseries but not in the Virginia nurseries (Table 2). Fourth, accompanying the shift to LS cultivars were reductions in HS plant sales, which were also cultivar dependent and differed between Virginia and non-Virginia nurseries (Supplementary Fig. 2). For example, ‘Green Velvet’ was reduced by half in Virginia but showed only a 4.32% drop in non-Virginia nurseries in 2021.

**Other factors considered in cultivar selection – towards a systems approach to boxwood health and production**

Table 3 shows a comparison of features of the top-ten cultivars now in production across the nursery locations in this study. This summary table suggests that, in addition to BB, boxwood cultivar selection may depend on other factors, such as resistance to leafminer and other pests as well as cold hardiness; it is also affected by new plant breeding and extension efforts (Table 3).

For example, HS ‘Suffruticosa’, which experienced one of the most drastic reductions in production across nurseries by 2021, was still cherished for its resistance to leafminer in 2016 even with the devastating impact of BB, especially in the non-Virginia locations. Likewise, the increasing demand for the LS cultivar ‘Winter Gem’ is attributed to its resistance to leafminer and evergreen winter color, as well as having low susceptibility to BB. All three of the new additions to LS boxwood cultivars in production in 2021 show some resistance to leafminer along with other desirable traits (Table 3).

## Discussion

Sustainable plant protection strategies aim to maintain crop production and, at the same time, protect the environment despite recent unprecedented emergence of invasive pathogens and pests due to increasing global trade and travel, aggravated by climate change (Movilla-Pateiro et al. 2020; Schäffer et al. 2018). Although cultivar selection is a common activity carried out in agricultural production for yield improvement, its role in sustainable plant protection including disease management is poorly understood and documented in ornamental crops. This study demonstrates that the American nursery industry has shifted their boxwood production towards the LS cultivars to address an emerging invasive disease – boxwood blight – that has become a lasting major concern for the horticultural supply chain from grower to consumer and all citizens that cherish plantings and gardening with the historic boxwood. This shift was reflected in both LS cultivar number and plant sales across all seventeen nurseries surveyed in this study (Table 1, Fig. 3) and further highlighted by the LS cultivars increasingly being among the top-ten sales and sellers’ list (Fig. 4). This shift differed with location – the Virginia nurseries having adopted more LS cultivars, and sold a greater percentage of LS plants than the non-Virginia nurseries (Table 2, Figs. 5 and 6).

The verification and demonstration of boxwood production inventory shift towards the LS cultivars explains the continued growth in demand for boxwood crops in the seventeen nurseries over a 10-year period from 2011 to 2021 surveyed in this study (Fig. 3, Supplemental Figure 1) and at the national scale from 2009 to 2019 (Hall et al. 2021), in spite of the mounting boxwood blight disease pressure (Daughtrey 2019; Hong 2019). The laudable adoption of LS cultivars has immediate impact and plays a significant role in the success of integrated and sustainable BB

management. LaMondia (2015) showed that both the level of resistance inherent in the boxwood cultivar and fungicide treatment can play significant roles in BB management. LS cultivars such as ‘Korean’ and ‘Winter Gem’ showed lower infection compared to HS cultivars such as common boxwood and True Dwarf (‘Suffruticosa’) (LaMondia 2015). The adoption of the newer less susceptible cultivars such as ‘SB 300’ (Freedom®), ‘SB 108’ (Independence®) and ‘Little Missy’, and continued use of ‘Green Beauty’, ‘Green Gem’ and ‘Winter Gem’ (Fig. 6) as first choices in garden reclamation and nursery re-establishment in both blight-infested and blight-free regions of the U.S are encouraged to further mitigate the spread of the boxwood blight pathogen. The additive effects of LS cultivars and non-conductive weather conditions may strongly curtail disease epidemics in blight-free regions of U.S.

The demonstrated shift to LS cultivars also has other important ramifications for blight mitigation and sustainable boxwood production and plantings. Recent studies on the biology and dispersal of *Cps* suggest that certain cultural practices now standard in boxwood such as crowding of cuttings and extended periods of overhead irrigation in production contribute to infection. These current cultural practices may be difficult to change, but when LS cultivars that accommodate only low levels of primary infection are used in production, pathogen dispersal and spread will be reduced in nurseries (Gehesquière et al. 2016; Daughtrey 2019). In gardens, spread via the use of leaf blowers and other human- and animal-mediated dispersal will be similarly reduced by reducing initial inoculum levels through the use of LS cultivars. Even pathogen dispersal and spread via the sale of winter holiday greenery using boxwood clippings will have less impact when boxwood cultivars in production are inherently less susceptible.

The observation that the reported shift to LS cultivars took place during the second 5-year period from 2016 to 2021 was expected and further highlights the importance of the research that is currently being conducted to fight against boxwood blight. In response to the first boxwood blight epidemics in the U.S. in 2011 (Ivors et al. 2012), a number of studies were immediately instituted to evaluate common boxwood species, varieties and cultivars for their susceptibility to this invasive pathogen (Ganci et al. 2013; Ganci 2014; Shishkoff et al. 2015; Kramer et al. 2020; Yoder 2022). Plant breeding efforts began through growers’ exploration of inherent plant resistance to the BB disease in boxwood cultivars (Fig. 1). While BB resistance breeding remains at its very early stage in the U.S., the evaluation studies of Ganci et al. (2013), Ganci (2014),

Shishkoff et al. (2015), Kramer et al. (2020) demonstrated that different levels of susceptibility to BB exist among boxwood species, varieties and cultivars—although none is immune. These studies made it possible to make informed cultivar selections and shifts during the second 5-year period. This effect is highlighted by the LS shift in the top-ten selling boxwood cultivars between 2016 and 2021. In 2016, only five LS cultivars made it to the top-ten seller list, while by 2021, this number increased to seven in the Virginia nurseries. The same level of LS cultivar increase was seen in the non-Virginia nurseries. Not only was the shift to LS cultivars observed in the cultivar inventory but also in plant sales (Fig. 3 and Fig. 5). These shifts towards LS cultivars are expected to continually increase in the coming years; new research and extension/outreach focused on LS cultivars will further expedite this improvement.

Our results show 17.94 and 31.24% additional sales in LS boxwood plants in 2021 at the non-Virginia and Virginia nursery locations, respectively (Fig. 5) with Virginia nurseries leading the non-Virginia nurseries with 13.30% additional sales of LS cultivars. Early adopters of change are critical to raise awareness in the nursery industry and effect change in the habits of other boxwood growers (Fig. 5 and Fig. 6).

Boxwood cultivars that show less susceptibility to BB in one location may not necessarily be suited for production in another environment, especially because of winter temperature differences and variations in severity of other pests and diseases (Table 3). Further attempts to establish consistent cultivar performance and resistance to BB tailored to specific locations should be explored.

Prevailing weather conditions at different location across the U.S such as cool temperatures have varying effects on *Cps* infection on various cultivars (Weiland et al. 2022). Growers reportedly have taken advantage of this to continue sales of HS cultivars in some states, shipping to regions that are not favorable for boxwood blight in the U.S. (Barker et al. 2022). This practice allows the industry to sell and utilize the HS plants that are already in production, while keeping crop losses at their destinations to the minimum. Nevertheless, these HS crops present significant blight risk to boxwood of all susceptibility types during propagation and later stages of production, as well as in the landscape. Keeping HS plants in production also endangers the nurseries that are currently free of blight, putting them at a higher risk of contamination when they purchase plant material for sale or replanting. National blight management efforts are undermined if HS boxwood



continue to be grown. Thus, growers currently with a large inventory of HS boxwood crops are advised to shift their production to LS cultivars as soon as possible in order to avert the potential for huge crop loss on their own premises and to mitigate the negative impacts on other horticultural businesses and consumers nationally. It should be taken into consideration that boxwood are slow growing plants with a several-year production cycle from propagation to ready-for-sale crops. Accordingly, this highly desirable shift to LS cultivars will be delayed in the marketplace.

Boxwood, like other woody perennial plants, has had limited breeding efforts because of its long-life cycle, which increases the cost of new cultivar development. According to Van Laere et al. (2011), useful sources of variation within *Buxus* have been utilized through selection from wild populations, lucky finds in open-pollinated seedlings, and spontaneous mutations. However, significant accomplishments in disease resistance have been seen in interspecific hybridization between *Buxus sempervirens* and *B. microphylla*, resulting in hybrids like ‘Green Mound’, ‘Green Velvet’, ‘Green Gem’ and ‘Green Mountain’ (Van Laere et al. 2015). Since the blight disease first became prevalent in the U.K., efforts to develop genotypes showing genetic resistance have been ongoing in Europe (Van Laere et al. 2019), some of which have resulted in hybrids collectively marketed as the BetterBoxwood™. BetterBoxwood cultivars, namely Skylight™, Babylon Beauty™, Heritage™, and Renaissance™ are the result of two decades of breeding and reportedly have shown resistant to blight in Europe, making them potential cultivars for evaluation in the U.S. and other areas of the world experiencing the blight menace. It is imperative to make the nursery industry aware of all existing LS cultivars and encourage growers to utilize them to their full potential for sustainable blight mitigation. Because of the limited number of current LS offerings and plant breeding efforts, it remains essential to take an integrated approach to blight mitigation for boxwood.

In summary, U.S. growers are utilizing cultivar selection as an environmentally sound, durable, inexpensive and effective option for combating the invasive boxwood blight disease. The observed inventory shift to the least susceptible cultivars, along with the geographical production shift to blight-free or less affected states (Hall et al. 2021), offers an immediate and long-lasting solution to a devastating global plant disease and gets the U.S. boxwood nursery and landscape industry onto a fast track to sustainability. This shift in ornamental production and gardening strategies, given momentum by trend-setting growers and extension/outreach efforts, sets a new

example of how to address plant biosecurity issues at both state and national scales. It will be important, in preparation for the next disease or pest pandemic on boxwood, that research continues to explore disease and pest resistance traits in the LS cultivars for progressive resistance breeding. Our findings are of direct interest to plant biosecurity and sustainability researchers, horticulturists, conservation biologists, and extension communities as well as growers, marketers, and other professionals in the green landscape industry.

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 603 *Buxus* Cultivars and Selections Against Boxwood Leafminer and Boxwood Blight. *Journal of*  
 604 *Environmental Horticulture* (In Press):16

607 Table 1 Boxwood plant sale quantity and percentage by cultivar in 2011, 2016, and 2021

Cultivar	2011 Boxwood Quantity	% of Total Quantity in 2011	2016 Boxwood Quantity	% of Total Quantity in 2016	2021 Boxwood Quantity	% of Total Quantity in 2021
<i>B. sinica</i> var. <i>insularis</i> 'Uptight'	4,539	0	1,051	0	6	0
B. 'Green Mountain'	189,664	14	155,924	13	193,136	13
B. 'Green Velvet'	272,432	21	284,228	24	254,655	17
B. 'Conrowe'	0	0	169	0	4,278	0
B. 'Glencoe'	12,153	1	13,644	1	18,493	1
B. 'Green Gem'	12,194	1	56,229	5	30,429	2
B. 'Green Ice'	3,649	0	504	0	20	0
B. 'Green Mound'	4,912	0	3,899	0	4,893	0
<i>B. harlandii</i> 'Richard'	0	0	561	0	650	0
<i>B. sinica</i> var. <i>insularis</i> 'Coles Evergreen'	1,251	0	190	0	0	0
<i>B. microphylla</i> 'Grace Hendrick Phillips'	3,048	0	1,366	0	1,155	0
<i>B. microphylla</i> 'Julia Jane'	11,800	1	5,253	0	6,061	0
<i>B. microphylla</i> 'Green Pillow'	1,923	0	1,219	0	34	0
B. 'John Baldwin'	2,757	0	250	0	616	0
<i>B. microphylla</i> 'Little Missy'	0	0	36	0	64,550	4
<i>B. microphylla</i> var. <i>japonica</i> 'Gregem'	0	0	0	0	6,244	0
<i>B. microphylla</i> var. <i>japonica</i> 'Morris Midget'	3,129	0	2,520	0	840	0
<i>B. microphylla</i> var. <i>japonica</i> 'Green Beauty'	85,132	6	59,630	5	76,937	5
<i>B. microphylla</i> var. <i>japonica</i> 'Faulkner'	19,546	1	13,824	1	4,366	0
<i>B. microphylla</i> var. <i>japonica</i> 'Grejade'	0	0	0	0	82	0
<i>B. microphylla</i> var. <i>japonica</i> 'Morris Dwarf'	4,269	0	6,577	1	747	0
<i>B. microphylla</i> var. <i>japonica</i> 'Triumph'	688	0	7,968	1	4,777	0
<i>B. microphylla</i> var. <i>japonica</i> 'Peergold'	815	0	935	0	4,673	0
<i>B. microphylla</i> var. <i>japonica</i> 'Jim Stauffer'	2,069	0	902	0	4,289	0
<i>B. microphylla</i> var. <i>japonica</i> 'MonAlex'	0	0	513	0	9,704	1
<i>B. microphylla</i> var. <i>japonica</i> 'Wedding Ring'	0	0	0	0	21	0
<i>B. microphylla</i> var. <i>japonica</i> 'Winter Gem'	432,210	33	270,151	23	378,304	26
<i>B. sempervirens</i> (American)	6,766	1	10,244	1	6,072	0
<i>B. sempervirens</i> 'Arctic Emerald'	0	0	54	0	896	0
<i>B. sempervirens</i> 'Buddy'	0	0	0	0	1,058	0

B. <i>sempervirens</i> ‘Dee Runk’	10,404	1	8,981	1	13,128	1
B. <i>sempervirens</i> ‘Elegantissima’	6,365	0	3,952	0	1,331	0
B. <i>sempervirens</i> ‘Graham Blandy’	438	0	345	0	60	0
B. <i>sempervirens</i> ‘Inglis’	13,581	1	77	0	0	0
B. <i>sempervirens</i> ‘Jensen’	4,245	0	3,169	0	0	0
B. <i>sempervirens</i> ‘Justin Brouwers’	44,595	3	46,797	4	1,913	0
B. <i>sempervirens</i> ‘Monrue’	30,274	2	23,602	2	56,724	4
B. <i>sempervirens</i> ‘Katerberg’	19	0	22	0	0	0
B. <i>sempervirens</i> ‘Pyramidalis’	145	0	0	0	0	0
B. <i>sempervirens</i> ‘Rotundifolia’	882	0	93	0	0	0
B. <i>sempervirens</i> ‘Suffruticosa’ (English)	72,841	5	108,143	9	14,396	1
B. <i>sempervirens</i> ‘Variegata’	34,527	3	41,868	4	11,647	1
B. <i>sempervirens</i> ‘Decussata’	4	0	0	0	0	0
B. <i>sempervirens</i> ‘DSNH 1216’	0	0	8	0	0	0
B. <i>sempervirens</i> ‘Fastigiata’	4,184	0	2,441	0	1,803	0
B. <i>sempervirens</i> ‘Furore’	361	0	770	0	0	0
B. <i>sempervirens</i> ‘Highlander’	0	0	2,138	0	684	0
B. <i>sempervirens</i> ‘Newport Blue’	630	0	637	0	840	0
B. <i>microphylla</i> var. <i>japonica</i> ‘Unraveled’	500	0	1,345	0	2,253	0
B. <i>sempervirens</i> ‘Vardar Valley’	3,062	0	3,144	0	2,028	0
B. <i>sempervirens</i> ‘Piney Mountain’	0	0	0	0	599	0
B. <i>sinica</i> var. <i>insularis</i> ‘Tide Hill’	2,100	0	2,310	0	1,500	0
B. <i>sinica</i> var. <i>insularis</i> ‘Franklin’s Gem’	5,775	0	14,701	1	22,068	1
B. <i>sinica</i> var. <i>insularis</i> ‘Nana’	5,349	0	6,882	1	8,243	1
B. <i>microphylla</i> var. <i>japonica</i> ‘Bulthouse’	0	0	2,369	0	1,661	0
B. <i>sinica</i> var. <i>insularis</i> ‘Wee Willie’	1,298	0	5,790	0	426	0
B. <i>sinica</i> var. <i>insularis</i> ‘Wintergreen’	10,813	1	10,821	1	33,524	2
B. ‘SB 300’ (NewGen Freedom®)	0	0	0	0	131,526	9
B. ‘SB 108’ (NewGen Independence®)	0	0	0	0	96,142	6
Total	1,327,338	100	1,188,246	100	1,480,482	100

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609

610 Table 2 Boxwood sale quantity and percentage of individual cultivars from the Virginia and non-  
 611 Virginia nurseries in 2021

Cultivar	Susceptibility	Year	Virginia	Non-Virginia	% of Virginia	% of Non-Virginia
<i>B. sempervirens</i> ‘Monrue’	High	2021	0	56689	0.00	5.53
<i>B. microphylla</i> ‘Grace Hendrick Phillips’	High	2021	1155	0	0.25	0.00
<i>B. sempervirens</i> ‘Justin Brouwers’	High	2021	1913	0	0.42	0.00
<i>B. microphylla</i> var. <i>japonica</i> ‘Morris Dwarf’	High	2021	747	0	0.16	0.00
<i>B. sempervirens</i> ‘Variegata’	High	2021	50	11597	0.01	1.13
<i>B. sempervirens</i> ‘American’	High	2021	6072	0	1.33	0.00
<i>B. sempervirens</i> ‘Buddy’	High	2021	1058	0	0.23	0.00
<i>B. sempervirens</i> ‘Dee Runk’	High	2021	13128	0	2.88	0.00
<i>B. sempervirens</i> ‘Elegantissima’	High	2021	1331	0	0.29	0.00
<i>B. sempervirens</i> ‘Graham Blandy’	High	2021	41	19	0.01	0.00
<i>B. sempervirens</i> ‘Piney Mountain’	High	2021	599	0	0.13	0.00
<i>B. sempervirens</i> ‘Suffruticosa’ (English)	High	2021	114	14282	0.02	1.39
<i>B.</i> ‘Green Mountain’	High	2021	54685	138451	11.99	13.52
<i>B.</i> ‘Green Velvet’	High	2021	74621	180034	16.36	17.58
<i>B.</i> ‘Green Gem’	Low	2021	6372	24057	1.40	2.35
<i>B.</i> ‘Green Ice’	Low	2021	0	20	0.00	0.00
<i>B.</i> ‘Green Mound’	Low	2021	4338	555	0.95	0.05
<i>B. harlandii</i> ‘Richard’	Low	2021	650	0	0.14	0.00
<i>B. microphylla</i> ‘Little Missy’	Low	2021	47360	17190	10.38	1.68
<i>B. microphylla</i> var. <i>japonica</i> ‘Gregem’	Low	2021	6244	0	1.37	0.00
<i>B. microphylla</i> var. <i>japonica</i> ‘Green Beauty’	Low	2021	13799	63138	3.03	6.16
<i>B. microphylla</i> var. <i>japonica</i> ‘Peergold’	Low	2021	3014	1659	0.66	0.16
<i>B. microphylla</i> var. <i>japonica</i> ‘Jim Stauffer’	Low	2021	4289	0	0.94	0.00
<i>B. microphylla</i> var. <i>japonica</i> ‘Wedding Ring’	Low	2021	21	0	0.00	0.00
<i>B. microphylla</i> var. <i>japonica</i> ‘Winter Gem’	Low	2021	82331	295973	18.05	28.89
<i>B. sempervirens</i> ‘Fastigiata’	Low	2021	1803	0	0.40	0.00
<i>B. sempervirens</i> ‘Highlander’	Low	2021	585	99	0.13	0.01
<i>B. sempervirens</i> ‘Newport Blue’	Low	2021	840	0	0.18	0.00
<i>B. sinica</i> var. <i>insularis</i> ‘Franklin’s Gem’	Low	2021	12760	9308	2.80	0.91
<i>B. sinica</i> var. <i>insularis</i> ‘Nana’	Low	2021	8243	0	1.81	0.00
<i>B. sinica</i> var. <i>insularis</i> ‘Wee Willie’	Low	2021	0	426	0.00	0.04



<i>B. sinica</i> var. <i>insularis</i> 'Wintergreen'	Low	2021	30580	2944	6.70	0.29
<i>B. sempervirens</i> 'Arctic Emerald'	Low	2021	516	380	0.11	0.04
<i>B. microphylla</i> var. <i>japonica</i> 'Grejade'	Low	2021	82	0	0.02	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Faulkner'	Low	2021	0	4366	0.00	0.43
<i>B. microphylla</i> 'Julia Jane'	Low	2021	0	6061	0.00	0.59
<i>B.</i> 'SB 300' (Freedom®)	Low	2021	38627	92899	8.47	9.07
<i>B.</i> 'SB 108' (Independence®)	Low	2021	27754	68388	6.09	6.68
<i>B. microphylla</i> var. <i>japonica</i> 'MonAlex'	Low	2021	0	9704	0.00	0.95
<i>B. sinica insularis</i> 'Tide Hill'	Low	2021	1500	0	0.33	0.00
<i>B.</i> 'Conrowe'	Moderate	2021	1649	2629	0.36	0.26
<i>B.</i> 'Glencoe'	Moderate	2021	2036	16457	0.45	1.61
<i>B. microphylla</i> 'Green Pillow'	Moderate	2021	34	0	0.01	0.00
<i>B.</i> 'John Baldwin'	Moderate	2021	616	0	0.14	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Morris Midget'	Moderate	2021	840	0	0.18	0.00
<i>B. sempervirens</i> 'Unraveled'	Moderate	2021	0	2253	0.00	0.22
<i>B. sempervirens</i> 'Vardar Valley'	Moderate	2021	2028	0	0.44	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Bulthouse'	Moderate	2021	1661	0	0.36	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Triumph'	Moderate	2021	0	4777	0.00	0.47
<i>B. sinica</i> var. <i>insularis</i> 'Uptight'	Moderate	2021	0	6	0.00	0.00
Total			456086	1024361	100.00	100.00

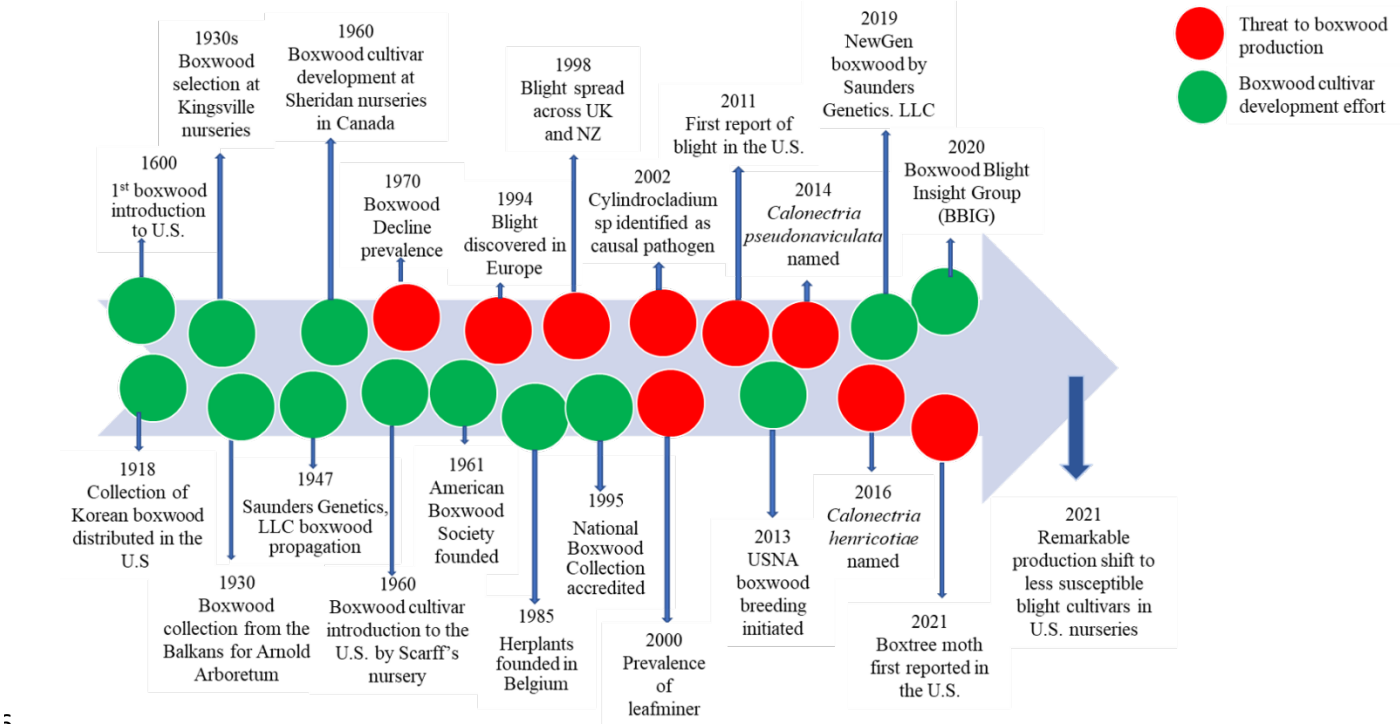
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613 Table 3 Feature highlights of top-ten boxwood cultivars across 17 nurseries from seven states

Cultivar	BB Susceptibility	Origin/Registrar/ Citation	Leaf miner	Growth rate	Form	Landscape	Winter color	Zone
B. 'Franklin's Gem'	Low	Conard-Pyle Company, PA	Resistant	Slow to medium	Low spreading, compact	Yes, low hedge, versatile	Olive- green	4 to 9
B. 'Monrue'	High	Europe, Monrovia, OR	Resistant	Medium to slow	Dense foliage, columnar	Yes, hedge, urban garden	Green	5 to 9
B. 'Variegata'	High	Beal-Garfield Botanic Garden, MI	Susceptible	Slow	Dense foliage, compact	Yes, hedges, holiday decorations	Variegated	5 to 8
B. 'Justin Brouwers'	High	Europe	Susceptible	Slow	Compact, mounding	Versatile; hedge, specimen	Green, need protection from frost	6 to 8
B. 'Green Gem'	Low	Canadian Ornamental Plant Foundation	Susceptible	Slow to medium	Compact, globe shaped	Hedge, foundation plant	Green, but prone to burn	4 to 6
B. 'Green Beauty'	Low	Sheridan Nurseries, Canada	Susceptible	Medium	Rounded	Yes	Yellow to Brown	5 to 7
B. 'Suffruticosa'	High	Europe	Resistant	Slow to medium	Compact shrub	Hedges	bronze in some winters	6 to 8
B. 'Wintergreen'	Low	First selected by Scarff's Nursery, OH	Somewhat resistant	Slow	Globe/semi- globe	Hedge; specimen	Green	5 to 8
B. 'Green Velvet'	High	Sheridan Nurseries, Canada	Susceptible	Medium	Rounded shrub	Yes, specimen plant	Green, but prone to color change	5b to 9

B. ‘Winter Gem’	Low	Various American Nurseries	North	Somewhat resistant	Medium to fast	Dwarf	Yes, hedge at maturity	Green	4 to 9
B. ‘Little Missy’	Low	Conard-Pyle Company, PA		Resistant	Medium to slow	Compact to rounded	Yes	Green	5 to 8
B. SB ‘108’ (Independence®)	Low	Saunders Genetics, VA		Resistant	Medium	medium sized, round	Specimen, hedge, foundation	Green, new growth may show frost burn	5b to 8
B. SB ‘300’ (Freedom®)	Low	Saunders Genetics, VA		Resistant	Medium to fast	Vigorous, rounded, slightly tall	Specimen, hedge,	Green, new growth may show frost burn	5b to 8
B. ‘Green Mountain’	High	Sheridan Nurseries, Canada		Susceptible	Medium to fast	Upright, low foliage density	Specimen, hedge, mass planting	Likely bronze in some winters	5b to 9
B. ‘Glencoe’	Moderate	International Plant Propagators Society		Susceptible	Slow to medium	grows wider than taller	Yes, hedges, specimen	Green, but prone to color change	4 to 8
B. ‘Faulkner’	Low	The New Royal Horticultural Society Dictionary of Gardening		Somewhat resistant	Slow	dwarf, compact	Yes, hedges	Green, likely bronze	5 to 9
B. ‘Dee Runk’	High	The Boxwood Bulletin 28(2);26.1988		Somewhat resistant	Medium to fast	Upright, vertical habit	Yes, hedges, versatile	Green, but prone to color change	6 to 8

5    **List of Figures**



7    Fig. 1 Historical milestones of boxwood production and health threats with focus on the boxwood blight  
3    disease in the U.S.

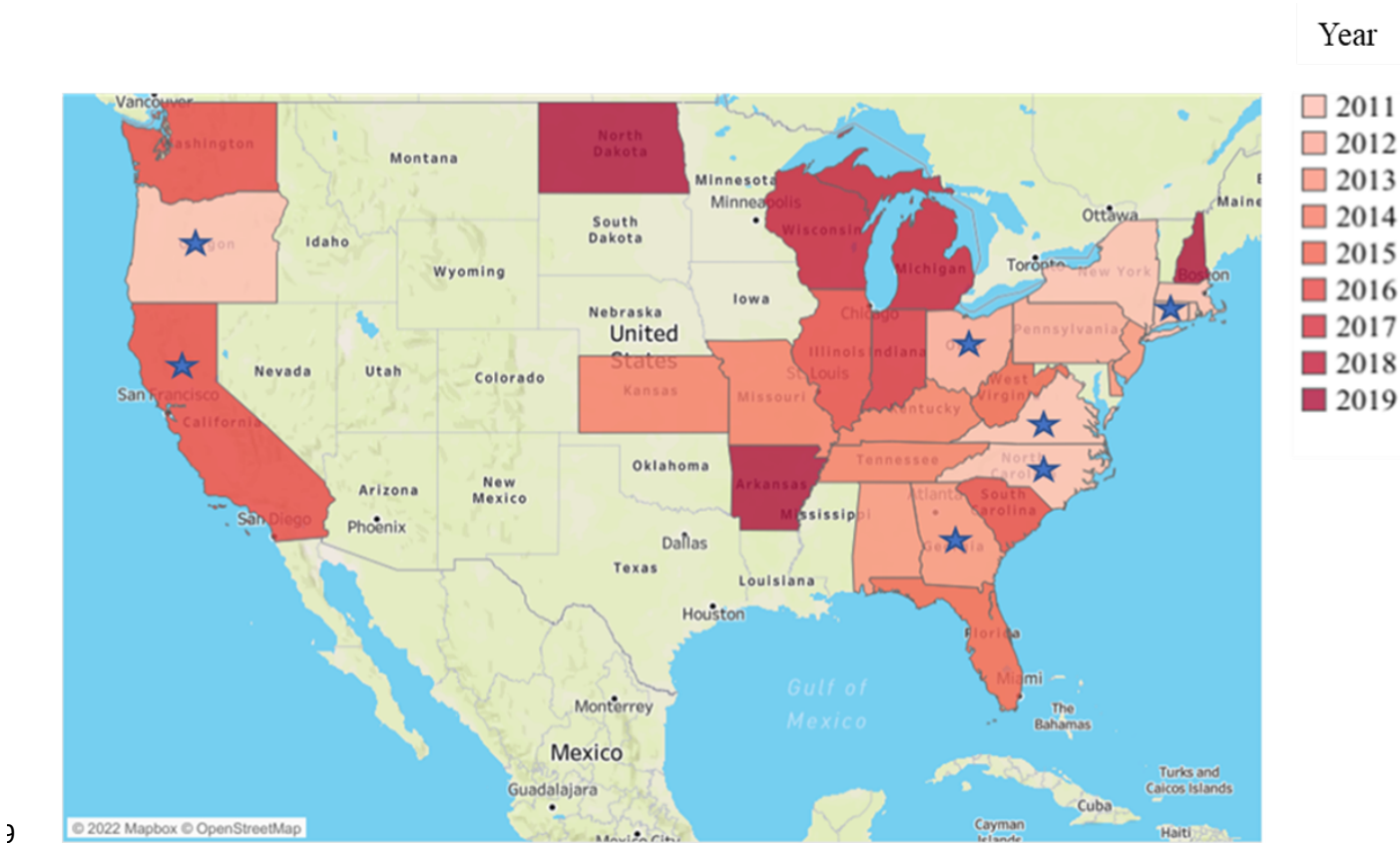
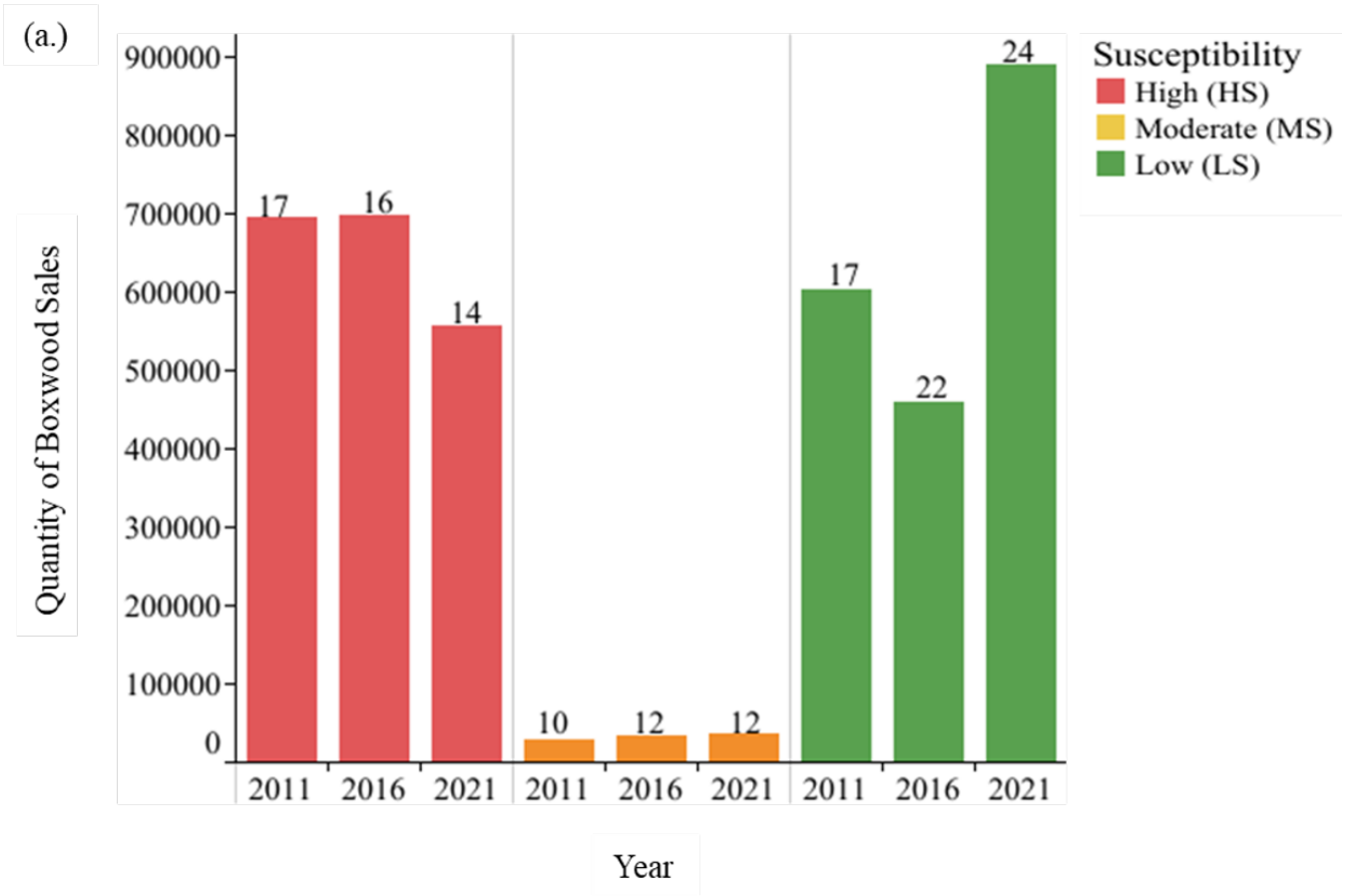
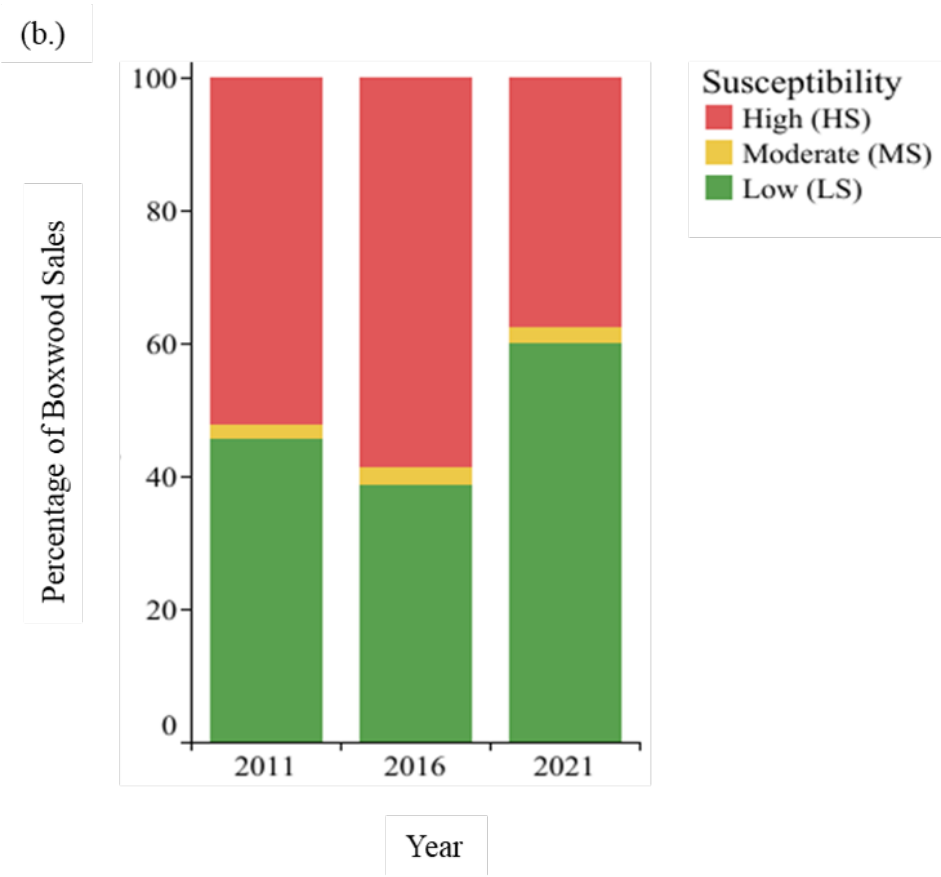


Fig. 2 Map showing the states where nurseries surveyed in this study are situated, color-coded by the year of their first boxwood blight report. Stars on the map indicate the seven boxwood producing states in the U.S. where boxwood sales surveys were conducted.

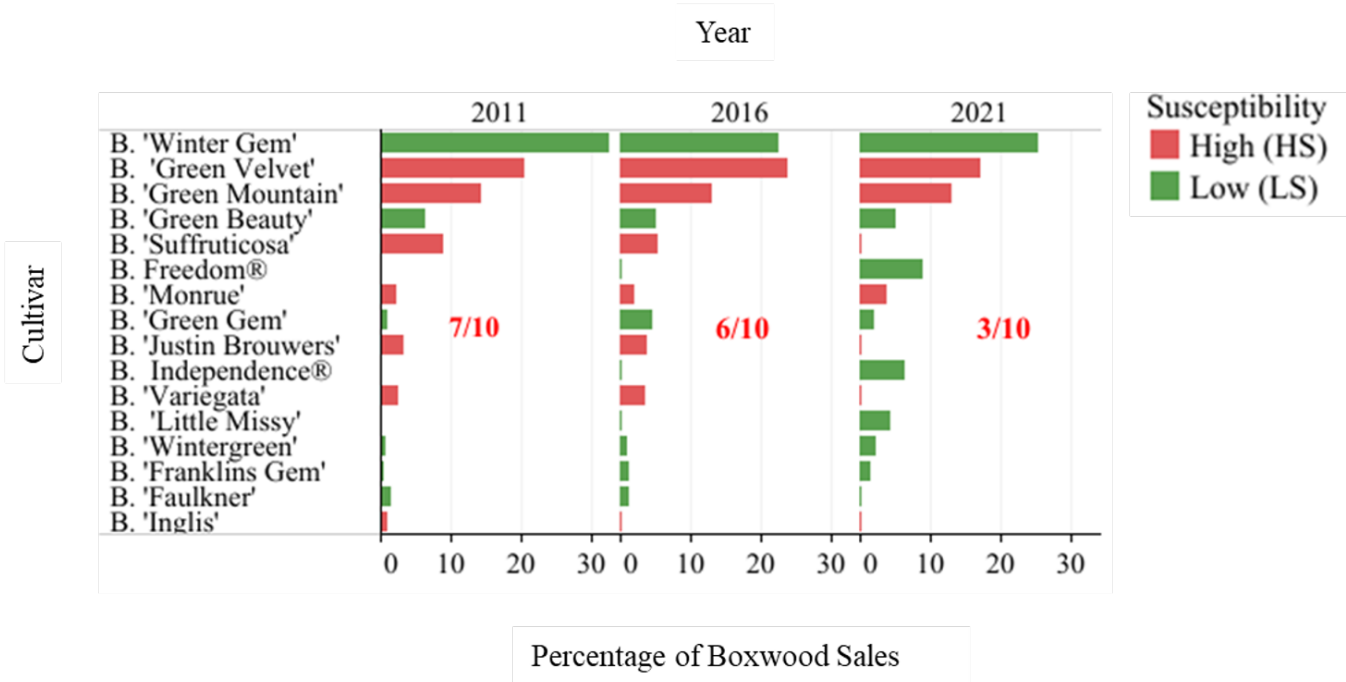


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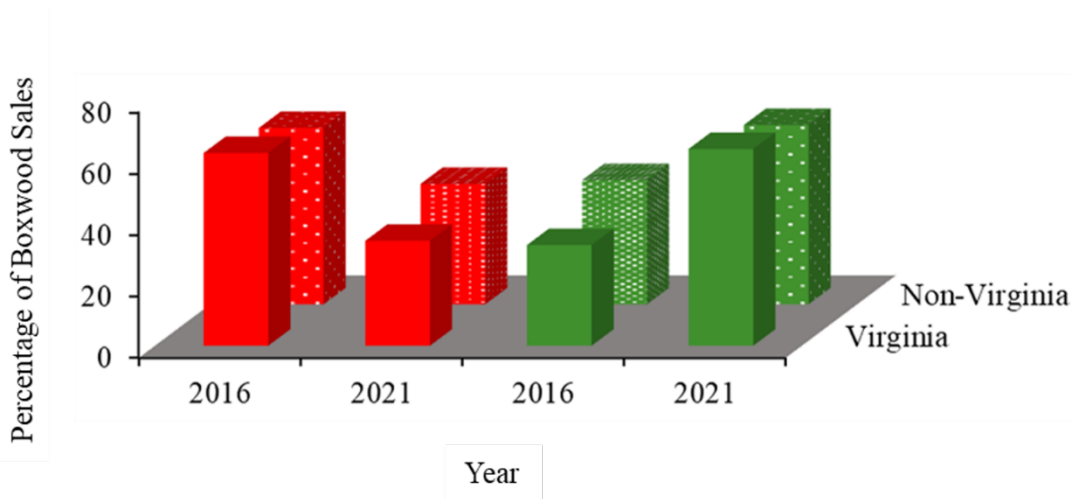
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5 Fig. 3 (a.) Quantity and count of boxwood cultivar sales in each year for the three boxwood blight  
5 susceptibility categories. Counts of cultivars in each of the susceptibility categories are on top of each  
7 bar. (b.) Percentage of highly, moderately and least susceptible boxwood plants sold from seventeen  
3 surveyed nurseries in 2011, 2016, and 2021.



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Fig. 4 Top ten cultivars shipped from seventeen surveyed nurseries in 2011, 2016 and 2021. Each bar represents the total quantity of boxwood plants sold, topped by a percentage of the total boxwood quantity it represents for each year. The fraction in red represents fraction of HS cultivars (of the top ten cultivars) for each year with the highest (7/10) in 2011 and the lowest (3/10) in 2021.



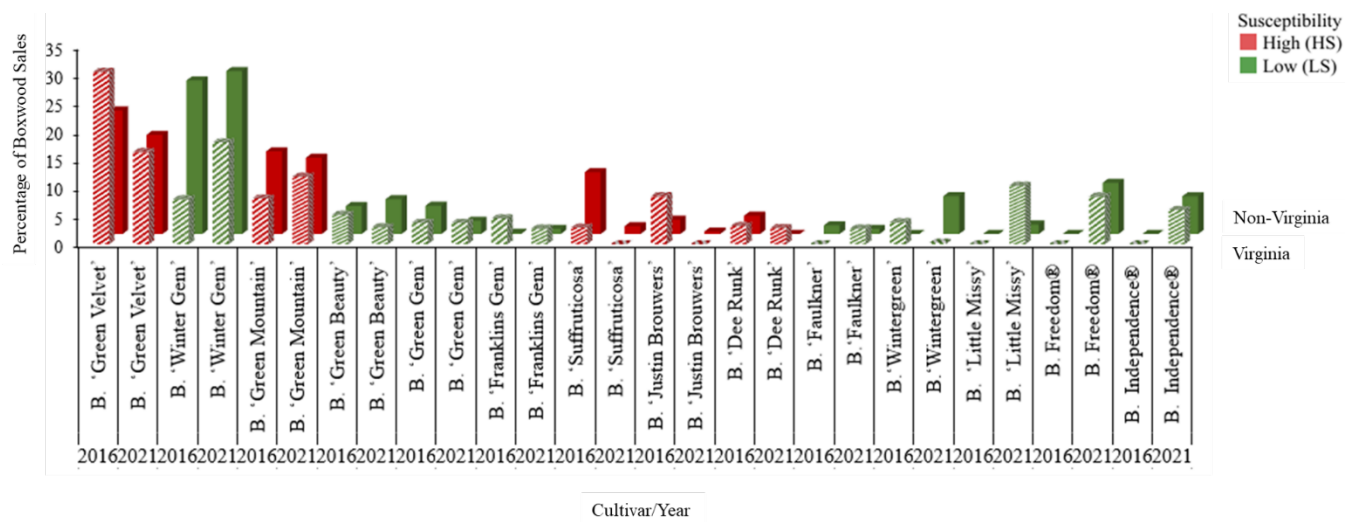
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Fig. 5 Shift of boxwood sales from boxwood blight HS in 2016 to LS cultivars in 2021 in Virginia and non-Virginia nurseries.

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Fig. 6 Shift of boxwood sales from highly susceptible to boxwood blight in 2016 to less susceptible cultivars in 2021 as illustrated by the top ten cultivars sold in all nurseries surveyed. Each bar represents the percentage of the total quantity of boxwood plants sold.



1    Supplementary Table 1 Nurseries, boxwood plant sizes and data types included in the study

Location	# of Nurseries	Data Type	Size/Type of Container
Virginia	#1	Quantity on hand	1G, 3G, 5G, 15G, QT, Liner,
	#2	Quantity sold	1G, 3G, 5G, 15G
	#3	Quantity sold	Cuttings
	#4	Production	
	#5	Quantity sold	
	#6	Quantity sold	3G, 5G, 7G, 10G, 15G,
	#7	Boxwood sales	
	#8	Sales	1L, 3G, 5G, 7G, 15G, 18", 15", 18", 21", 24", 30"
	#9	Production	3G, 5G, 7G, Tray, Field, 3.5"
Oregon	#1	Sales/shipped from Nursery	1G, 2G, 3G, 5G, 7G, 10G, 15G, QT,
	#2	Inventory of container grown	1G, 2G, 3G, 5G, 7G, 15G
Ohio	#1	Sales	1G, 2G, 2.5" Liner, 3G, 4" Liner, 5G, 7G, 18/24" Spread Shrub, 24/30" Liner
Georgia	#1	Sales/shipped from Nursery	1G, 2G, 3G, 5G, 10G, QT,
California	#1	Sales/shipped from Nursery	1G, 2G, 5G, 7G, 10G, 15G
Connecticut	#1	Sales/shipped from Nursery	1G, 2G, 3G, 5G
North Carolina	#1	Sales/shipped from Nursery	2G, 3G, 15G

2    G= Gallon, QT= Quart, L= Liter

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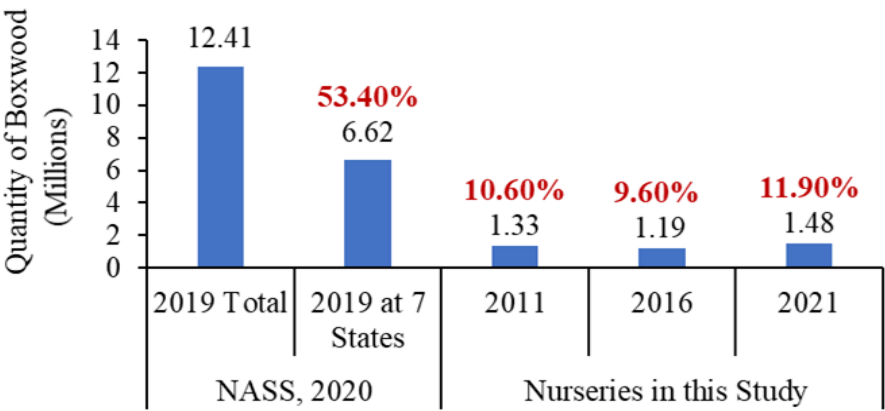
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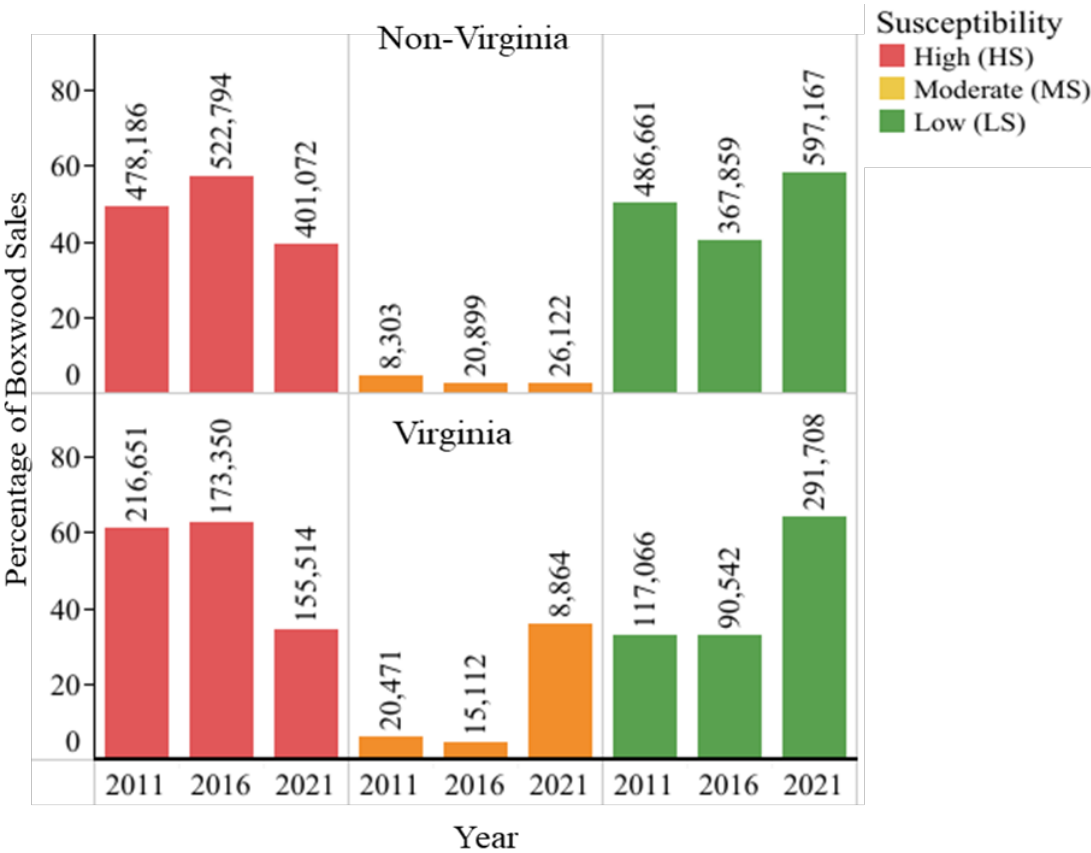
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Supplementary Fig. 1 National representation of boxwood sales in states and supporting nurseries included in this study. Production in the seven states surveyed accounted for 53% of national production in 2019 while that of selected nurseries in this study equaling to 10 to 12% of 2019 national production.



Supplementary Fig. 2 Shift of boxwood sales from highly susceptible (HS) in 2011 and 2016 to less susceptible (LS) cultivars in 2021 in non-Virginia (top) and Virginia (bottom) nurseries. On top of each bar is the total number of boxwood plants sold in all surveyed nurseries for each susceptibility category.

21 Supplementary Table 2 Quantity and percentage of each cultivar in Virginia and Non-Virginia  
 22 nursery categories in 2011

Cultivar	Susceptibility	Year	Virginia	Non-Virginia	% of Virginia Total	% of Non-Virginia Total
<i>B. sempervirens</i> 'Monrue'	High	2011	0	30274	0.00	3.11
<i>B. microphylla</i> var. <i>japonica</i> 'Grace Hendrick Phillips'	High	2011	3048	0	0.86	0.00
<i>B. sempervirens</i> 'Justin Brouwers'	High	2011	31449	13146	8.88	1.35
<i>B. microphylla</i> var. <i>japonica</i> 'Morris Dwarf'	High	2011	4269	0	1.21	0.00
<i>B. sempervirens</i> 'Variegata'	High	2011	0	34527	0.00	3.55
<i>B. sempervirens</i> 'Furore'	High	2011	0	361	0.00	0.04
<i>B. sempervirens</i> 'Inglis'	High	2011	0	13581	0.00	1.40
<i>B. sempervirens</i> 'American'	High	2011	6766	0	1.91	0.00
<i>B. sempervirens</i> 'Dee Runk'	High	2011	10404	0	2.94	0.00
<i>B. sempervirens</i> 'Elegantissima'	High	2011	6365	0	1.80	0.00
<i>B. sempervirens</i> 'Graham Blandy'	High	2011	438	0	0.12	0.00
<i>B. sempervirens</i> 'Jensen'	High	2011	4245	0	1.20	0.00
<i>B. sempervirens</i> 'Pyramidalis'	High	2011	0	145	0.00	0.01
<i>B. sempervirens</i> 'Rotundifolia'	High	2011	882	0	0.25	0.00
<i>B. sempervirens</i> 'Suffruticosa'	High	2011	19314	53527	5.45	5.50
<i>B. 'Green Mountain'</i>	High	2011	45154	144510	12.75	14.85
<i>B. 'Green Velvet'</i>	High	2011	84317	188115	23.81	19.33
<i>B. 'Green Gem'</i>	Low	2011	4677	7517	1.32	0.77
<i>B. 'Green Ice'</i>	Low	2011	2703	946	0.76	0.10
<i>B. 'Green Mound'</i>	Low	2011	4912	0	1.39	0.00
<i>B. harlandii</i> 'Richard'	Low	2011	0	0	0.00	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Little Missy'	Low	2011	0	0	0.00	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Green Beauty'	Low	2011	7577	77555	2.14	7.97
<i>B. microphylla</i> var. <i>japonica</i> 'Peergold'	Low	2011	815	0	0.23	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Jim Stauffer'	Low	2011	2069	0	0.58	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Winter Gem'	Low	2011	65854	366356	18.59	37.65

<i>B. sempervirens</i> 'Fastigiata'	Low	2011	4184	0	1.18	0.00
<i>B. sempervirens</i> 'Newport Blue'	Low	2011	630	0	0.18	0.00
<i>B. sinica</i> var. <i>insularis</i> 'Franklin's Gem'	Low	2011	4496	1279	1.27	0.13
<i>B. sinica</i> var. <i>insularis</i> 'Nana'	Low	2011	5349	0	1.51	0.00
<i>B. sinica</i> var. <i>insularis</i> 'Wee Willie'	Low	2011	0	1298	0.00	0.13
<i>B. sinica</i> var. <i>insularis</i> 'Wintergreen'	Low	2011	10438	375	2.95	0.04
<i>B. sinica</i> var. <i>insularis</i> 'Coles Evergreen'	Low	2011	1251	0	0.35	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Faulkner'	Low	2011	0	19546	0.00	2.01
<i>B. microphylla</i> 'Julia Jane'	Low	2011	11	11789	0.00	1.21
<i>B.</i> 'SB 300' (NewGen Freedom®)	Low	2011	0	0	0.00	0.00
<i>B.</i> 'SB 108' (NewGen Independence®)	Low	2011	0	0	0.00	0.00
<i>B. sinica insularis</i> 'Tide Hill'	Low	2011	2100	0	0.59	0.00
<i>B.</i> 'Glencoe'	Moderate	2011	6605	5548	1.86	0.57
<i>B. microphylla</i> 'Green Pillow'	Moderate	2011	1923	0	0.54	0.00
<i>B. microphylla</i> 'John Baldwin'	Moderate	2011	690	2067	0.19	0.21
<i>B. microphylla</i> v. <i>japonica</i> 'Morris Midget'	Moderate	2011	3129	0	0.88	0.00
<i>B. sempervirens</i> 'Decussata'	Moderate	2011	4	0	0.00	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Unraveled'	Moderate	2011	500	0	0.14	0.00
<i>B. sempervirens</i> 'Vardar Valley'	Moderate	2011	3062	0	0.86	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Triumph'	Moderate	2011	0	688	0.00	0.07
<i>B. sempervirens</i> 'Katerberg'	Moderate	2011	19	0	0.01	0.00
<i>B. sinica</i> var. <i>insularis</i> 'Uptight'	Moderate	2011	4539	0	1.28	0.00
Total			354188	973150	100.00	100.00

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25 Supplementary Table 3 Quantity and percentage of each cultivar in Virginia and Non-Virginia  
 26 nursery categories in 2016

Cultivar	Susceptibility	Year	Virginia	Non-Virginia	% of Virginia Total	% of Non-Virginia Total
<i>B. sempervirens</i> 'Monrue'	High	2016	4	23598	0.00	2.59
<i>B. microphylla</i> var. <i>japonica</i> 'Grace Hendrick Phillips'	High	2016	1366	0	0.49	0.00
<i>B. sempervirens</i> 'Justin Brouwers'	High	2016	23590	23207	8.53	2.55
<i>B. microphylla</i> var. <i>japonica</i> 'Morris Dwarf'	High	2016	6577	0	2.38	0.00
<i>B. sempervirens</i> 'Variegata'	High	2016	15	41853	0.01	4.59
<i>B. sempervirens</i> 'Furore'	High	2016	0	770	0.00	0.08
<i>B. sempervirens</i> 'Inglis'	High	2016	0	77	0.00	0.01
<i>B. sempervirens</i> 'American'	High	2016	10244	0	3.70	0.00
<i>B. sempervirens</i> 'Dee Runk'	High	2016	8981	0	3.25	0.00
<i>B. sempervirens</i> 'Elegantissima'	High	2016	3952	0	1.43	0.00
<i>B. sempervirens</i> 'Graham Blandy'	High	2016	80	265	0.03	0.03
<i>B. sempervirens</i> 'Jensen'	High	2016	3169	0	1.15	0.00
<i>B. sempervirens</i> 'Rotundifolia'	High	2016	93	0	0.03	0.00
<i>B. sempervirens</i> 'Suffruticosa'	High	2016	8191	99952	2.96	10.97
<i>B. sempervirens</i> 'DSNH 1216'	High	2016	8	0	0.00	0.00
<i>B.</i> 'Green Mountain'	High	2016	22492	133432	8.13	14.64
<i>B.</i> 'Green Velvet'	High	2016	84588	199640	30.57	21.90
<i>B.</i> 'Green Gem'	Low	2016	10563	45666	3.82	5.01
<i>B.</i> 'Green Ice'	Low	2016	504	0	0.18	0.00
<i>B.</i> 'Green Mound'	Low	2016	2989	910	1.08	0.10
<i>B. harlandii</i> 'Richard'	Low	2016	561	0	0.20	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Little Missy'	Low	2016	0	36	0.00	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Green Beauty'	Low	2016	14547	45083	5.26	4.95
<i>B. microphylla</i> var. <i>japonica</i> 'Peergold'	Low	2016	314	621	0.11	0.07
<i>B. microphylla</i> var. <i>japonica</i> 'Jim Stauffer'	Low	2016	902	0	0.33	0.00
<i>B. microphylla</i> var. <i>japonica</i> 'Winter Gem'	Low	2016	22058	248093	7.97	27.22
<i>B. sempervirens</i> 'Fastigiata'	Low	2016	2441	0	0.88	0.00
<i>B. sempervirens</i> 'Highlander'	Low	2016	2138	0	0.77	0.00

<i>B. sempervirens</i> ‘Newport Blue’	Low	2016	637	0	0.23	0.00
<i>B. sinica</i> var. <i>insularis</i> ‘Franklin’s Gem’	Low	2016	12685	2016	4.58	0.22
<i>B. sinica</i> var. <i>insularis</i> ‘Nana’	Low	2016	6882	0	2.49	0.00
<i>B. sinica</i> var. <i>insularis</i> ‘Wee Willie’	Low	2016	0	5790	0.00	0.64
<i>B. sinica</i> var. <i>insularis</i> ‘Wintergreen’	Low	2016	10821	0	3.91	0.00
<i>B. sempervirens</i> ‘Arctic Emerald’	Low	2016	0	54	0.00	0.01
<i>B. sinica</i> var. <i>insularis</i> ‘Coles Evergreen’	Low	2016	190	0	0.07	0.00
<i>B. microphylla</i> var. <i>japonica</i> ‘Faulkner’	Low	2016	0	13824	0.00	1.52
<i>B. microphylla</i> var. <i>japonica</i> ‘Julia Jane’	Low	2016	0	5253	0.00	0.58
<i>B.</i> ‘SB 300’ (Freedom®)	Low	2016	0	0	0.00	0.00
<i>B.</i> ‘SB 108’ (Independence®)	Low	2016	0	0	0.00	0.00
<i>B. microphylla</i> var. <i>japonica</i> ‘MonAlex’	Low	2016	0	513	0.00	0.06
<i>B. sinica</i> var. <i>insularis</i> ‘Tide Hill’	Low	2016	2310	0	0.83	0.00
<i>B.</i> ‘Conrowe’	Moderate	2016	169	0	0.06	0.00
<i>B.</i> ‘Glencoe’	Moderate	2016	5517	8127	1.99	0.89
<i>B. microphylla</i> var. <i>japonica</i> ‘Green Pillow’	Moderate	2016	1219	0	0.44	0.00
<i>B.</i> ‘John Baldwin’	Moderate	2016	250	0	0.09	0.00
<i>B. microphylla</i> var. <i>japonica</i> ‘Morris Midget’	Moderate	2016	2460	60	0.89	0.01
<i>B. microphylla</i> var. <i>japonica</i> ‘Unraveled’	Moderate	2016	0	1345	0.00	0.15
<i>B. sempervirens</i> ‘Vardar Valley’	Moderate	2016	3144	0	1.14	0.00
<i>B. microphylla</i> var. <i>japonica</i> ‘Bulthouse’	Moderate	2016	40	2329	0.01	0.26
<i>B. microphylla</i> var. <i>japonica</i> ‘Triumph’	Moderate	2016	0	7968	0.00	0.87
<i>B. sempervirens</i> ‘Katerberg’	Moderate	2016	3	19	0.00	0.00
<i>B. sinica</i> var. <i>insularis</i> ‘Uptight’	Moderate	2016	0	1051	0.00	0.12
Total			276694	911552	100.00	100.00

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