Key Pests and IPM Research and Extension Priorities for Urban Trees in the Eastern US

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Objective: Our goal is to identify key pests of urban trees and to document research and extension priorities that will improve IPM of urban trees.

Workshop and survey details: This discussion was initiated at the National Ornamental Workshop held biennially in Hendersonville, North Carolina. The discussion was attended by about 40 people in research or extension positions at land grant universities, county or area extension agents, tree care company representatives, and representatives from agricultural chemical companies. Key points of the discussion were compiled into a draft of this document by SDF.

The survey was prepared by SDF. The goal was to rank the importance of broad arthropod guilds as pests of ten most common genera of urban trees. Tree genera were derived from tree inventories of five Southeastern cities. The draft document and survey was shared with original members of the discussion and others involved in urban tree research, extension, or tree care industry. Contributor comments and survey responses were compiled by SDF into a final draft which was shared then shared with contributors for additional comments before submission to SIPM.

Scope: This is the first attempt in many years to rank pest species and set research and extension priorities for street trees. We consider it a preliminary assessment that is valuable in and of itself but also had the goal of establishing collaboration and informing a more extensive assessment in the future. As such, the scope of this survey and recommendations are limited to IPM for arthropod pests of street trees. It focuses on the southeastern US but includes contributors and data from northeastern and north central regions. We recognize the importance of IPM for plant pathogens of street trees which is also understudied. We also recognize the importance of improving horticultural practices for how they affect street tree health directly and indirectly by exacerbating arthropod and pathogen pests. However, these topics are beyond the scope of this initial effort and we hope to include them in a future document.

Status of IPM and Needs Assessment for Urban Trees

Value. Urban trees provide many ecological and societal benefits including stormwater management, air pollution reduction, support for biodiversity, carbon sequestration, and improving human health and well-being. The monetary value of these benefits can be calculated for individual trees with the USDA FS iTree products. For example, a red maple that is 30 cm diameter at breast height (DBH) in Raleigh, NC provides benefits of approximately $82 per year that can be separated into reducing stormwater ($23.09), increasing property value ($43.84), reducing electricity consumption ($6.05), reducing natural gas consumption ($3.36), improving air quality ($3.58), and sequestering carbon and reducing carbon emissions ($2.47) (http://www.treebenefits.com/calculator/). Several reviews assess the ecological and societal value of urban trees[1,2]. Less research has assessed the cost of urban tree maintenance and pest management in particular[3].

Need for IPM priorities. Integrated pest management for urban trees has been studied for decades[4]. Yet, key IPM components developed for agricultural systems, such as standard scouting and monitoring practices, decision making criteria, and cultural management tactics, are not well developed for urban trees [5-8]. A major difference between IPM for urban trees compared to agricultural crops is the diversity of plant and pest species and the complexities of the landscape. For example, cities may have dozens of street tree genera and hundreds of species[9]. Each tree species has a suite of specialist and generalist arthropod pests[5,10]. Therefore, even if each species has just one to three key pests [11] the number of pests for which monitoring tools (e.g. degree day models, traps) and decision making tools (e.g. economic injury or action thresholds) needed is immense.

Another important difference between developing IPM for urban trees, or landscape plants in general, and for agricultural crops is research capacity. Ornamental plants and plant systems are excluded from some USDA grant programs. In addition, financial and informational support for urban tree research from sources such as industry groups and foundations is limited compared to agricultural crops. State agricultural commissions or national organizations (e.g. Cotton Incorporated) help calculate yield and other economic indicators for agricultural commodities that can be used when applying for federal grants. In many cases, these industry groups also provide substantial funding for research and extension programs. Straight-forward yield and other economic indicators are difficult to calculate for urban trees and financial support from industry is small. The clientele that benefits from the 'yield' of urban tree air quality, cooling, and other services (the public) has limited corporate voice, organization, and understanding relative to urban trees' value and services. There are also less researchers at universities, government agencies, or corporations conducting research on urban trees than agricultural crops. Thus more plant and pest species get the attention of fewer research and extension faculty. Adding to these challenges is the inherently long time-frame required for comprehensive tree research. Trees live for decades. Evaluating the long-term consequences of pests and abiotic concerns requires a large investment of time and space.

There have been several attempts to assess the importance of arthropod pest species of urban trees based on prevalence, economic cost, and pesticide use[10,12-14]. Among the most comprehensive included surveys of urban foresters and tree care professionals by Frankie[12] and Wu[13]. Other work focused on landscape plants generally, including trees[15,16]. Likewise, the USDA IR-4 program has conducted recent surveys of green industry professionals that include 'Landscape' as a production site category but do not provide data specific to urban trees[17].

There are not many previous assessments of IPM tactics and priorities especially in the past 10 years. A review of forest pest monitoring tactics found "..a substantial lack of publications on shade tree insects…" with 92% of papers related to forests rather than urban or shade trees[8]. Significant work was conducted in the 1990's to develop and document urban tree and landscape IPM[6,11,15,18-20]. Particularly rigorous IPM programs were developed for some pests including elm leaf beetles, tulip tree aphids, and orangestriped oakworms that included monitoring, decision making criteria, and management tactics[21-24]. The amount of research that went into developing IPM for these three pests documents the extraordinary task of developing IPM for the multitude of important urban tree pests.

In the past 10 years, considerable work and great progress has been made on emerald ash borer, *Agrilus planipennis*, IPM[25]. Less work has focused on chronic pest species that comprise the bulk of arthropod pests on most species of trees. **The diversity of urban tree species and their arthropod pests combined with less research capacity than other crops necessitates development of research priorities to improve IPM for the most common or damaging pests or those that require the most insecticide applications.** It is also essential to identify extension priorities to deliver existing IPM knowledge and new knowledge as it accrues.

Description of arthropod pest guilds and damage

Previous pest assessments have used many different taxonomic groups and ranking systems. Some simply asked respondents to list pests. We created 6 broad pest categories for this survey, based on feeding guild and damage caused. Respondents completed two tables in the survey. The first had a row for each of the ten tree genera and a column for each pest category. Respondents recorded a value of 3 (very common/damaging), 2 (moderate), 1 (rare/ not very damaging), or 0 (not a pest) in each cell of the first table based on their expertise and experience in research, extension, or industry. We calculated a mean for each tree/pest combination recorded by southern and northern respondents(Tables 1, 3).

Respondents completed a second table in which, for each tree genus, they were asked to list the most important pest species in the pest category they considered most important. These data are presented as the pest category with the highest mean in Tables 1 and 3 followed by the pest species in that category and pest species listed by respondents who considered other pest categories most important (Tables 2, 4).

Sucking insects on bark. This category primarily includes scale insect species. Pests in this category feed on fluid in vascular or parenchyma cells and damage trees by reducing the energy available for growth and storage. Infested trees may have slow growth, sparse canopies, and dead branches[26]. Some bark-sucking insects feed on phloem and create the damage and problems associated with honeydew described below.

Sucking insects on leaves. Important pests in this category include phloem-feeding scales, aphids, whiteflies, and lace bugs. Phloem feeders damage trees trees by removing carbon and nutrients needed for growth and storage and can reduce photosynthesis and other leaf processes[26]. This reduces tree growth and can cause leaf-loss, branch death, and reduce growth[27,28]. Phloem feeding can also change leaf appearance causing yellowing or in the case of lace bugs, fine stippling that reduces the aesthetic quality of plants. Phloem feeders excrete a sticky sugar-based solution called honeydew that coats leaves, cars, sidewalks, and other surfaces[29]. This creates a nuisance and homeowner complaints.

Defoliators and leafminers. Leaf-feeding caterpillars are important pests of some tree species. They can defoliate susceptible species and repeated defoliation can reduce tree growth and survival[30,31]. Even partial defoliation can reduce tree growth and beauty and provoke citizen complaints[32]. Caterpillar frass can be a nuisance accumulating on sidewalks, decks, cars, and other surfaces causing homeowner complaints[32]. Many of these species also wander in search of pupation sites, accumulating in sheltered locations such as window sills, soffits, patio door runners and decks, prompting additional complaints. Since many lepidopteran species have outbreak cycles they may not be important every year.

Leaf-feeding beetles eat tree leaves as larvae, adults, or both depending on species. Coleopteran defoliators, like Japanese beetles, willow leaf beetles, and elm leaf beetles, can be severe pests on certain tree species[33]. As with caterpillars, defoliation reduces tree growth and beauty[31]. Sawflies can be important defoliators, primarily of evergreen tree species, that reduce tree growth, survival, and aesthetic quality[31,34].

Leaf and stem gall forming arthropods. Certain wasps, aphids, adelgids, and mites produce galls on the leaves and stems many urban tree species. Galls, such as horned oak gall, become important pests in some situations[33,35-37]. Galls can reduce branch elongation, leaf expansion, tree growth, and aesthetic quality of trees[38,39]. The complex biology of many gallers complicates research and development of IPM tactics.

Trunk and twig borers and bark beetles. Important trunk boring insects are primarily beetles and lepidopterans. Borers are often difficult to control and the consequences of borer attacks can be rapid and severe. Recent invasive species of borers include emerald ash borer, Asian longhorned borer, and walnut twig beetle. Other borer pests include Scolytine beetles such as southern pine beetle and ambrosia beetles, longhorn beetles (Cerambycidae), and flatheaded borers (Buprestidae) such as flat-headed apple tree borer and bronze birch borer. Important lepidopteran borers primarily include several species of clearwing borers such as the greater and lesser peachtree borers, dogwood borers lilac ash borer, dogwood borer, and rhododendron borers[33].

Mites. Spider mites can be important pests of some urban tree species. Although spider mites typically suck fluid from leaves we made them a separate category due to differences in management compared to leaf feeding insect pests. Spider mite abundance tends to erupt in response environmental conditions such as heat, drought, or dust[40-44] or in response to anthropogenic inputs such as insecticides [45], fertilizer[46], or road salts[47]. Thus, they are often innocuous until some environmental conditions or level of disturbance is met. Spider mites damage trees by removing the contents of leaf cells and in severe cases causing leaf abscission which reduce photosynthetic capacity and plant growth[48-50]. Broad mites can disfigure trees, particularly when in the seedling and sapling stages.

Ranking pest importance on common tree taxa. In this section contributors added values from 0-3 in each cell of the tables to indicate the importance based on frequency or severity of infestations or damage or the need for insecticide applications.

Table 1. Common tree genera and ranking of pest guilds or damage types in the southeastern US. 3 = very common/damaging, 2 = moderate, 1 = rare/ not very damaging, 0 = non-issue. Values are means of responses followed by the number of times the category was ranked by respondents as 3.

Genus	Bark suckers (scales)	Leaf suckers (aphids, lacebugs, scales)	Defoliators (Lepidopterans,Coleopterans, sawflies)	Leaf and stem gallers	Borers and bark beetles	Mites
Acer (n=15)	2.67 (11)	1.67 (1)	1.38 (1)	0.73 (1)	1.33 (1)	1.31 (0)
Fraxinus (n=14)	0.50 (0)	0.71 (0)	0.57 (0)	0.86 (1)	2.57 (12)	0.69 (0)
Lagerstroemia (n=15)	1.47 (4)	1.87 (3)	0.73 (1)	0.07 (0)	0.67 (1)	0.15 (0)
Liquidambar (n=15)	0.33 (0)	0.53 (0)	0.73 (1)	0.20 (0)	0.60 (0)	0.31 (0)
Liriodendron (n=15)	1.33 (2)	2.07 (6)	0.87 (0)	0.27 (0)	0.73 (1)	0.31 (0)
Pinus (n=15)	0.87 (0)	1.20 (0)	1.40 (2)	0.27 (0)	2.13 (7)	0.67 (0)
Platanus (n=15)	0.13 (0)	1.73 (4)	0.73 (0)	0.13 (0)	0.47 (0)	0.77 (0)
Prunus (n=15)	1.07 (3)	1.13 (1)	2.27 (6)	0.33 (0)	1.87 (6)	0.62 (0)
Pyrus (n=15)	0.40 (0)	0.53 (0)	0.73 (0)	0.27 (0)	0.67 (0)	0.46 (0)
Quercus (n=15)	1.73 (5)	1.93 (5)	2.07 (5)	2.06 (4)	1.53 (2)	1.23 (1)
Ulmus (n=15)	0.87 (1)	1.13 (1)	1.40 (1)	0.67 (0)	1.20 (2)	0.58 (0)
Zelkova (n=15)	0.53 (0)	0.33 (0)	0.40 (0)	0.13 (0)	0.53 (0)	0.07 (0)

TABLE 2. Top pest categories for each genus and key pest species within those categories. Top pest category reflects the category with the highest value in Table 1. If equal values appeared in Table 1, both pest categories and associated species are presented. The most commonly identified pest species appears first followed by the number of times it was listed in parentheses. Important pests listed by respondents who selected a different top category are listed in the final column.

Genus	Top pest group	Species in top category	Species listed as important from other categories
Acer	Bark suckers	Armored scales: Gloomy scale, *Melanaspis tenebricosa* (7); Japanese maple scale, *Lopholeucaspis japonica*; Obscure scale, *Melanaspis obscura;* White peach scale, *Pseudaulacaspis pentagon*; Oyster shell scale, *Lepidosaphes ulmi*; Soft scales: Cottony maple scale, *Pulvinaria innumerabilis*; Cottony maple leaf scale, *Pulvinaria acericola;* Terrapin scale*, Lecanium nigrofasciatum*; Calico scale, *Eulecanium cerasorum; Lecanium*	Flatheaded appletree borer, *Chrysobothris femorata*; Japanese beetles, *Popillia japonica*; green-striped mapleworm, *Dryocampa rubicunda*; spring cankerworm, *Paleacrata vernata*; fall cankerworm, *Alsophila pometaria*; ambrosia beetles;

		spp.	
Fraxinus	Borers	Emerald ash borer, *Agrilus planipennis* (9); clearwing borers, *Podosesia* spp.	
Lagerstroemia	Leaf suckers	Crape myrtle aphid, *Tinocallis kahawaluokalani* (8);	Crape myrtle bark scale, *Acanthococcus lagerstroemiae*; Japanese beetle, *Popillia japonica*; ambrosia beetles; Sri Lanka weevil, *Myllocerus undecimpustulatus undatus*
Liquidambar	Defoliators	Fall webworms, *Hyphantria cunea* (3);	Camphor shot borer, *Cnestus mutilatus*; ambrosia beetles
Liriodendron	Leaf suckers	Tulip tree aphid, *Illinoia liriodendri* (9);	Tulip tree scale, *Toumeyella liriodendri*; Yellow poplar weevil, *Odontopus calceatus*; root collar borer, *Euzophera ostricolorella*; American plum borer, *Euzophera semifuneralis*
Pinus	Borers	Bark beetles (8); Southern pine beetle, *Dendroctonus frontalis*; Black turpentine beetle, *Dendroctonus terebrans*; *Ips* spp.	Pine needle scale, *Chionaspis pinifoliae*; Nantucket pine tip moth, *Rhyacionia frustrana*; Redheaded pine sawfly, *Neodiprion lecontei*; Pine bark adelgid, *Pineus strobi*; Pine sawyer, *Monochamus scutellatus*; Longhorned beetles
Platanus	Leaf suckers	Sycamore lace bug, *Corythucha ciliata* (11);	
Prunus	Defoliators	Eastern tent caterpillar, *Malacosoma americanum* (5); Japanese beetle, *Popillia japonica*; Spring cankerworm, *Paleacrata vernata*; Fall cankerworm, *Alsophila pometaria*;	Flatheaded appletree borer, *Chrysobothris femorata*; Peachtree borer, *Synanthedon exitiosa*; Lesser peachtree borer, *Synanthedon pictipes*; White peach scale, *Pseudaulacaspis pentagon*; Oyster shell scale, *Lepidosaphes ulmi*; San Jose scale, *Quadraspidiotus perniciosus*; ambrosia beetles
Pyrus	Defoliators, Borers	Defoliators: Cankerworms (2); Spring cankerworm, *Paleacrata vernata*; Fall cankerworm, *Alsophila pometaria*; Borers: Ambrosia beetles (3); Flatheaded appletree borer, *Chrysobothris femorata*; Clearwing borers;	Spider mites; Psyllids, Aphids; Pearleaf blister mite, *Phytoptus pyri*;
Quercus	Defoliators & Stem/Leaf gallers	Defoliators: Orangestriped oakworm, *Anisota senatoria* (3); Pink-striped oakworm, *Anisota virginiensis*; spring cankerworm, *Paleacrata vernata*;fall	Lecanium scale, *Parthenolecanium* spp. (5); Oak lecanium scale, *Parthenolecanium quercifex*; Obscure scale, *Melanaspis obscura*; Oak

		cankerworm, *Alsophila pometaria*; Yellownecked caterpillar, *Datana ministra*; Stem/Leaf gallers: Horned oak gall, *Callirhytis cornigera* (3); Gooty oak gall, *Callirhytis quercuspunctata* (3); Jumping oak gall, *Neuroterus saltatorius*; Oak apple gall, ;	erriococcid, *Eriococcus quercus*; Kermes scale, *Allokermes kingii*; Twig Girdler, *Oncideres cingulata*; Oak leaf itch mite, *Pyemotes herfsi*; Flatheaded appletree borer, *Chrysobothris femorata*; Two-lined chestnut borer, *Agrilus bilineatus*;
Ulmus	Defoliators	Elm leaf beetle, *Xanthogaleruca luteola* (4);	Native elm bark beetle, *Hylurgopinus rupes*; Smaller European elm bark beetle, *Scolytus multistriatus*; Banded elm bark beetle, *S. schevyrewi*; Japanese maple scale, *Lopholeucaspis japonica*; calico scale, *Eulecanium cerasorum*; *Parthenolecanium* spp.; Elm cocks comb gall, *Colopha ulmicola;* Elm Sack Gall, *Tetraneura ulmi*; Plant hoppers;
Zelkova	Bark suckers, Borers	Bark suckers: Japanese maple scale, *Lopholeucaspis japonica* (2); calico scale, *Eulecanium cerasorum* (2); Borers: Native elm bark beetle, *Hylurgopinus rupes* (1); Smaller European elm bark beetle, *Scolytus multistriatus* (1); Ambrosia beetles (1);	

Table 3. Common tree genera and ranking of pest guilds or damage types in the northeastern and north central US. Values are means of responses followed by the number of times the category was ranked by respondents as 3.Common tree genera and relative importance of pest guilds or damage types in the . 3 = very common/damaging, 2 = moderate, 1 = rare/ not very damaging, 0 = non-issue.

Genus	Bark suckers (scales)	Leaf suckers (aphids, lacebugs, scales)	Defoliators (Lepidopterans,Coleopterans)	Leaf and stem gallers	Borers	Mites
Acer (n=6)	2.3 (2)	2.2 (2)	1.3 (0)	1.3 (0)	2.0 (1)	0.8 (0)
Fraxinus (n=6)	0.8 (1)	0.8 (1)	1.2 (1)	0.8 (0)	3.0 (6)	0.3 (0)
Lagerstroemia (n=3)	2.3 (1)	2.0 (0)	0.7 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Liquidambar (n=6)	0.7 (0)	0.3 (0)	0.8 (0)	0.0 (0)	0.3 (0)	0.0 (0)
Liriodendron (n=6)	1.5 (0)	1.5 (0)	0.5 (0)	0.2 (0)	0.5 (0)	0.2 (0)
Pinus (n=6)	1.3 (0)	1.7 (1)	2.0 (1)	0.8 (0)	2.5 (4)	0.3 (0)

Platanus (n=6)	0.0 (0)	1.8 (2)	0.5 (0)	0.2 (0)	0.3 (0)	0.2 (0)
Prunus (n=6)	1.7 (2)	1.5 (0)	1.7 (1)	0.5 (0)	2.2 (3)	0.5 (0)
Pyrus (n=6)	0.7 (0)	0.8 (0)	0.8 (0)	0.2 (0)	0.8 (0)	0.3 (0)
Quercus (n=6)	1.8 (1)	1.3 (1)	1.8 (2)	1.8 (0)	1.5 (0)	1.2 (0)
Ulmus (n=6)	1.7 (0)	1.3 (0)	2.2 (1)	0.3 (0)	1.5 (2)	1.0 (0)
Zelkova (n=6)	0.2 (0)	0.2 (0)	0.7 (0)	0.0 (0)	0.2 (0)	0.2 (0)

TABLE 4. Top pest categories for each genus and key pest species within those categories. Top pest category reflects the category with the highest value in Table 3. If equal values appeared in Table 3, both pest categories and associated species are presented. The most commonly identified pest species appears first followed by the number of times it was listed in parentheses. Important pests listed by respondents who selected a different top category are listed in the final column.

Genus	Top pest group	Species in top category	Species listed as important from other categories
Acer	Bark suckers	Cottony maple scale, *Pulvinaria innumerabilis* (3); Gloomy scale, *Melanaspis tenebricosa*; Cottony maple leaf scale, *Pulvinaria acericola;* Japanese maple scale, *Lopholeucaspis japonica*; Oyster shell scale, *Lepidosaphes ulmi*;	Flatheaded appletree borer, *Chrysobothris femorata*; Asian longhorned beetle, *Anoplophora glabripennis*; Leafhoppers;
Fraxinus	Borers	Emerald ash borer, *Agrilus planipennis* (6); clearwing borers, *Podosesia* spp.	
Lagerstroemia	Bark suckers	Crape myrtle bark scale, *Acanthococcus lagerstroemiae* (1); mealybugs (1);	Crape myrtle aphid, *Tinocallis kahawaluokalani*;
Liquidambar	Defoliators	Fall webworms, *Hyphantria cunea* (3); Gypsy moth, *Lymantria dispar*;	
Liriodendron	Leaf suckers, Bark suckers	Leaf suckers: Tulip tree aphid, *Illinoia liriodendri* (4); Bark suckers: Tulip tree scale, *Toumeyella liriodendri* (2);	Root collar borer, *Euzophera ostricolorella*;
Pinus	Borers	Bark beetles (3); *Ips* spp.; Southern pine beetle, *Dendroctonus frontalis*; Black turpentine beetle, *Dendroctonus terebrans*;	Redheaded pine sawfly, *Neodiprion lecontei*; European pine sawfly, *Neodiprion sertifer*; Pine needle scale, *Chionaspis pinifoliae*; Zimmerman pine moth, *Dioryctria Zimmermani*;
Platanus	Leaf suckers	Sycamore lace bug, *Corythucha ciliata* (3); Plant bugs, *Erythroneura* spp.	mites
Prunus	Borers	Clearwing borers (4); American plum borer, *Euzophera semifuneralis*;	Eastern tent caterpillar, *Malacosoma americanum*; Japanese beetle, *Popillia japonica*; Fall webworm, *Hyphantria cunea*; White prunicola scale, *Pseudaulacaspis prunicola*; Cottony cushion scale, *Icerya purchasi;*
Pyrus	Leaf suckers, Defoliators, Borers	None listed	None listed
Quercus	Bark	Bark suckers: Obscure scale,	Two-lined chestnut borer, *Agrilus*

	suckers, Defoliators, Gallers	*Melanaspis obscura* (1); Oak lecanium scale, *Parthenolecanium quercifex*; Oak erriococcid, *Eriococcus quercus*; Defoliators: Gypsy moth, *Lymantria dispar* (2); Lepidopteran defoliators; Gallers: Cynipid wasps (1);	*bilineatus*; Oak lacebug, *Corythucha arcuata*;
Ulmus	Bark suckers	European elm bark scale, *Gossyparia spuria* (3); Oyster shell scale, *Lepidosaphes ulmi*;	European elm flea weevil, *Orchestes alni*; Elm leaf beetle, *Xanthogaleruca luteola*; Native elm bark beetle, *Hylurgopinus rupes*; Smaller European elm bark beetle, *Scolytus multistriatus*; Japanese beetle, *Popillia japonica*; Asian longhorned beetle, *Anoplophora glabripennis*;
Zelkova	Defoliators	None listed	None listed

Discussion of Survey Results

Key pests. This survey identified some pest categories that were clearly most important for some tree genera such as ‘Bark suckers’ on *Acer*, ‘Leaf suckers’ on *Liriodendron*, ‘Defoliators on *Prunus*, and ‘Borers’ on *Fraxinus*. Except in certain cases such as ‘Leaf suckers’ on *Liriodendron* for which only one pest, tulip tree aphid, is common, there was often less consensus on the top pest species within a pest category. This reflects the limitations of grouping trees by genus. For example, *Lecanium* spp. scales may be most common in areas where willow oaks are prevalent but obscure scale or caterpillars in areas with lots of pin oaks. The spread of invasive species also complicates a survey over broad regions. For example, crape myrtle bark scale is spreading throughout the southeast but has not reached every state. Thus ‘Bark suckers’ were the top pest for respondents from regions with crape myrtle bark scale but ‘Leaf suckers’ in regions without crape myrtle bark scale.

Another limitation of the pest categories used in this survey was that, due to the diversity of arthropod species and their life histories, some key species fall into more than one category. The most frequently cited in this situation were *Lecanium* spp. that feed on leaves in summer but bark in other seasons. Some respondents placed *Lecanium* spp. in ‘Bark suckers’ and others in ‘Leaf suckers’ which may dilute the importance of these key pests or others with varied feeding strategies. Some respondents suggested a separate category for bark beetles rather than grouping them in with borers and creating a category for leafminers rather than grouping them with ‘Defoliators’ due to differences in management and damage.

Key trees. The tree genera used in this survey were the most common genera from tree inventories acquired by SDF from 5 southeastern cities. Southern respondents suggested adding the genera *Magnolia*, *Cornus*, *Cercis*, *Cupressus, Sabal* to future surveys. Northern respondents suggested adding *Cornus, Cercis, Magnolia, Gleditsia, Tilia, Malus, Betula, Crataegus, Tsuga,* and *Picea*. There was general consensus that future surveys need to consider trees at lower taxonomic levels.

Scope and participation. Many respondents emphasized the need for an interdisciplinary approach to developing priorities that includes pathogens and abiotic disorders. In addition, respondents emphasized the need for more input from tree care professionals in future surveys. In this survey 19 of 25 contributors work at universities in research, extension, or diagnostic positions.

Research priorities

This section identifies basic and applied research that was identified by respondents as a foundation on which to develop IPM rather than research that will lead directly to new IPM tools or tactics.

Pest Biology. For some pest species not even basic life history information, such as voltinism, phenology, and natural enemies, is well documented. These traits can vary by region, host plant, or other factors. To develop monitoring tools, predictive models, and management tactics pest biology has to be understood.
Specific topics include:

- Life history traits that influence IPM including voltinism, phenology, oviposition, pupation
- Identify key pests on which to focus from this and future surveys
- Identify key specialist and generalist natural enemies of key pests
- Pests of tree species newly introduced or reintroduced as urban trees such as elm and chestnut

Specific pest species or categories include:

- Armored scales including pests from the survey such as Gloomy scale, *Melanaspis tenebricosa*; Japanese maple scale, *Lopholeucaspis japonica*; Obscure scale, *Melanaspis obscura;* White peach scale, *Pseudaulacaspis pentagon*; Oyster shell scale, *Lepidosaphes ulmi*; false oleander scale, Pseudaulacaspis cockerelli; Pine needle scale, *Chionaspis pinifoliae*;
- Soft scales including pests from the survey such as *Lecanium* spp. Cottony maple scale, *Pulvinaria innumerabilis*; Cottony maple leaf scale, *Pulvinaria acericola;* Terrapin scale*, Lecanium nigrofasciatum*; Calico scale, *Eulecanium cerasorum; Lecanium* spp*.;* Oak erriococcid, *Eriococcus quercus*; Tulip tree scale, *Toumeyella liriodendri;* Crape myrtle bark scale, *Acanthococcus lagerstroemiae*
- Spider mites including oak spider mite, *Oligonychus bicolor;* maple spider mite, *Oligonychus aceris*;
- Caterpillars including Orangestriped oakworm, *Anisota senatoria*; Pink-striped oakworm, *Anisota virginiensis*; spring cankerworm, *Paleacrata vernata*; fall cankerworm, *Alsophila pometaria*; Yellownecked caterpillar, *Datana ministra*; green-striped mapleworm, *Dryocampa rubicunda*;
- Lace bugs including Sycamore lace bug, *Corythucha ciliata*
- Aphids including crape myrtle aphid, *Tinocallis kahawaluokalani*; tulip tree aphid, *Illinoia liriodendri*;
- Borers including flatheaded appletree borer, *Chrysobothris femorata*; clearwing borers; root collar borer, *Euzophera ostricolorella*;
- Bark beetles including *Ips* spp.; southern pine beetle, *Dendroctonus frontalis*; black turpentine beetle, *Dendroctonus terebrans*; ambrosia beetles, *Xylosandrus crassiusculus, X. germanus*, *Xyleborus* spp.; Camphor shot borer, *Cnestus mutilatus*;
- Elm pests including European elm bark scale, *Gossyparia spuria*; elm leaf beetle, *Xanthogaleruca luteola*; native elm bark beetle, *Hylurgopinus rupes*; smaller European elm bark beetle, *Scolytus multistriatus*; banded elm bark beetle, *S. schevyrewi*; elm cocks comb gall, *Colopha ulmicola;* elm Sack Gall, *Tetraneura ulmi*;

Pest phenology, distribution, and range shifts. The distribution and life history of many pests is changing due to climate change or the influence of urban warming or movement by humans. The most recent geographic range descriptions for many pests are decades old. These are inadequate to inform pest managers of current pest threats or predict threats in the near future. USDA Hardiness zones have changed indicating tree species can be grown in areas where they didn't previously which could affect the pests and natural enemies associated with them. Thus, a pest manager trying to diagnose a pest may not consider species that are not listed in out-dated resources.
Specific topics include:

- Range expansion of native species such as southern pine beetle, gloomy scale, bagworm that have northern limits influenced by winter minimum temperature
- Phenological mismatch between pests and natural enemies due to urban or global warming

- Pests and natural enemies associated with trees in new ranges such as crape myrtle
- Distribution and range expansion of exotic species such as crape myrtle bark scale
- Influence of urbanization on pest distribution, phenology, biological control

Specific pest species or categories include:
- Southern pine beetle
- Gloomy scale
- Bagworm
- Mimosa webworm
- Sri Lanka weevil
- Chilli thrips
- Crape myrtle bark scale
- Japanese maple scale
- Crape myrtle bark scale
- Emerald ash borer

Plant culture effects on tree susceptibility. The effects of cultural practices on pest abundance and damage have not been thoroughly studied. These include irrigation, fertilization, micronutrient supplement, soil type and condition (e.g. structural soil), mulching, and topping. Many of these have not been studied well enough from a horticultural perspective to know how they benefit or harm trees overall or how they affect tree susceptibility to pests or pest biology.
Specific topics include:
- How urban landscape features such as impervious surface affect plant susceptibility to pests
- How irrigation practices and drought influence tree susceptibility to pests particularly ambrosia beetles, scales, borers, mites.
- Differences in responses of sap suckers, defoliators, borers, and mites to irrigation or nitrogen fertilization
- Post-harvest persistence of plant production practices such as fertilizer and pesticides
- Transplant stress on pest susceptibility, particularly flatheaded borer attacks
- Effects of plant growth regulators on tree health and pest susceptibility

Specific pest species or categories include:
- Flatheaded appletree borer
- Ambrosia beetles
- Scales
- Mites

Effects of environmental stress. The stress imposed by abiotic factors arising from urbanization and climate change will have increasingly strong effects on trees and tree pests but are among the least studied. The effects of air and water pollution on tree health, as well as pest biology and ecology, is poorly understood.
Specific topics include:
- Effects of urban warming, drought stress, and soils on herbivores and urban trees
- Effects of NO_x and sulfurous compounds on the biology and management of mites and scale insects
- Effects of elevated CO_2, nitrogen deposition, and/or ozone on pest biology and tree functions

Specific pest species or categories include:
- Scales
- Flatheaded and clearwing borers

- Native caterpillars such as cankerworms, eastern tent caterpillar, fall webworm, bagworms, orange striped oakworms
- Spider mites such as oak spider mite, maple spider mite, twospotted spider mite
- Pollinators of trees

Tree function, value, and services. The value and services provided by trees is based on their physiological health and functions. These services can be reduced by pests, tree stress, or both. Tree value helps justify economic investment by municipalities and granting agencies but research on the ecological and societal services provided by trees and how they are affected by pests is limited.
Specific topics include:
- Different physiological functions and services of cultivars and wild type trees due to morphology, stress, or pests
- How tree services (e.g. cooling, carbon sequestration, conservation) are affected by urban habitat and pests
- Effects of trees and tree diversity on conservation of natural enemies and biological control of tree pests and other landscape pests
- Conservation of arthropod and vertebrate biodiversity by urban trees and how conservation value is affected by:
    - tree species, size, status and native, exotic, or cultivar
    - tree health and pest infestations
- Effect of systemic insecticides on nectar/pollen quality and pollinator conservation in urban environments.
- Pollinator conservation by urban trees

Specific pest species or categories include:
- Emerald ash borer
- Damage and nuisance caused by phloem feeders particularly crapemyrtle aphid, tuliptree aphid, scales honeydew/sooty mold damage on vehicles
- Armored scales particularly gloomy scale, Japanese maple scale, obscure scale
- Phloem feeding scales particularly lecanium scales, calico scale, felt scales
- Native bees

Socioeconomics of urban tree IPM. Many decisions to treat urban trees are driven by customer complaints which may have limited relationship to tree health or damage or pest biology. Interdisciplinary research is needed that explores consumer perceptions and underlying causes of complaints and management decisions. This could provide insight into new areas for extension programming.
Specific topics include:
- Aesthetic perceptions of pests and damage (e.g.[51-53])
- Frass and honeydew removal
- Perception of arthropod products such as webbing and cast exoskeletons relative to treatment

Specific pest species or categories include:
- Aphids particularly tulip tree aphids and crape myrtle aphids
- Caterpillars particularly orangestriped oakworm, greenstriped and pinkstriped mapleworms, cankerworms, fall webworms, eastern tent caterpillars, bagworms, mimosa webworms

IPM Development Priorities

This section identifies specific IPM tools and tactics that are needed and specifies some research directions to help develop them.

Efficient scouting and monitoring protocols. With so many different plant and pest species spread over a large geographic areas IPM practitioners need efficient ways to identify infested trees and monitor pest phenology. Traditional methods used in agriculture may not be feasible in many urban situations. Innovative methods are needed that use new technologies to monitor pest phenology, abundance, and damage.
Specific topics include:
- New technology for scouting.
- Remote sensing to identify susceptible locations based on conditions such as temperature, impervious surface cover, or plant diversity
- Identify commonalities among related pests so a tool could be applied to multiple taxa
- Regional predictive models for scale insects and borers
- Sentinel trees or plots to monitor invasive species and range expansion of native species

Aesthetic, economic injury, and action thresholds. Economic injury levels or treatment thresholds are not available for most urban trees. These are key components of IPM programs but may be cumbersome for tree care professionals that care for many trees across a large geographic area. Innovative solutions are needed to inform IPM decisions.
Specific topics include:
- Quantify the consequences of key arthropod pest species on urban tree functions and services
- Predictive models of biological control potential based on plant diversity or other habitat features
- Impervious surface thresholds (e.g. [54])

Tree species and site selection criteria. Matching plants to site characteristics - right plant, right place - is a critical IPM tactic. Proper site selection and preparation reduces stress to trees, which in turn, become more tolerant or resistant to pest infestation.
Specific topics include:
- Quantify the stress or detrimental effects of planting trees in unsuitable site or urban conditions.
- Quantify differences in pest and stress resistance among cultivars and wild type trees
- Identify tree species that could thrive in urban heat islands
- Identify species that will be tolerant of future climate
- Impervious surface thresholds and Pace to Plant

Urban landscapes as ecosystems. Considering urban landscapes as ecosystems rather than a collection of individual trees could reduce pest abundance and damage due to actions of natural enemies and plant diversity[55]. Minimizing disturbances such as insecticide applications also fits this perspective.
Specific topics include:
- Quantify the effects of mosquito control programs on pests, natural enemies, and pollinators
- Evaluate the influence and interconnection of non-tree habitat such as flower beds, gardens, lawns, natural areas on tree pests and beneficials
- Development of augmentative biological control programs for urban trees and landscapes
- Development of conservation biological control programs for urban trees and landscapes
- Horizontal IPM approaches that address multiple pest groups

Least toxic management tactics. Active management of damaging arthropod populations is often necessary. Urban trees exist among high densities of people, pets, and other non-target organisms, and environmentally sensitive site such as streams. Research is needed to evaluate the efficacy of new and least toxic insecticides, miticides, and biological control tactics.
Specific topics include:

- Insecticide and miticide efficacy and safety for beneficial arthropods
- Efficacy and safety of different application techniques (i.e. foliar spray, drench, soil injection, trunk injection, etc.)
- Efficacy and safety of biologically-based insecticides

Protecting trees from invasive species and conserving trees during and after the initial invasion wave. Invasive species will continue to be problems for urban trees. IPM should focus on a multiple phased response strategy that initially relies on insecticides, and shift toward a monitoring based response after the initial wave has passed.
Specific topics include:
- Economic analyses of approaches such as tree removal or insecticide applications (e.g.[56])

Extension priorities

Missing clientele. In many cases the people managing pest problems are not the people, such as landscape architects, landscape designers, ground managers, and homeowners, who selected or planted the trees. The people who make tree selection and site decisions are a critical group that is not being reached by many IPM extension efforts. It is critical to include landscape architects and designers and others in extension programing which will likely require different resources and marketing efforts.

Other missing clientele for tree extension is municipalities and other organizations, such as HOAs, that regulate tree planting. These groups often create lists of tree species that are permitted based on aesthetics, non-interference of utilities, or factors other than pest susceptibility. Educating these decision makers on the relationship between tree and site selection, site preparation, and pest management may help advance the science of pest management on urban trees.
Specific examples include:
- Regular outreach and training to landscape architecture schools or programs
- Develop a list of urban tree species that include pest susceptibility and sites requirements

New pests without resources. New pests arrive frequently, especially in Florida, so there is a lag between pest arrival and even general information about their biology and management. As tree and pest species distribution expands new information and resources will be needed.
Specific topics include:
- Sri Lanka weevil, *Myllocerus undecimpustulatus undatus*
- Whiteflies in Florida
- Crape myrtle bark scale
- Expanding native species

Modernize existing resources. There was a lot of research on urban tree and urban landscape IPM in the 1980s and 1990s. This resulted in valuable books, extension publications, and papers in practitioner-accessible journals. However, some of these resources are hard to find or a new generation of practitioners are not aware of them. These resources need to be updated, in format or content, to make them accessible via app development and use of responsive design of web pages (e.g. https://www.purdueplantdoctor.com/). Since the publication of above mentioned resources, additional observations and experiment results on urban tree pest biology and management have become available. These old and new resources need to be updated regularly, in both format and content. These resources also need to be deposited in a centralized location where information can be easily accessible.
- IPM manual for tree care professionals with subjects such as scouting, record keeping, mapping, conserving natural enemies, host plant resistance etc. including a a checklist of things you should do and information that you need to acquire

Modern marketing for urban IPM. The decline in European honey bee and native bees have changed perspectives and behaviors in the landscape and at the point of purchase. This demonstrates a success in marketing and provides a path for the future adoption of IPM practices.

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