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Threats to Oaks in the Eastern United States: Perceptions and Expectations of Experts

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Abstract

Oaks (*Quercus* spp.) are keystone species in many ecosystems and are ecologically as well as economically valuable. The objective of this study was to gather and evaluate information from a diverse group of oak experts on current and future biotic and abiotic threats to oaks in the eastern United States. Using a Delphi survey method with three iterative surveys, we found that oak decline and climate change were identified as critical current and future threats, respectively, in this region. Focusing on climate change, experts were asked a series of questions to assess its potential future temporal and spatial impact on oaks. With respect to climate change, the majority of experts surveyed believe climate change will manifest gradually, although they were generally uncertain about the geographical distribution of climate change in the future, i.e., the areas where oaks are likely to be impacted by climate change in the future. New/emerging pests and pathogens were seen as the most critical future threat by the third survey round. Results from this study can be used to better inform management practices and research priorities for ensuring resilient oak resources for the future.

Keywords: *Quercus* spp., Delphi survey, abiotic threats, biotic threats, climate change

Forest ecosystems are being altered at increasingly rapid rates because of anthropogenic drivers of change such as global redistributions of forest pests and pathogens (Santini et al. 2013, Lovett et al. 2016) and more severe droughts (Allen et al. 2015). These threats often have both ecological and economic ramifications (Lovett et al. 2016), especially for widespread and foundational forest tree species, such as those within the genus oak (*Quercus* spp.). Oaks are a common and widespread tree genus in the eastern United States (defined here as the Eastern and Southern Regions of the US Forest Service). Species in this group occupy a wide range of ecological niches, and many are of high economic value. For example, oak timber is used in a range of wood products including furniture, flooring, and specialty products such as cooperages, supplying barrels for wine and bourbon industries.

Since the late 20th century, the abundance of oaks in the eastern United States has decreased. This is in large part related to management practices that exclude fire and decrease oak regeneration. In addition, aging oak forests are increasingly vulnerable to a variety of existing and emerging biotic threats (Fei et al. 2011, Hanberry and Nowacki 2016). Oak decline, a general term for the progressive dieback and eventual mortality of oak trees, has been observed across the central

Management and Policy Implications

Tree species across the world are facing widespread mortality because of a range of biotic and abiotic threats. From the arrival of invasive species to changing climate patterns and increased drought, these threats can have devastating economic and ecological impacts. It is important to anticipate, prepare for, and guard against potential threats to key trees species. Oak species (*Quercus* spp.) are vitally important to the eastern United States, acting as essential components of forest ecosystems and timber markets. Better understanding of current and future threats to oaks is critical for informing research needs and prioritizing the actions of policymakers, regulators, and land managers. Results of this study suggest that forest researchers and policymakers should work with on-the-ground experts to monitor and manage current oak threats such as gypsy moth, oak wilt, sudden oak death, oak decline, or the introduction of some new currently unknown insect or pathogen. In the future, these and other threats should also be considered in light of a changing climate that may have impacts on oaks that are variable and hard to predict. Taking a proactive approach to ensuring long-term oak health is key to avoiding future problems from new or emerging threats.

hardwoods region of the United States as well as in Europe (Oak et al. 1996, Thomas et al. 2003). Oak decline is typically attributed to compounding tree stress because of a combination of predisposing factors (e.g., aging red oak stands), inciting factors (e.g., drought and severe spring defoliation), and contributing factors (e.g., a wide range of insects and pathogens that opportunistically affect trees) (Shifley et al. 2006). In North America, contributing factors are commonly thought to include *Phytophthora cinnamomi*, *Agrilus bilineatus*, *Armillaria* sp., *Biscogniauxia* spp., and other pathogen species. Patterns of oak decline vary from a few trees in stands with diverse species composition and age structure to areas covering several thousand hectares in landscapes with a more uniform composition of susceptible, physiologically mature oak species. In some areas, more rapid versions of oak decline have also been noted, such as Acute Oak Decline in the United Kingdom and Rapid White Oak Mortality in Missouri (Denman et al. 2014, Reed et al. 2017).

In addition, there are several diseases and insects that can directly cause oak mortality in the United States and worldwide. Although these and other threats have the capacity to damage or kill oaks, calculating their impact depends on accurate estimates of which oak species will be most affected and how damage will manifest spatially and temporally. A few of these threats include:

- Oak wilt: Caused by the fungal pathogen *Ceratocystis fagacearum*, oak wilt is the most significant disease of oaks in the oak–hickory-dominated forests of the central hardwood region of the eastern United States (Juzwik et al. 2008). Evidence suggests the pathogen is not native to the United States (Juzwik et al. 2008). The disease is currently found in many eastern and midwestern states (Haight et al. 2011), and it affects many oak species, but is most damaging to the red oak group.
- Sudden oak death: The invasive oomycete pathogen *Phytophthora ramorum* causes the disease sudden oak death on coast live oak and tanoak in California and Oregon. Where established, it has resulted in high mortality of susceptible oak species (McPherson et al. 2015). Given the broad host range of *P. ramorum,* suitable climate, and its repeated introduction to the eastern United States, it presents a major risk to oak species in this region (Venette and Cohen 2006).
- Gypsy moth: Several species of both European and Asian gypsy moths in the genus *Lymantria* are invasive in North America and known to cause severe and repeated spring defoliation through larval feeding. The European gypsy moth has been established in the eastern United States for many years and is associated with oak decline and mortality (Davidson et al. 1999). However, its spread is very slow because of flightless females and an active "Slow-the-Spread" collaborative management program (Tobin and Blackburn 2007). Asian gypsy moth, a more recent arrival, affects a wider range of tree species and is able to move more rapidly because of females' ability to fly (Hajek and Tobin 2009).
- Agrilus beetles: There are several different species of beetles in the genus *Agrilus* known to cause oak mortality that are potential threats to oaks in the eastern United States if introduced. For example, *Agrilus biguttatus*, the oak splendor beetle, is a European insect that has been tied to acute oak decline, and *Agrilus auroguttatus*, the goldspotted oak borer, native to the American southwest, was recently introduced to southern California where it has caused mortality in red oak species (Moraal and Hilszczanski 2000, Coleman et al. 2011).

It is unclear how changes in climate will affect oaks or their pests and pathogens. McKenney-Easterling et al. (2000) assessed the potential impacts of climate change and variability on forests and forestry in the mid-Atlantic region and found that it may result in large increases in the amount of forest dominated by oak and pine, and large decreases in maple/beech/birch forests. These findings were based on the assumption that trees are able to migrate in pace with climate change. At the same time, climate change may also make conditions more conducive for oak pathogens or pests in the region. Increased concentration of atmospheric CO_2 may cause enhanced growth and greater efficiency of water use, although it is uncertain whether these effects will persist under field conditions (Bazzaz 1990, Eamus 1996).

To advance our understanding of these threats and their potential impacts, a diverse group of oak experts were surveyed using Delphi survey methodology to develop a consensus (i.e., a general agreement) about current and future threats to oaks in the eastern United States. Delphi is a widely used method designed to collect expert opinions about complex issues (Linstone and Turoff 1975, Landeta 2006). The Delphi method uses a series of surveys to elicit opinions from a group of experts with specific knowledge (Dalkey and Helmer 1963). In our study, the goal was to establish and prioritize a full range of problems impacting oaks, from diverse experts with differing perspectives, and eventually for experts to converge toward a consensus opinion in regard to which threats may be the most consequential. This approach does not replace empirical research, but can gather information on threats that are not yet established, or for which impact data are not yet available. This information can provide forest health researchers and managers insight on oak threats that should be prioritized for empirical-based studies and management.

In Delphi survey methodologies, multiple survey iterations are delivered to participants, and participants are able to reassess their initial judgments based on summary responses and comments from other participants in previous rounds. When applied rigorously, the Delphi survey method is recognized to produce reliable information, especially when there is an absence of sufficient data or when there is high uncertainty in the decision-making process (Gotsch 1997, Morgan et al. 2001). The method is used in various fields of study and has been extensively applied to environmental science and natural-resource management (Turoff and Hiltz 1996, Hess and King 2002, MacMillan and Marshall 2006).

The objective of this study was to increase our understanding of current and potential future threats to oaks in the eastern United States, and to obtain specific information on the potential impact of the most critical future threat to oaks in this region. This study focused on biotic and abiotic threats to better understand their potential impact, but did not include management issues. This is intended not to downplay the importance of management, which is a central driver of oak dynamics in the region, but to shed more light on other threats that have the potential to interact with management decisions in the future. Management-related impacts on oak sustainability are complex and likely to express differently from biotic and abiotic threats, meriting their own focused survey.

Methods

Survey Recruitment

We identified a list of experts who are actively managing, working with, or conducting research on oak resources in the United States (Novakowski and Wellar 2008). Based on their online affiliation, 100 percent of experts were based in the study region (i.e., eastern United States). To ensure a heterogeneous range of opinions, we invited experts from a variety of geographic locations and professional backgrounds, including academia (51 percent), government (federal 36 percent; state 7 percent), private and nonprofit groups (4 percent), and no current affiliation (1 percent) (N = 69) (see Figure 1a and b for the distribution of survey participants by geographic location and region of work, respectively). Potential participants were identified primarily through existing professional networks or academic publication databases as well as through online searches of academic institutions and government agencies throughout the region.

Survey Development

We followed the procedures proposed by Everett (1993) to develop a three-round Delphi survey (Edwards et al. 2011). First, the biology and forestry experts on our team drafted a series of questions aimed at identifying and assessing threats to eastern United States oak species. Then, the social science subgroup of our team provided feedback to ensure that Delphi procedures were followed. Finally, before distributing the survey to potential participants, we tested the first two rounds with three forest health professionals. Based on feedback received at each stage, survey questions were revised and refined for clarity and content. An Institutional Review

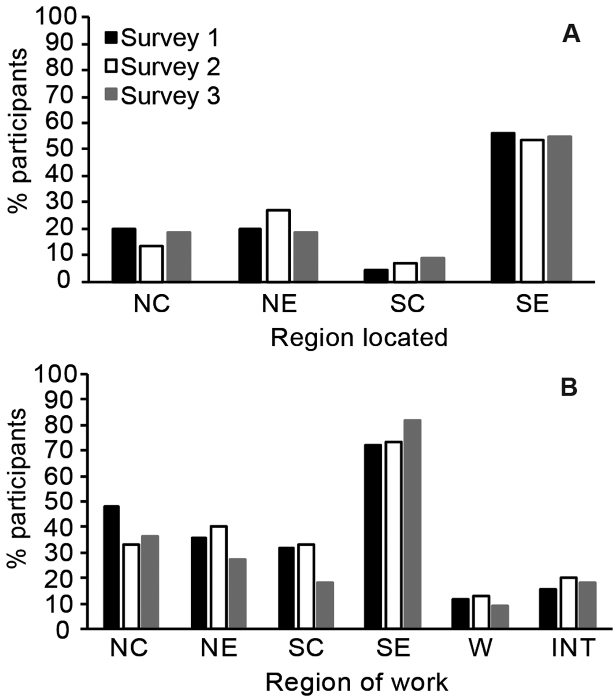

Figure 1. Region(s) where survey participants are physically located—(NC) north central, (NE) northeast, (SC) south central, and (SE) southeast (A) and conduct work—(NC) north central, (NE) northeast, (SC) south central, (SE) southeast, (W) west, and (INT) international (B). Note, some participants conduct work in multiple regions. Survey 1 (black, $N = 25$), survey 2 (white, $N = 15$), and survey 3 (gray, $N = 11$).

Board (IRB) exemption (16-0337-X4B) was acquired from the University of Kentucky IRB review board to support this work. Copies of the distributed surveys can be found in Supplement 1.

In the first round, we asked participants to list what they considered to be the top five current and future biotic and abiotic threats to oaks in the eastern United States. For the purpose of this survey, threats were defined as biotic stresses—those caused by pathogens and pests—and abiotic stresses, which included abnormal weather and climate change. Although this definition is incomplete, it was provided to establish a common context and distinguish these types of threats from management issues, which are also very important but not addressed in the survey. We also asked experts about the general health status of oak trees in this region. Finally, we collected demographic information on participants, including information about participants' professional background, and asked them to self-evaluate their level of expertise related to oaks (Gotsch 1997).

To rank the threats listed by experts in the first round, we employed a weighted score method to define the top five current and future threats. Weighted scores from 5 to 1 were assigned to threats listed from most to least critical, respectively. Then, weighted scores were summed for every listed threat and ranked in order from largest to smallest. We also summed the number of times each threat was listed, regardless of order, and ranked from largest to smallest to check the robustness of our results. Threats that were not classified as being biotic or abiotic in nature (e.g., related to management practices) were excluded. This is not a reflection of how significant these other threats are but a consequence of our desire to better understand biotic and abiotic threats to oak resources.

In the second round, we provided participating experts with the ranking of the top five current and future threats identified from the first round of the Delphi survey. Participants were invited to reconsider their previous ranking in light of the aggregated group's response. Then, participants were asked to select the potential impact on oaks from the top future threat identified in the first round based on their own opinions and professional experience. If they did not agree with the top future threat identified in the first round, participants were also provided the opportunity to predict the potential future impact on oaks based on the future threat they listed as most important. Questions about future impact covered a wide range of topics including the following: listing potentially impacted oak groups/species, indicating the proportion of trees likely to be impacted, how mortality would manifest, impact on regeneration, specifying at which life stage damage was likely to occur, estimating potential spatial distribution (i.e., which geographic locations are the effects of climate change likely to be felt) and severity of damage, and asking what factors would make oaks more susceptible to this threat. Participants were also asked to estimate the confidence they held in their responses to specific questions.

Responses from the second round were summarized, and the aggregated results were provided to participants in the third round of the survey. The questions in the third round were identical to the questions in the second round, thus giving participants the opportunity to revise their answers based on the aggregated results, if they so desired. At the end of the third survey, participants were provided the option to comment on their answers or the entire survey process.

Survey Distribution

The three rounds of the survey were conducted between August 2017 and December 2017 via an online survey system. Responses were collected anonymously, but participants were given a unique code, so that changes in a participant's responses could be tracked, if needed, while still maintaining a participant's anonymity. Prior to the distribution of survey 1, an invitation letter was sent to 69 experts via e-mail, inviting them to participate. For each survey round, respondents were given approximately one month to review and answer survey questions, and two e-mail reminders were sent prior to closing each survey. Twenty-eight experts completed or partially completed the first round of the survey. Based on survey 1 results, the second survey was developed and sent out to panel members who participated in the first round. Seventeen experts completed or partially completed the second round. The third survey was then developed and distributed to those who participated in the second survey round, with 12 experts completing or partially completing the third and final survey. Participants could skip individual survey questions without answering. Therefore, the number of participants surveyed varied not only between surveys, but among questions within surveys. This number of participants is consistent with past Delphi surveys, which are known to have between 10 and 100 participants and retention rates from 19.5 percent to 87.1 percent (Hall et al. 2018). According to MacMillan and Marshall (2006 p. 12): "A group of c. 10 individuals is considered appropriate for a Delphi expert panel."

Analysis of Consensus

There is no single accepted method for assessing consensus in Delphi surveys, and the method(s) used depend upon the manner in which questions are asked and the goals of the surveys (Hsu and Sandford 2007, von der Gracht 2012). In general, the stability of subjects' responses across iterations should be considered, and statistical measures such as mode, mean, and standard deviations are commonly used (von der Gracht 2012, p. 1529).

In this study, we view a consensus opinion as representing a general agreement among participating experts. This does not imply that all experts agree or disagree with specific aspects of threats to oaks; nor does it imply that a simple majority represents a consensus. Rather, we suggest that consensus be considered as a relative measure, with greater or lesser degrees. In order to assess the degree of consensus, we consider the tendency of expert opinion to converge toward a common understanding or agreement. Further, we focus our measures on the core group of participants who participated in all three rounds of the survey series to avoid potential bias from attrition.

Consensus was considered for two types of variables in our survey. First, we used a weighted score of respondent rankings to determine the top five current and future threats. The sum of the weighted scores provides an indication of the summary opinion of respondents, which was compared across survey rounds. Decreasing standard deviation values for the sum of the weighted scores are taken as evidence that expert opinion is converging, representing greater consensus. Specifically, if the standard deviation measure computed from survey 3 (sd_3) divided by the standard deviation measure computed from survey 2 (sd_2) is less than 1 ($sd_3/sd_2 < 1$), expert opinions are converging, and greater consensus is revealed. The closer the ratio is to 0, the greater the level of consensus. The second set of variables that we evaluated for consensus are categorical variables that are amenable to analysis using mean, range, and standard deviation. For example, standard deviation has been used to compare movement between Delphi rounds as a measure of convergence (Greatorex and Dexter 2000, Holey et al. 2007). We also calculated the coefficient of variation (standard deviation/mean) to measure consensus for select questions with continuous answers (Buck et al. 1993, Zinn et al. 2001).

The consensus opinion here is meant not for empirical prediction of oak threats, but rather for a more general indication of where things are going in a broader sense. The iterative survey process is not anticipated to result in complete agreement among survey respondents, particularly for emerging threats where substantial scientific uncertainty remains. However, greater consensus of expert opinion is useful for identifying perceived primary threats to oaks, and these results are helpful for risk analysis and for helping to design improved forest-management strategies and research priorities. Furthermore, residual scientific uncertainty should not be ignored, but rather provide a basis for further hypothesis testing that can help develop a more robust understanding of the factors that will ultimately influence the health of oak forests in the eastern United States.

Results

Twenty-eight of 69 experts invited to participate completed or partially completed the first survey. All of the participants who provided demographic information (89 percent of survey 1 respondents) were based in the eastern United States (Figure 1) and had some level of familiarity with threats to oak trees in the study area (Figure 2). Specifically, 64 percent (*N* = 25) of participants who provided demographic information self-identified as being very or extremely familiar with threats to oak trees in the study area. Seventy-two percent (*N* = 25) had conducted work related to oaks for >10 years (Figure 3). By the third survey, the majority of experts considered themselves very familiar with threats to oaks (73 percent, *N* = 11), with 73 percent (*N* = 11) of experts having worked with oaks for >10 years. Although there was attrition during the course of the survey series, the demographics of participants was generally similar, including the proportion of experts from different work focal groups (e.g., research, education/outreach, forest management, extension, consulting) and primary source of employment (e.g., academia, extension, government, private industry) (Figures 4 and 5).

Based on the first survey, the top five current threats to oaks in the eastern United States were (from most to least critical): gypsy moth, oak wilt, oak decline, climate change (including global warming), and drought (Table 1). The top five future threats to oaks were (from most to least critical): climate change, oak wilt, sudden oak death (*P. ramorum*), oak decline, and some unknown new or emerging (exotic) pest/pathogen (Table 1). In addition, many experts identified management-related threats as concern to oaks (e.g., fire suppression and land-use change) in the eastern United States. Per our definition of abiotic and biotic threats, these threats were excluded, although they are included with the complete list of threats provided by experts as presented in the supplemental materials (Supplement 2). In the second survey, gypsy moth and climate change remained the most critical current and future threats, respectively, although the order of other threats changed slightly

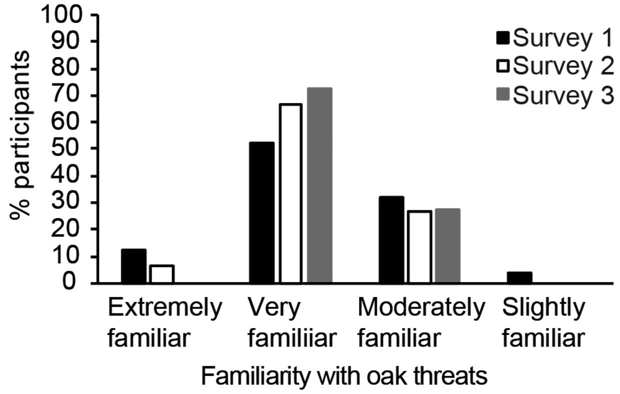

Figure 2. Survey participants level of familiarity with threats to oaks in the Eastern and Southern regions of the United States. Survey 1 (black, *N* = 25), survey 2 (white, *N* = 15), and survey 3 (gray, *N* = 11).

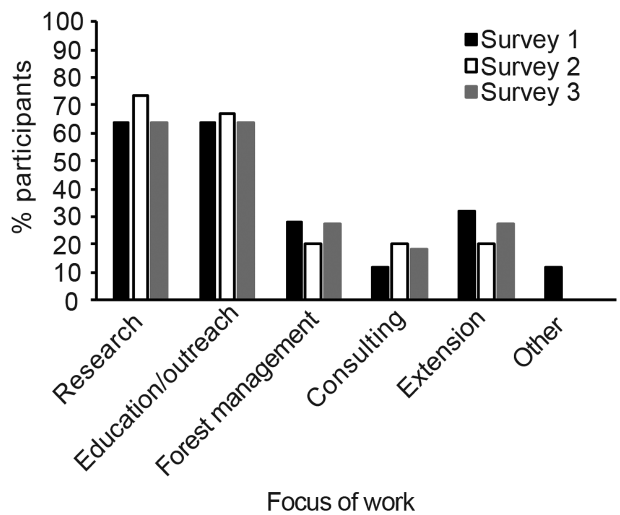

Figure 4. Survey participants work focus. Survey 1 (black, *N* = 25), survey 2 (white, *N* = 15), and survey 3 (gray, *N* = 11).

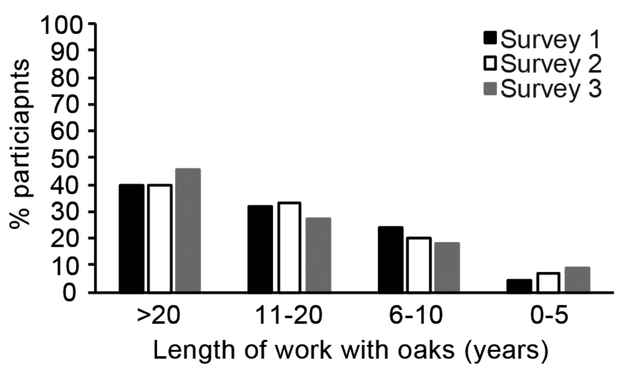

Figure 3. Length of time (years) that survey participants have worked with oaks. Survey 1 (black, *N* = 25), survey 2 (white, *N* = 15), and survey 3 (gray, *N* = 11).

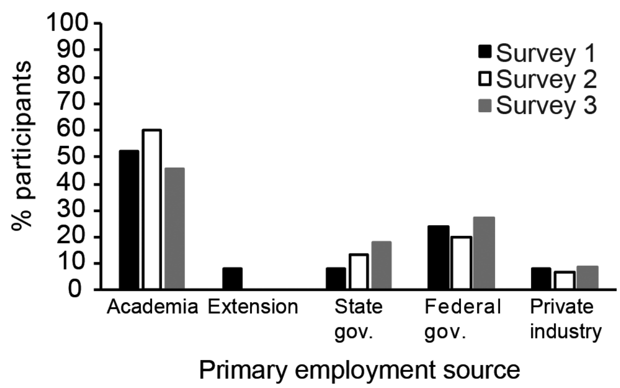

Figure 5. Primary employment source for experts participating in survey 1 (black, *N* = 25), survey 2 (white, *N* = 15), and survey 3 (gray, *N* = 11).

(Table 1). By the third survey, gypsy moth and climate change were replaced by oak decline and an unknown new or emerging (exotic) pest/pathogen as the most critical (based on weighted total) current and future threats, respectively. Climate change was identified as the second most critical future threat in the third survey based on rankings from weighted totals. However, climate change and new or emerging (exotic) pest/pathogen received the same number of first place (most critical) votes (three votes each, *N* = 8). This suggests that experts could not come to a clear consensus in terms of the most critical future threat to oaks in the eastern United States.

In the second and third surveys, questions were focused on identifying the potential impact of the most critical (based on weighted sum) potential future threat, climate change, based on expert opinions in the first survey. Before distributing survey 1 to participants, we decided to focus on one threat so that it would be possible to ask in-depth questions on the potential impact of that threat, without making the survey too lengthy for participants to complete in a reasonable amount of time. Following the results of the first survey, we decided to focus on the future threat, since there is uncertainty in the literature as to what the potential impact of climate change may be on oaks. Eighty-eight percent (*N* = 17) of experts in the second survey and 92 percent of experts (*N* = 12) in the third survey believe that climate change is likely to impact other tree species, besides oaks. The remaining proportion of experts was uncertain. In both surveys, experts responded that white oaks, red oaks, and live oaks would be impacted by climate change, with experts (*N* = 12) on average saying 52 percent and 56 percent of oaks would be impacted, as calculated from the second and third survey, respectively. However, only 20 percent of experts (*N* = 15) in the second survey were somewhat certain, and 33 percent of experts (*N* = 12) in the third survey were somewhat or very certain of their answer pertaining to the proportion of susceptible oaks in impacted areas. In addition, a great deal of uncertainty exists among our experts regarding the proportion of oaks in impacted areas that are vulnerable to future threats.

Furthermore, the majority of experts said that mortality of oaks as a result of climate change would be gradual, although experts were split in regard to the degree to which mortality would manifest (e.g., pronounced versus less pronounced) (Table 2). Specifically, most surveyed experts (43 percent in survey 2 with *N* = 14 and 58 percent in survey three with *N* = 12) believe that it will take >10 years to observe dead or dying oaks, with all age classes being impacted according to the group of experts as a whole. In addition, almost all experts believe that climate change will impact oak regeneration—100 percent in survey 2 (*N* = 14) and 92 percent in survey 3 (*N* = 12)—with the majority of

Table 1. Top five current and future threats based on expert opinions from all participants regardless of whether or not they completed all three rounds of the survey.

Survey	Ranking	Current		Future	
		Threat	Weighted total	Threat	Weighted total
Survey 1	Most critical	Gypsy moth	50	Climate change	43
		Oak wilt	48	Oak wilt	39
		Oak decline	39	Sudden oak death (*P. ramorum*)	30
		Climate change	34	Oak decline	28
	Least critical	Drought	19	New or emerging (exotic) pest/pathogen	27
Survey 2	Most critical	Gypsy moth	52	Climate change	53
		Oak decline	51	New or emerging (exotic) pest/pathogen	50
		Oak wilt*	46	Oak wilt	44
		Drought*	46	Oak decline	43
	Least critical	Climate change	45	Sudden oak death (*P. ramorum*)	35
Survey 3	Most critical	Oak decline	37	New or emerging (exotic) pest/pathogen	34
		Gypsy moth	28	Climate change	30
		Oak wilt	27	Oak decline	22
		Climate change	22	Oak wilt	20
	Least critical	Drought	21	Sudden oak death (*P. ramorum*)	14

Note: The number of survey participants differs between surveys.
*Tied based on weighted total.

experts predicting that climate change will moderately decrease oak regeneration (64 percent in survey 2 and 67 percent in survey 3).

Results pertaining to the assessment of the spatial distribution of climate change impacts were mixed, with 47 percent of experts (*N* = 15) in the second survey believing that climate change is currently impacting oaks in the eastern United States. However, between 79 percent (*N* = 14) and 100 percent (*N* = 12) of experts in the second and third surveys, respectively, believe that climate change is likely to impact areas beyond where its impact is currently being observed, and experts believe that forest types with various proportions of oaks are likely to be impacted in the future (Table 3). The majority of experts were uncertain as to where climate change may impact oaks in the eastern United States in the future, based on forest type (80 percent were uncertain in survey 2 with *N* = 10 and 67 percent were uncertain in survey 3 with *N* = 12), although most experts (83–92 percent) believe that climate change is likely (somewhat or extremely) to impact oaks in >10 years (Table 4). The top factors contributing to oak susceptibility to climate change were identified and included drought, host old age, extreme variations in temperature, host outside climatically adapted range, fire, presence of defoliating insects, and human activity (Table 5). Finally, other key issues that respondents felt were left out of the survey included: the impact of deer herbivory on oak regeneration, the lack of markets for poor stem quality trees and for midrotation activities, and the lack of education on proper prescribed burning practices.

Table 2. Potential manifestation of oak mortality as a result of climate change.

	Proportion of experts (percent)	
Category	Survey 2¶	Survey 3‖
Sudden and pronouced*	0	0
Sudden, but less pronouced†	0	8
Gradual, but pronounced‡	54	42
Gradual and less pronounced§	46	50

*>50 percent of oaks die in <5 years.
†<50 percent of oaks die in <5 years.
‡>50 percent of oaks die in >5 years.
§<50 percent of oaks die in >5 years.
¶*N* = 13.
‖*N* = 12.

Table 3. Forest types with different proportions of oaks predicted to be impacted by climate change in the future according to experts surveyed.

	Proportion of experts (percent)	
Proportion of oaks (percent)	Survey 2*	Survey 3†
<25	10	25
25–50	20	33
>50	0	25
Uncertain	80	67

Note: Experts could select multiple categories; thus, the total proportion exceeds 100 percent.
**N* = 10.
†*N* = 12.

Assessing Consensus

Using the results of the ranking of threats (Table 6) and a subset of questions from survey 2 and survey 3 (Table 7) from the core group (the group of participants who participated in all rounds of the survey) and all participants in the second survey, we assessed whether or not the degree of consensus among expert opinions increased over survey iterations. These results include summary statistics for responses to these questions. Table 6 shows that greater consensus (indicated by decreasing standard errors: $sd_3/sd_2 < 1$) was reached for the top (rank = 1) critical current and future threats, respectively, and for both current and future threats, greater consensus was reached for three of the five threats. The greatest degree of consensus for the top-ranked current threat (oak decline, $sd_3/sd_2 = 0.78$) was not as great as the degree of consensus for the top-ranked future threat (new pest/pathogen, $sd_3/sd_2 = 0.44$). Table 7 shows that in general, responses tended to converge by the third round, after participants were shown the average answers from the second round of the survey. The standard deviations of responses became smaller, and the ranges of responses decreased compared to the previous round.

Since several participants dropped out between the second and third rounds of the survey, we checked the responses from the participants who participated in both the second and third rounds of the Delphi survey (i.e., the core group). Still, the standard deviations of responses became smaller in the third round than responses from the core group in the second round. Therefore, the results suggest that convergence toward greater consensus was not introduced by respondents dropping out. For example, for the question "is climate change likely to spread beyond the present area?," 11

Table 4. Likelihood of climate change impacting the eastern and southern United States in the future.

Survey	Timescale (years)	Proportion of experts (percent)				
		Extremely likely	Somewhat likely	Neither likely nor unlikely	Somewhat unlikely	Extremely unlikely
Survey 2 (*N* = 12)	1–2	0	17	33	17	33
	3–5	0	33	25	17	25
	6–10	25	17	33	17	8
	>10	33	50	8	0	8
Survey 3 (*N* = 12)	1–2	0	42	17	17	25
	3–5	0	42	33	8	17
	6–10	25	33	25	17	0
	>10	42	50	8	0	0

Table 5. Top factors contributing to oak susceptibility to climate change.

	Survey 2	Survey 3
Greatest proportion	Drought (**9**)	Drought (**8**)
	Host old age (**7**)*	Host old age (**6**)
	Extreme variations in temperature (**7**)*	Extreme variations in temperature (**4**)
Least proportion	Host outside climatically adapted range (**5**)†	Host outside climatically adapted range (**3**)‡
	Fire (**5**)†	Human activity (**3**)‡
	Presence of defoliating insects (**5**)†	
	Human activity (**5**)†	

Note: Numbers shown in bold indicate the number of responses for each factor.
*Tied for second place.
†Tied for third place.
‡Tied for fourth place.

out of 14 respondents chose "yes" in the second survey. Of those 11 participants, eight participated in both the second and third rounds of the survey. In the third round of the survey, all 12 respondents choose "yes." For the question asking about "the percentage of oak trees susceptible to climate change," the standard deviation was 29.87 for all respondents in second survey and 31.63 for those respondents participating in both the second and third rounds. However, the standard deviation decreased to 19.29 in the third survey, and the coefficient of variance followed the same trend. The "certainty of the proportion of susceptible oak trees" also increased from 1.93 in survey 2 (or 2.00 for respondents participating in both survey 2 and 3) to 2.75 in survey 3. Moreover, for several questions, such as "forest types where oaks make up *X* percent of the trees are impacted," and "forest types where oaks make up *X* percent of the trees are likely to be impacted, if the threat spreads," many respondents in survey 2 did not provide answers to these questions, whereas in survey 3 all respondents provided answers. This suggests that participants had more confidence and more certainty in their responses after viewing the responses from the previous round. However, the variance in responses did not decrease in all cases between surveys 2 and 3. For example, for the question "would climate change likely impact oak regeneration?," all 14 participants choose "yes" in survey 2; however, one out of 12 respondents chose "no" in survey 3.

Discussion

Climate change and new and/or emerging (exotic) pathogen/pest emerged as two future threats of particular concern. Climate change was also identified as a current threat to oaks, and in other parts of the world it (specifically variation in precipitation and temperature) is associated with oak mortality and reduced growth (Natalini et al. 2016). In Swanston et al. (2018), climate change was also identified as a threat to forests of the midwest and northeastern United States. We also asked experts a series of questions to gage the potential impact of the most critical future threat identified in the first survey, climate change, on oaks in the eastern

Table 6. Rank and standard deviation of current and future threats in surveys 2 and 3 based on the responses of experts who participated in all three rounds of the survey (i.e., the core group).

		Survey 2		Survey 3			
	Threat	Rank	SD	Rank	SD	Greater consensus	Ratio*
Current	Gypsy moth	3	1.41	2	1.54	No	1.09
	Oak wilt	5	1.22	3	1.22	No	1.00
	Oak decline	1	1.50	1	1.17	Yes	0.78
	Climate change	2	1.83	4	1.59	Yes	0.87
	Drought	4	1.36	5	1.12	Yes	0.82
Future	Sudden oak death	4	1.39	5	1.39	No	1.00
	Oak wilt	5	1.66	4	0.76	Yes	0.46
	Oak decline	2	1.19	3	1.39	No	1.17
	New pest/pathogen	1	1.60	1	0.71	Yes	0.44
	Climate Change	3	1.93	2	1.01	Yes	0.52

Note: SD, standard deviation.
*Ratio of survey 3 and survey 2 standard deviations. Ratio <1 suggests there was convergence toward a consensus, i.e., variance decreased.

United States. Although expert judgment is not a substitute for empirical scientific research, it can provide useful insights for researchers, forest managers, and policymakers, and may be useful for directing ongoing and/or future research aimed at addressing threats as part of forest-management plans and policy, as well as helping to identify data gaps and uncertainty.

By the third iteration of our Delphi survey, experts determined that the most critical future threat to oaks in this region is some heretofore-unknown new or emerging (exotic) pest/pathogen. The purpose of the Delphi method is to achieve consensus among a group of experts. However, attrition during the course of our survey series combined with differing viewpoints on the relative importance of different threats made it difficult to achieve a consensus on this topic. Still, we were able to glean useful information on the potential future impacts of climate change on oak resources, although experts varied in their level of certainty, depending on the topic.

Given past examples of the devastating impact of nonnative pathogens and pests, e.g., chestnut blight fungus (*Cryphonectria parasitica*) decimating American chestnut populations and the emerald ash borer (*Agrilus planipennis*) causing widespread mortality of ash species (*Fraxinus* spp.), it is not surprising that the possibility of some new pathogen or pest with the ability to cause extensive oak mortality is a serious concern. These threats at one time were also unknown, emerging threats. Changing climatic conditions may also facilitate the spread, establishment, and intensity of unknown future and even known current threats (e.g., southern pine beetle, *Dendroctonus frontalis*) (reviewed in Weed et al. 2013). As with other invasive insects and pathogens, it is likely that accidental human introduction via global trade would be the source of this potential threat (Hulme 2009). Indeed, during the past one and a half centuries, nonnative forest insect species have been accumulating in United States forests at the rate of approximately 2.5 insects per year, and high-impact insects and pathogens have been accumulating at the rate of about 0.5 pests per year (Aukema et al. 2010). A recent analysis of the economic impacts of high-impact, nonnative forest insects in the United States concluded that there is a 32 percent risk that a new wood-boring insect that is as damaging as, or costlier than, the emerald ash borer will become established in the next 10 years (Aukema et al. 2011). Thus, whereas there are clear precedents for these types of events resulting from international trade, because of the uncertain nature of this threat and the end of the survey series, informed estimates could not be made about when and how this threat would impact oak species. However, the findings of our survey lend support to national regulatory and awareness efforts to prevent the introduction and establishment of novel exotic insects and pathogens because of potential unanticipated consequences.

Climate change was identified by experts as the most critical future threat in the first two surveys and as the second most critical future threat in the third survey based on the responses of all experts, regardless of whether or not they participated in all three survey rounds (Table 1). This discrepancy is likely

Table 7. Summary of responses from the second and third surveys used to evaluate consensus.

Question	Measurement	Survey 2 (core)*	Survey 2 (all)†	Survey 3‡
Is climate change likely to impact other tree species, besides oaks?	Yes	11	15	11
	Uncertain	1	2	1
Would climate change likely impact oak regeneration?	Yes	11	14	11
	No	0	0	1
Is climate change likely to spread beyond the present area?	Yes	8	11	12
	No	3	3	0
Percentage of oak trees susceptible to climate change	Mean	54.70	51.83	55.75
	SD	31.63	29.87	19.29
	Min	15	15	25
	Max	100	100	100
	CV	0.58	0.58	0.35
	N	10	12	12
How certain of the proportion of susceptible oak trees?	Mean	2.00	1.93	2.75
	SD	1.26	1.28	1.29
	Min	1	1	1
	Max	4	4	5
	N	11	15	12
How long does it take to observe dead or dying oaks?	Mean	3.00	3.07	3.33
	SD	0.89	0.92	0.89
	Min	2	2	2
	Max	4	4	4
	CV	0.30	0.30	0.27
	N	11	14	12
To what degree will climate change impact oak regeneration?	Mean	3.45	3.43	3.42
	SD	1.21	1.56	0.90
	Min	1	1	2
	Max	5	5	4
	CV	0.35	0.45	0.26
	N	11	14	12
Likelihood of threat in the future: 1–2 years	Mean	2.38	2.33	2.75
	SD	1.19	1.15	1.29
	Min	1	1	1
	Max	4	4	4
	CV	0.50	0.49	0.47
3–5 years	Mean	3.25	3.00	3.00
	SD	1.28	1.28	1.13
	Min	1	1	1
	Max	5	5	4
	CV	0.39	0.43	0.38
6–10 years	Mean	3.75	3.33	3.67
	SD	1.64	1.30	1.07
	Min	2	1	2
	Max	5	5	5
	CV	0.44	0.39	0.29
>10 years	Mean	4.25	4.00	4.33
	SD	0.71	1.13	0.65
	Min	3	1	3
	Max	5	5	5
	CV	0.17	0.28	0.15
	N	8	12	12

Note: For questions with multiple (>3) categories of choices, answers from low to high were ranked as 1, 2, 3, 4… Summary statistics were calculated based on the rankings. CV, coefficient of variation; SD, standard deviation.

*Summarizes the responses from the second round from respondents who remained in the third round of the Delphi survey (i.e., core group).

†Summarizes all responses from the second round of the Delphi survey.

‡Summarizes all responses from the third round of the Delphi survey.

attributed to differing opinions among experts as to the most pressing threats to oaks in the eastern United States and attrition. Climate change is likely to impact other tree species besides oaks, impact all oak groups, and also have negative impacts on oak regeneration. Furthermore, the impact of climate change may differ depending on the specific location of oaks within the eastern United States. However, teasing apart regional differences of climate change effects within the eastern United States was beyond the scope of the present survey. This is of particular concern given historical and current systemic issues with oak regeneration in the United States (reviewed in Dey 2014), and may have serious ecological and economic implications. Furthermore, whereas experts agreed that the impacts of climate change would likely be gradual and are somewhat or extremely likely to be observed >10 years in the future, a majority consensus could not be achieved on where climate change is likely to impact oaks, either in the present or in the future. This was due primarily to a great degree of uncertainty among participating experts, which is likely a result of the complex and interacting factors that make tree species in general vulnerable to climate change. The majority of surveyed experts were able to agree that the impact of climate change on oaks is likely to spread beyond its current distribution. Furthermore, given that experts tend to be systematically overconfident in their responses (Morgan et al. 2001), the subjective evaluations provided in our survey responses, regarding the proportions of oaks in impacted areas that are vulnerable to future threats, are likely to be overly optimistic.

Experts identified a list of factors that may make oaks more susceptible to climate change in the future including biotic and abiotic stressors and management-related factors, e.g., drought, host old age, extreme variations in temperature, host outside climatically adapted range, and human activity. Although drought and extreme variation in temperature are often associated with climate change, these and the other factors can affect oak susceptibility to pests and pathogens, and are associated with altering pest/pathogen life cycles leading to outbreaks (reviewed in Weed et al. 2013). Furthermore, host old age and host outside climatically adapted range can be attributed to management-related decisions.

Limitations and Future Directions

It is difficult to achieve total agreement among all respondents for topics with large uncertainty, such as climate change. However, the Delphi survey is designed to help experts attain greater consensus over iterations of the survey through opinion filtering. Our survey results show that consensus increased for questions related to the impacts of climate change on oaks and for the top current and future threats likely to impact oaks. Although limited time and resources only allowed for three survey rounds, another round may have helped clarify areas where consensus could have been improved (e.g., spatial extent of the threat).

In addition, the survey would likely have benefited from asking respondents to provide reason and logic for their responses, which then could have been summarized and included along with the summary of results from previous rounds. This would have allowed us to better understand the reasoning behind participants' choices, and also evaluate the impact, if any, of each expert's level of familiarity with oaks on their choices. Future Delphi surveys should provide opportunities for respondents to provide reasoning for their choices, and include opportunities for discussion among participants at each stage, for example via face-to-face discussions led by survey coordinators. Conducting the survey in person, e.g., at professional or industry meetings, may provide a better environment for fostering discussion and also encouraging continued participation from experts (Donohoe and Needham 2009).

However, we note that processes that permit experts to meet for extended periods of time have been shown to result in a greater diversity of opinions regarding complex topics such as climate change impacts on forests (Morgan et al. 2001). Because residual scientific uncertainty may provide the basis for fruitful hypothesis testing, diverse opinions should not be mistakenly dismissed simply because they do not represent majority views. Care should be exercised in how consensus opinions are communicated (Pearce et al. 2017) and used in subsequent scientific research and decisionmaking.

To obtain a more comprehensive understanding of threats to oaks and their potential impact on this region, the focus of future research should include an investigation of the impacts of management-related threats, as well as the combined impact of other threats (like climate change). This study has implications for prioritizing the future management of oak resources to minimize impacts from biotic and abiotic stressors in the eastern United States in the future as well as pointing to areas where more research is needed. In addition, more research on management and economic drivers (and their interaction with biotic and abiotic threats) would greatly inform our understanding of current and future oak threats.

Supplementary Materials

Supplementary data are available at *Journal of Forestry* online.

Supplement 1. PDF of three-part Delphi survey used in this study.

Supplement 2. Table listing current and future threats to oaks in the eastern and southern United States identified by experts in survey one and ordered based on weighted totals.

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