Research Article

Characteristics of Information Available on Fire and Invasive Plants in the Eastern United States

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ABSTRACT

Wildland managers need detailed information about the responses of invasive species to fire and the conditions that increase site invasibility in order to effectively manage fire without introducing or increasing populations of invasive plants. Literature reviews and syntheses of original research are important sources of this information, but the usefulness of a review is limited by the quantity, quality, and geographic coverage of information available when it is written. This study analyzed the information available for 61 syntheses published in the Fire Effects Information System (www.fs.fed.us/database/feis) between 2008 and 2011, covering 74 species of invasive plants in the eastern United States. The study focused especially on the origin of information available in source documents, particularly whether or not it was based on actual observations. We found that observation-based information available on fire and eastern invasive species was sparse, typically came from a small portion of the species' North American range, and had many other limitations. Nine of the 61 reviews contained no observation-based information on fire at all. Observations of postfire abundance of invasive species were constrained by inconsistent metrics and short postfire time frames, making it difficult for reviewers to assess patterns or evaluate the relevance of the research to long-term fire effects and land management strategies. More high-quality information is needed for fire managers to avoid exacerbating problems with invasive plant species. Long-term studies are needed that compare burned and unburned sites, evaluate postfire changes in plant communities, and report burning conditions and fire parameters. Reviews and syntheses of research can be improved by not only identifying patterns and knowledge gaps, but also by reporting the geographic areas represented by studies cited and hedging information so that readers can assess its quality and applicability to local management issues. Managers need to recognize the limitations of scientific information, monitor results of their management programs for consistency with reports in the literature, and adapt plans for future work based on an integration of science-based knowledge and experience.

Keywords: fire, fire effects, fire regimes, fuels, invasive species, monitoring, prescribed fire, research, synthesis

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INTRODUCTION

When a wildland area includes populations of invasive or potentially invasive plants (i.e., plant species that establish, persist, spread, and cause ecological harm in at least part of their range [Randall 1997, Westbrooks 1998]), all aspects of fire management, from initial plans to burn objectives and follow-up, must be fine-tuned based on an understanding of how these plants are likely to respond to various kinds of fire, fire management activities, and the postfire environment. To plan, make decisions, and take action regarding fire management without promoting or exacerbating plant invasions, managers need detailed knowledge about complex issues. Specific information includes the likelihood of establishment, persistence, and spread of invasives in various plant communities under various disturbance regimes; probable interactions of invasive plant species with desired native plant species; ways in which these interactions influence community and ecosystem properties over time; and short- and long-term consequences of wildfires and fire management, including prescribed fire, fire exclusion, fire suppression, and postfire rehabilitation.

A resource manager planning to use prescribed fire or deciding how to manage a wildfire needs to translate resource objectives, such as optimizing conditions for desired species, into burn objectives, which might address litter and duff removal, scorch height, spatial uniformity, and burn size. Weather and fuel conditions, fire season, and fire frequency are then selected to safely meet burn objectives and help meet resource objectives. Where invasive species are present or occur nearby, managers also need to anticipate potential impacts of invasives on the postfire community; these impacts may include interference with desired species, changes in community structure, and alterations in fuel characteristics and behavior of future fires.

Ideally, all available knowledge is integrated to determine a wise course of action (Krueger and Kelley 2000, Peters 2010). To do this, managers utilize their own experience and that of colleagues; monitoring data from past fires; and science-based information from technical and scientific sources, including publications that review earlier studies and synthesize results (e.g., Brooks and Lusk 2008, Zouhar *et al.* 2008*b*). The information basis for such syntheses and its limitations are the focus of this paper. In particular, we analyzed the information available on relationships between fire and selected invasive plant species in the eastern United States. The species were selected for a project to increase information in the Fire Effects Information System (FEIS, at www.fs.fed.us/database/feis) on eastern invasive plant species, with a goal of helping land managers better anticipate interactions between fire and invasive plants and plan for desired outcomes. The project, supported by the Joint Fire Science Program, followed up on an earlier, nationwide project in which 60 nonnative invasive plant species were reviewed.

Syntheses not only organize and analyze existing information, but also create new, "emergent" knowledge, in which the whole is greater than the sum of the parts (e.g., Pickett *et al.* 2007, Carpenter *et al.* 2009, Peters 2010). In addition to providing insights about general patterns (and lack thereof), a carefully constructed, well documented synthesis can address several of the needs identified in a survey of land managers, including the need for papers that aggregate the results of multiple studies, screen information and present what is most relevant to managers' needs, and clarify the applicability of research results to specific locations and management strategies (Barbour 2007).

Although syntheses are useful to managers and are frequently requested, they have limitations. Most importantly, a synthesis is limited to the quantity and quality of information available when it is written. Therefore, it may be just as important to explain what is not known about an issue as to report what is known. Several authors have commented on this problem in regard to the temporal and geographical coverage of ecological research (e. g., Belovsky *et al.* 2004, Peters 2010).

In disturbance ecology, information from long-term studies is essential for assessing the rate and direction of change in an ecosystem, distinguishing directional trends from short-term variability, determining the effects of infrequent events, and describing time lags in ecosystem responses (Peters 2010). Information from long-term assessments is also needed for understanding plant invasions, since invasive populations often increase after disturbances (e.g., Hobbs and Huenneke 1992), including fire (e.g., D'Antonio 2000). Syntheses on plant invasions have noted that invasive populations can fluctuate over time, staying small for long periods then increasing dramatically (e.g., Ewel 1986, Kowarik 1995). According to a review on plant invasions in eastern forests (Luken 2003), low light availability limits invasions in eastern forests, and canopy gaps may lead to establishment and spread of nonnative plants, depending on proximity of propagules. When establishment or spread of nonnative species is observed or anticipated following a disturbance such as fire, long-term data are needed to understand whether these populations will become invasive.

The spatial extent of ecological research is often limited to a portion of the range in which a species or process occurs (Svejcar and Havstad 2009). For example, information regarding the distribution of plant species in the United States appears to be biased by the distribution of botanists, tending to be most abundant in counties containing universities (Moerman and Estabrook 2006). Similarly, the locations of studies describing the postfire ecology of birds represent tropical ecosystems poorly, even though tropical ecosystems experience very large fires (Prodon and Pons 1992). The authors comment that the distribution of research on this topic "reflects more the distribution of the fire-ecologists than the fires themselves" (Prodon and Pons 1992: 332). The distribution of research regarding fire and invasive species is likely to be biased toward communities where the invasive plants are well established and most problematic, communities with frequent fire (wild or prescribed), and communities that are easily accessed, such as university arboretums or experimental forests. The scientific literature is less likely to contain information on recent invasions or geographical outlier populations.

A synthesis should inform readers about the lack of important information and the nature of the information presented, including its strength as a basis for generalization. It should specify whether the information is based on direct observation, inference, extrapolation, or speculation, and whether it is based on a few casual observations or a rigorous, randomly sampled study design. It should also address whether the results cover a wide range of ecosystems or focus on a limited area and set of conditions. If the limits of the information or the nature of its source are not pointed out in a synthesis, the information can take on the appearance of scientific authority just because it is followed by a citation.

Some authors recommend indicating the type of publication being cited as a way to describe the nature and limits of information. For example, the text and bibliography of a paper could be coded to inform readers about the type of publication, such as by using DCH to indicate originally researched Documented Case History, ER to indicate Experimental Research, PRK for Professional Resource Knowledge, and SS for Scientific Synthesis (Krueger and Kelley 2000). A "quality of evidence" scale based on research design and statistical robustness could also be used to rate each study used in a review (e.g., Peppin *et al.* 2010). Other criteria, such as the type of analysis (original research, naturalist observations, conceptual review, etc.) and publication outlet (peer-reviewed journal, proceedings, dissertation or thesis, government report, etc.), could also be used to classify articles used in a review (e.g., Leidolf and Bissonette 2009).

All three of these methods (Krueger and Kelley 2000, Leidolf and Bissonette 2009, Peppin *et al.* 2010) classify entire sources (articles, reports, etc.) rather than specific assertions within the sources. This practice can be somewhat misleading. For example, if the author of a synthesis is reporting a study's experimental results, then Krueger and Kelley's (2000) category Experimental Research would be appropriate. However, if the synthesis author is reporting speculations from the conclusions section of the same paper, the same classification scheme would indicate incorrectly that these are experimental results. Whether authors of reviews and syntheses use formal classification schemes or simple hedging (e.g., expressing uncertainty or noting conditions that limit the applicability of information), they should describe the nature of the information with sufficient detail for readers to assess its potential relevance to a particular management issue in a particular location.

Synthesis is the mission of FEIS, which was initiated in 1985 to provide managers with literature reviews of scientific information about individual species' relationships with fire. Syntheses (species reviews) produced by FEIS now cover more than 1 200 taxa that occur in the United States, providing information on their biology, ecology, and relationships to fire. In 2008, we began a project to increase FEIS coverage of invasive plant species in the eastern United States by adding or updating 61 species reviews covering 74 taxa. In the process, we noted many topics for which information was often missing or seemed weak as the basis for generalizing or applying to management issues. Upon completion of the 61 species reviews, we quantified and classified these information gaps.

This paper describes the quantity and quality of information on eastern invasive plants and their relationship to fire, based on the species reviews published through the project, and describes the difficulty of detecting patterns of change in invasive plant abundance after fire. Comprehensive reviews on fire and nonnative invasive plants in the northeastern (Dibble *et al.* 2008) and southeastern United States (Stocker and Hupp 2008) noted a lack of peer-reviewed literature and abundant information needs. This analysis may help managers understand the limitations of knowledge presented in syntheses and apply that knowledge to management with appropriate caution. Our description of the gaps and shortcomings of information found in this project may help focus future research on topics and species for which information is poor or absent, improve the design of future studies, and improve the usefulness of future syntheses. The objectives of this analysis were to:

1) evaluate the quantity and quality of information on fire and invasive plants in the eastern United States,
2) explore relationships between reported changes in postfire abundance and the quantity and quality of available information,
3) evaluate the quantity and quality of nonfire information that could be used to make inferences about fire, and
4) evaluate the geographic scope of information available on fire and eastern invasive plants.

METHODS

We selected the plant species to review for this project based on management concerns combined with an estimate of the amount of biological and ecological information available for synthesis. Regional ecologists in the eastern and southern regions of the US Forest Service provided lists of priority invasive plants (that is, plants considered invasive in at least part of their US range); additional suggestions were provided by managers of federal and Nature Conservancy lands in the eastern states; and species were also considered if they were mentioned in previous syntheses of relationships between fire and invasive plants (Dibble *et al*. 2008, Grace and Zouhar 2008, Stocker and Hupp 2008). From these sources, we selected the species to review as follows:

1) We prioritized species occurring in several wildland areas, especially those in both the eastern and southern regions of the Forest Service.
2) We sought balance with regard to the number of species from each region.
3) We excluded the following: aquatic species, species for which an initial search of the scientific literature yielded few sources, and 36 eastern invasive species that had been reviewed in FEIS since 2000.
4) After reviews of two major forage grasses were completed, we assigned this category a low priority because the literature's predominant focus on treatments to increase productivity makes it particularly difficult to interpret in terms of fire effects.

Thus, the species reviewed for this project represent a subjective selection rather than a random or systematic sample of invasive plant species in eastern North America.

For this project, 61 reviews, which covered 74 invasive plant species, were published in FEIS. We grouped species into a single review if they were within the same genus, and if morphological and ecological similarities suggested that they might respond similarly to fire. Results reported here are based on counts of FEIS literature reviews rather than counts of individual species.

Information Included in Species Reviews

Authors of FEIS reviews surveyed all relevant English-language literature available on a species, including literature from both the species' invaded range and the native range, if available. The Citation Retrieval System (the bibliographic database that supports FEIS, at feis-crs.org) was searched for information on every species. Scientific and government literature databases were also searched, including some combination of the following:[1] JSTOR®, ISI Web of Knowledge℠, Ovid®, DigiTop, Tall Timbers Fire Ecology Database©, ProQuest Digital©, and WorldCat®. These searches yielded journal articles, theses, dissertations, proceedings articles, and some gray literature such as weed management handbooks, fact sheets, and extension pamphlets. If search results were sparse, the Internet was explored for additional information. When information gaps remained after these searches, authors attempted to contact managers familiar with the species and included their insights, identified as personal communications, in species reviews.

Species reviews for FEIS describe the distribution of each species, its basic biology and ecology, its relationship to fire, and other management issues. Most of these topics were identified by managers in the mid-1980s as being critical to understanding fire effects (Fischer *et al.* 1996). A few topics have been added as management issues have evolved; for example, reviews of invasive species written in recent years describe impacts of the species on native ecosystems and survey control methods. Species reviews for this project were written using a template and protocols developed specifically for invasive species. Each review was examined and edited by two ecologists before publication on the FEIS website.

Assessing the Information Available for Species Reviews

We examined the 61 species reviews to determine the quantity, quality, and geographic scope of information available on the species' relationships to fire. We focused on eight topics directly related to fire (Table 1) and nine botanical and ecological topics indirectly related to fire that might be used to make inferences about fire responses (Table 2).

[1] The use of commercial software names in this article publication is for reader information and does not imply endorsement of any product or service by any of the organizations represented here.

Table 1. Fire-related topics targeted in literature searches for information on relationships between fire and invasive plants.

Topic	Description
Fire regimes	Fire regime characteristics (season, frequency, severity) that can be tolerated by an invasive species and effects of invasive species on the prevailing fire regime.
Fuels	Information on fuel characteristics of invasive plants and changes in fuel characteristics of invaded plant communities.
Heat tolerance of seed	Information about seed survival or mortality after fire or heating.
Immediate fire effects on plant	Indications of plant survival, damage, or mortality immediately following fire.
Postfire occurrence	Documentation of plants occurring on burned sites, but without abundance measurements, comparisons to prefire or unburned conditions, timing of postfire establishment, or indication of whether individuals were sprouts or seedlings.
Postfire abundance	Data from specific measures of abundance (e.g., cover, frequency, density) after fire, compared with measurements before fire or on similar unburned sites.
Postfire seedling establishment	Reports of seedling establishment after fire or on burned sites, typically within one to two growing seasons after fire.
Postfire vegetative response	Information on postfire sprouting, including both qualitative and quantitative reports.

Quantity and Quality of Information on Fire Topics

To quantify the number of unique sources that included direct observations within each review, we counted every reference that contained observation-based information on fire. Our definition of "observation-based" was similar to Leidolf and Bissonette's (2009) definition of "original research," which includes empirical research as well as more casual field observations. We also counted the number of "fire experiments" found in the literature for each review, a subset of the count of unique sources. Fire experiments were defined as studies that provided information on fire conditions and fire behavior, and reported quantitative comparisons between burned and unburned, or prefire and postfire, communities. Fire experiments were singled out because they generally give a clearer, more objective, and complete description of fire and fire effects than less rigorous fire studies, so their results can more readily be compared with those of other fire experiments.

To quantify the information available on individual fire topics, we recorded, for each species review, every instance in which a source was cited for a fire topic. These discrete instances differed from the count of unique sources because, using this technique, we counted a source more than once if it was cited in regard to more than one topic within a review. We then classified the information given in each instance as to its "quality," as indicated by evidence that the information was based on field observations or measurements (Table 3). "Observation-based" information was considered to be the highest quality because it could be traced back to direct observations or measurements. "Experience-based" information was considered to be intermediate in quality because it did not have a clear basis in observation. "Unverifiable" information

Table 2. Botanical and ecological topics targeted in this study and their potential indirect relationship to fire and the fire topics listed in Table 1.

Botanical or ecological topic	Potential relationship to fire	Fire regimes	Fuels	Heat tolerance of seed	Immediate fire effect on plant	Postfire occurrence, abundance	Postfire seedling establishment	Postfire vegetative response
Seed production	May indicate potential for establishment from on- or off-site seed after fire.					X	X	
Seed dispersal						X	X	
Seed banking				X		X	X	
Seedling establishment						X	X	
Belowground phenology	May indicate when fire will have the greatest impact on perennial species.				X	X		X
Asexual reproduction	May indicate potential for sprouting and potential abundance after fire.				X	X		X
Shade tolerance		X	X			X		
Response to nonfire disturbance		X	X		X	X	X	X
Other succession information	May indicate potential to establish and thrive in postfire environment and ability to persist through succession.	X	X			X	X	X

was considered to be the lowest quality because it consisted of inferences and assertions with no citations, so the basis was unknown.

Unlike the classification of entire sources recommended by Krueger and Kelley (2000), this approach can account for different kinds of information within a single source. For example, a source could be listed under one topic as providing observation-based information (if, for example, results of field experiments were cited), and under another topic as providing experience-based or unverifiable information (if, for instance, speculations from the conclusions section were cited).

Information on Postfire Abundance

Because trends in postfire abundance are of particular interest to managers dealing with invasive species, we examined each report of postfire abundance for the species reviewed. We recorded whether the invasive species population increased, decreased, or was unchanged after fire, and noted how long after fire the measurements or observations were made. We also recorded information on the fires reported in these studies, including frequency, severity, and season, and we recorded whether the data were analyzed statistically.

Information on Nonfire Topics

To quantify information on nonfire topics that might form the basis for inferences about potential fire responses, we recorded, for each species review, every instance in which a source was cited for one of nine botanical and ecological topics (Table 2). In the rare cases

Table 3. Categories used to describe quality of information used in FEIS reviews of invasive plants in the eastern United States.

Category	Information type	Description
Observation-based	Direct observations or measurements by a researcher or manager	Direct measurements and observations, even if not compared with a control group. Includes results from experiments, published or unpublished; information recorded in floras; personal communications from managers.
Experience-based	Information likely based on a history of direct observations	Information from publication that does not identify basis in observations. This information typically came from syntheses, weed guides, and fact sheets that were written by resource managers or field scientists familiar with the species but did not contain in-text citations, so the source of an assertion could not be determined.
Unverifiable	Synthesis not clearly based on observations	Information given in a literature review or synthesis for which the basis was not clear or not verifiable
	Inference	Assertion based on a collection of information, often found in syntheses and also in introduction and conclusion sections of research papers
	Unknown	Information from fact sheets or similar publications that contain neither bibliographies nor in-text citations
	Unsubstantiated claim	Unverifiable statement, typically from literature lacking both in-text citations and bibliography

where substantial fire information was available, we abbreviated this analysis, so it was not as comprehensive as the analysis of information on fire topics.

Geographic Scope of Information

Biological and ecological information related to invasive species often comes from areas where the species is most invasive or problematic, or where its study is most convenient. Thus, because many invasive species are widespread and continue to spread in their invaded range, information about their ecology and relationship to fire is likely to come from only part of their US range. To approximate the geographic scope of information on fire for each review, we counted the US states in which observation-based fire information was available. We then compared that number to the total number of states in which the reviewed species occurs, based on distribution maps in the Natural Resources Conservation Service's PLANTS Database (USDA Natural Resources Conservation Service 2011). Thus, we used state distributions as a surrogate for the actual geographic scope of information. We did not assess geographic scope of information on biological and ecological topics.

RESULTS

Quantity and Quality of Information on Fire Topics

Nine of the 61 reviews (15%) cited no sources with observation-based information on fire. Fewer than half of reviews cited more than five such sources (Table 4). For this project, review authors examined more than 2000 sources that had information about fire and at least one of the reviewed species. Only 23 of these were classified as fire experiments; that is, quantitative comparisons between burned and unburned (or prefire and postfire) communities that included details about the

Table 4. Species reviewed for this project, number of sources with observation-based information, number of sources with fire experiments, and highest quality of information available on each fire-related topic. A = observation-based; B = experience-based; C = unverifiable; None = no fire information available.

Species covered by review	Number of observation-based fire information sources	Number of fire experiments sources	Fire regimes	Fuels	Heat tolerance of seed	Immediate fire effect on plant	Postfire occurrence[a]	Postfire abundance	Postfire seedling establishment	Postfire vegetative response
Aegopodium podagraria L.	0	0	None	None	None	None	None	None	None	None
Ailanthus altissima (Mill.) Swingle	12	2	C	A	None	A	A	A	A	A
Albizia julibrissin Durazz.	9	0	A	A	A	None	A	A	A	None
Ampelopsis brevipedunculata (Maxim.) Trautv.	0	0	None	None	None	None	None	None	C	C
Berberis vulgaris L.	2	0	None	A	B	A	None	None	None	A
Celastrus orbiculatus Thunb.	6	0	None	A	None	None	None	None	None	None
Cirsium palustre (L.) Scop.	1	0	None	None	None	None	A	None	None	None
Coronilla varia (L.) Lassen	4	0	None	B	A	None	A	C	None	None
Cynanchum louiseae Kartesz & Gandhi, *C. rossicum* (Kleopow) Borhidi	5	0	None	A	None	C	A	A	None	A
Dioscorea alata L., *D. bulbifera* L., *D. pentaphylla* L., *D. polystachya* Turcz., *D. sansibarensis* Pax	4	0	None	A	None	C	None	A	None	A
Dipsacus fullonum L., *D. laciniatus* L.	2	0	A	A	None	A	A	None	None	None
Elaeagnus pungens Thunb.	0	0	None	None	None	None	None	None	None	None
Eragrostis curvula (Schrad.) Nees	26	3	A	A	A	A	A	A	A	A
Euonymus alatus (Thunb.) Siebold	0	0	None	B	None	None	None	None	None	None
Euonymus fortunei (Turcz.) Hand.-Maz.	3	0	A	A	None	A	None	A	None	A
Euphorbia cyparissias L.	2	0	None	None	None	None	A	A	None	None
Euphorbia esula L.	10	0	C	B	A	A	A	A	A	A
Frangula alnus Mill.	8	3	A	A	None	A	None	A	A	A
Glechoma hederacea L.	2	0	None	None	None	None	A	A	None	None
Hedera helix L.	7	0	A	A	C	C	None	None	A	None

[a] This category was used for sources that reported presence or absence but included no measures of abundance, such as frequency, density, and cover; and no indication of whether individuals were seedlings or sprouts. If abundance measures were given, the source was tallied under Postfire abundance rather than Postfire occurrence. If seedlings or sprouts were identified as such, the source was tallied under Postfire seedling establishment or Postfire vegetative response, respectively, rather than under Postfire occurrence.

[b] NA indicates reviews that covered annual species, which were not expected to regenerate vegetatively following fire.

Table 4, continued. Species reviewed for this project, number of sources with observation-based information, number of sources with fire experiments, and highest quality of information available on each fire-related topic. A = observation-based; B = experience-based; C = unverifiable; None = no fire information available.

Species covered by review	Number of observation-based fire information sources	Number of fire experiments sources	Fire regimes	Fuels	Heat tolerance of seed	Immediate fire effect on plant	Postfire occurrence[a]	Postfire abundance	Postfire seedling establishment	Postfire vegetative response
Heracleum mantegazzianum Sommier & Levier	1	0	A	None	None	C	None	None	None	None
Hieracium aurantiacum L.	7	1	A	None	None	None	A	A	A	None
Hieracium caespitosum Dumort.	4	0	None	None	None	None	A	None	A	None
Hieracium piloselloides Vill.	4	0	None	None	None	A	A	None	A	A
Holcus lanatus L.	23	2	A	A	A	C	A	A	A	C
Iris pseudacorus L.	1	0	C	None	None	C	A	None	C	C
Kummerowia stipulacea (Maxim.) Makino, *K. striata* (Thunb.) Schindl.	11	0	C	A	A	A	A	A	A	NA[b]
Lespedeza bicolor Turcz.	14	1	A	A	A	A	None	A	A	A
Lespedeza cuneata (Dum. Cours.) G. Don	12	3	A	C	A	A	None	A	A	A
Lysimachia nummularia L.	0	0	C	None	None	None	None	None	None	None
Melia azedarach L.	5	0	A	C	None	None	A	A	A	A
Melilotus alba Medik., *M. officinalis* [L.] Lam.	40	1	None	None	A	A	A	A	A	A
Microstegium vimineum (Trin.) A. Camus	14	0	None	A	None	C	None	A	A	NA[b]
Miscanthus sinensis Andersson	11	0	A	A	None	A	A	A	A	A
Morus alba L.	4	0	None	A	None	None	None	None	None	A
Nandina domestica Thunb.	4	0	None	A	None	A	None	None	A	A
Neyraudia reynaudiana (Kunth) Keng ex Hitchc.	2	1	None	A	None	None	None	A	None	None
Paederia foetida L.	7	1	A	A	None	A	None	A	A	A
Panicum repens L.	9	0	None	A	None	A	A	A	None	A
Paulownia tomentosa (Thunb.) Siebold & Zucc. ex Steud.	9	0	None	A	A	C	None	None	A	None
Persicaria longiseta Blume var. *longisetum* (Bruijn) A.N. Steward	1	0	None	None	None	None	None	None	A	NA[b]

[a] This category was used for sources that reported presence or absence but included no measures of abundance, such as frequency, density, and cover; and no indication of whether individuals were seedlings or sprouts. If abundance measures were given, the source was tallied under Postfire abundance rather than Postfire occurrence. If seedlings or sprouts were identified as such, the source was tallied under Postfire seedling establishment or Postfire vegetative response, respectively, rather than under Postfire occurrence.

[b] NA indicates reviews that covered annual species, which were not expected to regenerate vegetatively following fire.

Table 4, continued. Species reviewed for this project, number of sources with observation-based information, number of sources with fire experiments, and highest quality of information available on each fire-related topic. A = observation-based; B = experience-based; C = unverifiable; None = no fire information available.

Species covered by review	Number of observation-based fire information sources	Number of fire experiments sources	Fire regimes	Fuels	Heat tolerance of seed	Immediate fire effect on plant	Postfire occurrence[a]	Postfire abundance	Postfire seedling establishment	Postfire vegetative response
Phalaris arundinacea L.	16	1	A	A	A	A	A	A	A	A
Phyllostachys aurea Carrière ex A. Rivière & C. Rivière	2	0	A	A	None	A	None	None	None	A
Polygonum aviculare L.	12	0	A	None	None	None	A	A	A	NA[b]
Polygonum perfoliatum L.	1	0	None	None	A	None	None	None	None	NA[b]
Polygonum sachalinense F. Schmidt ex Maxim., *P. cuspidatum* Siebold & Zucc., *P.* × *bohemicum* (J. Chrtek & Chrtkovß) Zika & Jacobson	8	0	None	A	None	A	None	None	None	None
Populus alba L.	3	0	None	A	None	A	None	None	None	None
Rhamnus cathartica L., *R. davurica* Pall.	22	0	None	A	None	A	A	A	A	A
Robinia pseudoacacia L.	33	5	A	A	A	A	A	A	A	A
Rubus phoenicolasius Maxim.	1	0	None	C	None	None	A	None	None	None
Schefflera actinophylla (Endl.) Harms	0	0	None	None	None	C	None	None	None	None
Schedonorus pratensis (Huds.) P. Beauv.	3	0	None	None	None	None	None	None	None	A
Schinus terebinthifolius Raddi	21	0	A	A	None	A	A	A	None	A
Solanum dulcamara L.	4	0	None	A	None	None	A	None	None	None
Solanum viarum Dunal	0	0	None	None	None	None	None	None	None	None
Tanacetum vulgare L.	0	0	None	C	None	None	None	None	None	None
Triadica sebifera (L.) Small	12	0	A	A	None	A	A	A	A	None
Tussilago farfara L.	5	0	None	None	None	None	A	None	A	None
Urochloa mutica (Forssk.) T.Q. Nguyen	5	0	A	A	None	A	A	A	A	A
Vinca major L., *V. minor* L.	7	0	None	A	None	A	A	A	None	C
Wisteria floribunda (Willd.) DC., *W. sinensis* (Sims) DC.	0	0	None	C	None	None	None	None	None	None

[a] This category was used for sources that reported presence or absence but included no measures of abundance, such as frequency, density, and cover; and no indication of whether individuals were seedlings or sprouts. If abundance measures were given, the source was tallied under Postfire abundance rather than Postfire occurrence. If seedlings or sprouts were identified as such, the source was tallied under Postfire seedling establishment or Postfire vegetative response, respectively, rather than under Postfire occurrence.

[b] NA indicates reviews that covered annual species, which were not expected to regenerate vegetatively following fire.

fire(s) (e.g., fire weather, fire behavior, fire severity, etc.). Six species reviews cited two or more fire experiments, and six reviews cited one fire experiment. No fire experiments were available for 49 reviews (80 %) (Table 4).

For many reviews, fire topics were not covered by observation-based information. Only three reviews (weeping lovegrass [*Eragrostis curvula*], reed canarygrass [*Phalaris arundinacea*], and black locust [*Robinia pseudoacacia*]) contained observation-based information on all eight fire topics. Twenty-seven reviews (44 %) contained observation-based information on two or fewer fire topics. For 21 reviews (34 %), discussion of at least one fire topic was based entirely on unverifiable information (Table 4).

The number of instances of cited information based on direct observations (versus experience-based and unverifiable information) varied among fire topics. Nearly two-thirds of the reviews contained at least some information on fuels, most of it based on direct observations (Figure 1). While only about half of the reviews contained information on postfire occurrence and abundance, most of this information was also based on observations. In contrast, about half of the reviews contained information on the immediate effects of fire on plants, and nearly a third of that information was unverifiable. The topic with poorest coverage by any type of information was heat tolerance of seed.

Information on Postfire Abundance

Observation-based information on postfire abundance was cited in 30 of the 61 species reviews. A close examination of this information revealed no patterns of postfire changes in

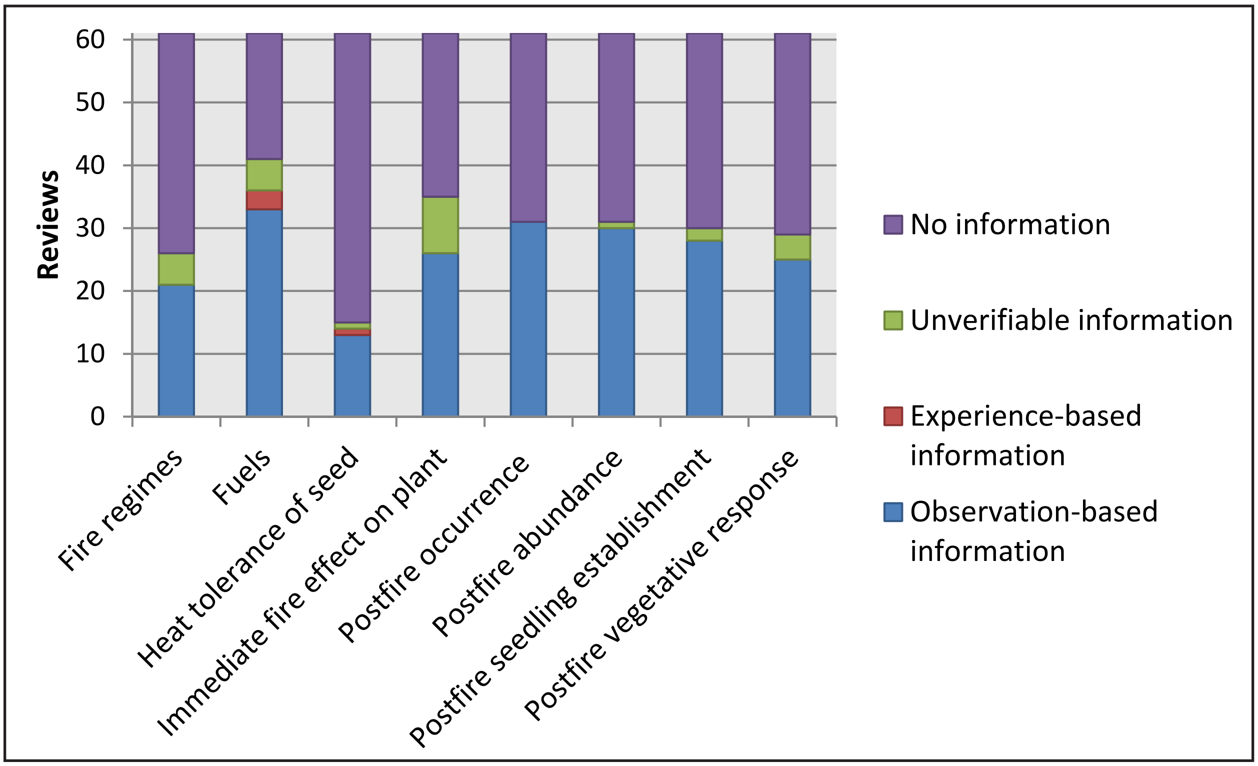

Figure 1. Distribution of information quality available for each fire topic in 61 FEIS species reviews. Bars are divided to show the highest quality of information available per review: observation-based, experience-based, unverifiable, or no information at all. Bar divisions show the number of reviews for which each information quality category is highest.

abundance that could be generalized to all (or most) of the invasive species covered. Clear patterns were evident for only four individual species. Nepalese browntop (*Microstegium vimineum*) and shrub lespedeza (*Lespedeza bicolor*) increased in abundance after fire, according to two instances of observation-based information for each species. According to three instances of observation-based information, common buckthorn (*Rhamnus cathartica*) abundance decreased after fire. Three instances indicated no change in leafy spurge (*Euphorbia esula*) abundance after fire.

In the remaining 26 species reviews that contained observation-based information on postfire abundance, the information was either inconsistent or too sparse to reveal patterns. In 18 of these reviews, only one or two instances of postfire abundance measurements were available. In the remaining 12 reviews, patterns of change in postfire abundance were difficult to discern due to variability in metrics, fire characteristics, and time since fire. Several studies used only qualitative terms to described changes in abundance, and no metrics were provided. Other studies typically reported frequency, cover, or density of plants, but none provided all of these metrics, and some reported less commonly used metrics, such as biomass, number of flowering stems, or seed production.

Other shortcomings related to the nature of the postfire abundance data and their analyses included the following:

- Seventeen of 99 instances failed to provide information on how much time had elapsed since fire.
- Thirty-eight instances reported results within only one year of burning, 23 within two years. Only 21 gave results beyond the second postfire year.
- Nine instances were from unverifiable information, so their basis in observation and scope of inference were unknown.
- Fewer than one-third of instances provided statistical comparisons of burned and unburned (or prefire and postfire) abundance.
- Several studies combined fire with other treatments (e.g., cutting, mowing, seeding) in ways that made it impossible to discern effects of fire alone for comparison with other research.
- Postfire abundance was seldom reported with or analyzed in relation to fire season, fire behavior, or fire severity, further hindering comparisons between studies.

Information on Nonfire Topics

For reviews with limited observation-based fire information, discussions about fire relationships required inference from botanical and ecological information, which was available for most species reviews. For example, of the nine reviews that had no information on any fire topic, all had observation-based information on seed dispersal, asexual reproduction, and shade tolerance, and many had observation-based information on seed production, seedling establishment, and response to nonfire disturbance. However, only about half of these reviews had information on seed banking and succession, and none had information on belowground phenology (Table 5).

Geographic Scope of Information

Observation-based information on fire topics generally came from a small fraction of the states in a species' US range. Of the 61 species reviews analyzed in this study, only one had observation-based fire information available from more than 50% of states in its US range: silkreed (*Neyraudia reynaudiana*), which only occurs in Florida (Figure 2). For 38 reviews, observation-based fire information originated in 25% or fewer of states in their US range and, for 26 of these, the information

Table 5. For species reviews with no observation-based fire information, the highest quality information provided on each botanical and ecological topic. A = observation-based; B = experience-based; C = unverifiable; None = no information available.

Species covered by review	Seed production	Seed dispersal	Seed banking	Seedling establishment	Belowground phenology	Asexual reproduction	Shade tolerance	Response to nonfire disturbance	Other succession information
Aegopodium podagraria	A	A	A	C	None	A	A	A	A
Ampelopsis brevipedunculata	A	A	None	A	None	A	A	None	A
Elaeagnus pungens	A	A	None	A	None	A	A	A	A
Euonymus alatus	A	A	None	None	None	A	A	None	B
Lysimachia nummularia	A	A	A	None	None	A	A	A	A
Schefflera actinophylla	B	A	A	A	None	A	A	A	None
Solanum viarum	A	A	A	A	None	A	A	A	B
Tanacetum vulgare	None	A	None	A	None	A	A	A	A
Wisteria floribunda, W. sinensis	None	A	None	C	None	A	A	None	B

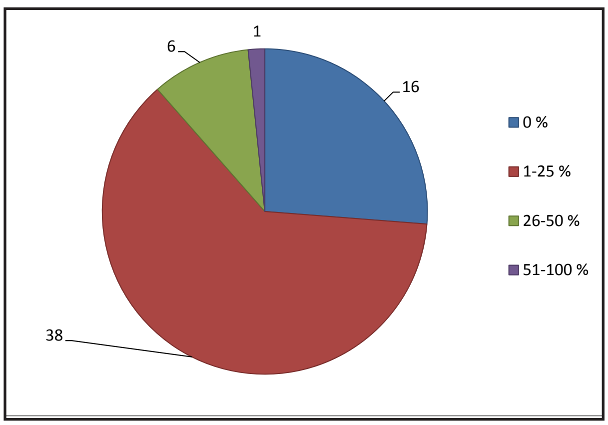

Figure 2. Geographic scope of observation-based fire information for species reviews. Number of species reviews with observation-based fire information from a given percentage of US states in which the species occurs. Zero indicates that no observation-based fire information was available.

originated in 5% or fewer. Even the species with numerous site-specific fire observations or studies (from within the United States) were rarely studied in more than a few states. For example, all site-specific fire observations or studies of weeping lovegrass came from only three of the 32 states where it occurs (Gucker 2009*b*). White mulberry (*Morus alba*) occurs in 48 states, but fire information comes from only one state (New Mexico) (Stone 2009*b*).

DISCUSSION

The relationship between fire and invasive plants in the eastern United States is well documented for only a handful of species. For most species, studies are sparse and information is incomplete. A similar lack of information was found for 60 nonnative invasive plant species occurring throughout the United States (Zouhar *et al.* 2008). This study focused on the quality of information as indicated by its basis in observation. This emphasis was not intended to denigrate the value of generalizing and making inferences, but rather to examine the field-based foundation of information available for generalizing, making inferences, and informing management decisions. A few species reviews completed in this project referred to numerous studies with observation-based information, but these were typically still inadequate to make predictions with confidence. Fire experiments, which should provide the most reliable observation-based information, were sparse and typically presented an incomplete picture of an invasive species' relationships to fire. Fact sheets and management guidelines, while generally available, typically lacked documentation to support their assertions.

Quantity and Quality of Information

Six species reviews in this project had more than 20 sources with observation-based fire information (Table 4), but coverage of fire topics was uneven and the information often had limited applicability to wildland management. For example, fire information on Brazilian peppertree (*Schinus terebinthifolius*) was relatively plentiful (probably because it occurs in ecosystems that are managed with frequent prescribed fire [e.g., Loope and Dunevitz 1981, Gunderson 1983, Doren *et al.* 1991, Dooley 2003]), but most of it addressed fuel characteristics and none addressed heat tolerance of seed or postfire seedling establishment (Meyer 2011). In contrast, 40 sources provided observation-based information on fire topics for the sweetclovers (*Melilotus alba* and *M. officinalis*), but none addressed fire regimes or fuels (Gucker 2009*d*). While fire information on weeping lovegrass and common velvetgrass (*Holcus lanatus*) seemed abundant, most of it came from research in US deserts (e.g., see Brooks 2008, Rice *et al.* 2008), so it had limited application to management in the eastern states. Furthermore, much of the information on weeping lovegrass addressed the use of prescribed fire to increase its productivity as a forage species (McIlvain and Shoop 1970, Klett *et al.* 1971), information with little relevance for managers attempting to reduce the species' abundance in wildlands. Because substantial resources must be invested to locate field sites for a study and carry out fire treatments, it seems unfortunate that few studies provide complete descriptions of burning conditions and fire behavior, and few report details that are easily observed in the field, such as whether individuals establishing after fire were seedlings or sprouts.

Fire Experiments

We found few controlled experiments addressing relationships between fire and invasive species in the eastern United States (Table 4), and even fewer focusing on the invasive plant or the invasion process. For most of the 23 fire experiments cited in species reviews, information on the invasive species was incidental to the study—included only because the invasive species happened to occur in the area. Only seven fire experiments focused on the invasive species being reviewed. A fire experiment can provide information that cannot be obtained in any other way, including quantitative comparisons of invasive populations between prefire and postfire (or burned and unburned) plant communities, and information on the effects of varying fire frequencies, severities, and seasons on postfire succession in invaded and uninvaded plant communities. Without experimental data and clear descriptions of fuels, burning conditions, and fire behavior, managers cannot assess the likelihood that an invasive species' response to a specific kind of fire in their management area will resemble the responses described in the studies.

Experience-Based and Unverifiable Information

While fire experiments were sparse, management guidelines and fact sheets on invasive plants were plentiful. These typically lacked bibliographies or in-text citations or both, making it impossible for review authors to verify the information, determine its basis, or assess its scope of inference. In some cases, publications offered fire management recommendations for species for which we found no observation-based information on fire. For example, two sources noted that creeping jenny (*Lysimachia nummularia*) may be controlled by frequent prescribed fire (Kennay and Fell 1992, Czarapata 2005), yet no observation-based fire information was available for this species (Table 4). Managers could find this information more useful and apply it appropriately if the sources explained the basis for their recommendations, such as the plant communities observed and the fire frequencies used in treatment. In other cases, experience-based or unverifiable information was inconsistent with observation-based information. For example, information from management guides and fact sheets on leafy spurge suggests controlling this species with prescribed fire in conjunction with herbicide treatments (Lym and Zollinger 1995, Solecki 1997, Biesboer and Eckardt 2004). However, two studies with observation-based, quantitative information found that combining prescribed fire and herbicide treatments did not improve leafy spurge control compared to herbicide treatments alone (Wolters *et al.* 1994, Prosser *et al.* 1999).

Information on Individual Fire Topics

Several problems with fire-related information were unique to specific topics. Among the eight fire topics studied, heat tolerance of seed not only had the poorest coverage in the literature, but also was based mostly on laboratory rather than field studies. If a paper reports germination before and after heating in an oven or boiling water, it is difficult to know if results will be similar after heating by a prescribed fire or wildfire—especially if no information is available on seed bank characteristics, such as seed density and depth of burial, for that species.

The topic of fire regimes was also poorly covered in the literature—both the fire regime characteristics that can be tolerated by an invasive species and the effects of invasives on prevailing fire regimes. The latter knowledge gap is not surprising, since many years of data are needed to document changes in fire regimes. Centuries of data are needed in the case of vegetation types with long fire-return intervals (Brooks 2008), and most studies evaluating the effects of invasive species on ecosystem processes only identify initial effects and span only a few years (Mack and D'Antonio 1998). However, because plant assemblages and communities are most likely adapted to disturbance regimes rather than to individual disturbances (Pickett *et al.* 1987), the understanding of invasive species' interactions with fire regimes may be critical for long-term protection of biodiversity and continuation of ecosystem-sustaining processes. More experimental studies are needed to investigate the effects of variation in fire season, fire severity, and fire-return intervals on native plant communities and invasive species.

Observation-based information on fuels, postfire occurrence, and postfire seedling establishment was available for about half of species reviews. This information may have been readily available in the literature because it is easily detected by casual observation; however, it rarely contained enough detail to assess how widely and reliably it could be applied. Fuels information, for example, often consisted of qualitative observations such as a species' tendency to form dense stands, produce abundant litter, or shade out understory herbs. Quantitative comparisons of fuel characteristics on invaded versus uninvaded sites were much less common; in fact, this information was available in the literature only for the reviews of common velvetgrass (Gucker 2008), common buckthorn (Zouhar 2011), and black locust (Stone 2009*c*).

Observation-based information regarding postfire vegetative response was available for nearly half of the reviews of biennial and perennial species. The information typically consisted of reports of sprouts on a burned site. Details useful for understanding the likelihood and magnitude of postfire sprouting, such as plant size, plant age, fire timing, fire severity, and comparisons to unburned sites, were rarely included. When no observation-based information was available on vegetative response to fire, review authors typically inferred potential for postfire sprouting from evidence of belowground reproductive structures or evidence of sprouting after other disturbances such as cutting, herbicide treatments, grazing, or browsing. However, fire effects may vary with plant phenology, fuel characteristics, fire severity, and site conditions in ways that are not reflected in the plants' responses to other top-killing disturbances.

Information on Postfire Response

This study revealed several limitations in the information available on postfire responses of invasive plants. In this study, we classified instances in which sources were cited in regard to the presence or absence of a species on burned sites as "postfire occurrence," while instances providing measurements such as density or cover were classified as "postfire abundance." Reports of postfire occurrence had limited usefulness. They lacked quantitative information, and they seldom indicated when or how the plant established relative to fire—whether it was an adult unharmed by fire, a sprout that emerged after top-kill by fire, or a seedling that established some time (possibly years) after fire. These reports only documented species present in a particular burned area at a particular time; they did not provide enough information to estimate the likelihood that the species would establish, persist, or change in abundance on burned sites in general. Similarly, reports of postfire seedling establishment were often limited to observations of seedlings on a burned site without details about time of establishment, distance to the nearest seed source, and seed bank characteristics—information that could help managers judge the vulnerability of specific areas or plant communities to postfire establishment of invasive plants and expansion of existing populations.

Information on postfire abundance of invasive plant species is important for assessing the potential impact of that species in plant communities affected by wildfire or managed with prescribed fire, because relative abundance may be used to infer ecological impact (e.g., Luken 2003). This analysis highlighted several shortcomings in the quantity and quality of postfire abundance information that limited its usefulness for estimation of trends and application to places and circumstances outside the scope of the individual studies. The most obvious challenge in comparing results of different studies is their use of different metrics to indicate abundance. Because it is possible for one of these metrics to increase while another decreases, they cannot be directly compared.

Another limitation of information on postfire abundance was its short-term nature. Managers are charged with sustaining biodiversity and ecosystem processes for generations to come, but most of the research on fire effects used in this project covered no more than two postfire years. Information on postfire abundance was available for about half of the species reviews in this project, but responses to fire were measured at a variety of times since fire, so studies could not be directly compared. Additional shortcomings included failure to report fire season and severity, failure to account for effects of nonfire treatments such as grazing and herbicide use, and lack of statistical analyses. Given these problems, it is not surprising that our analysis of information on postfire abundance did not demonstrate any consistent patterns across all species. It was difficult to discern patterns even at the species level, because most reviews included only one or two studies that described postfire abundance, and when multiple studies were available, they often reported contradictory results.

Inferences about Fire Based on Biological and Ecological Information

Where observation-based information on fire was absent, review authors often inferred potential fire relationships from botanical and ecological data, which was available for most species reviews. When authors based an assertion on inference, they described the basis for the inference rather than presenting it as though based on observation. For example, although immediate fire effects on common tansy (*Tanacetum vulgare*) were not reported in the literature, the species review (Gucker 2009*e*) reports that its rhizomes are generally robust, sturdy, and stout, suggesting that they would likely survive fire. Several species reviews had no information on postfire seedling establishment but noted the species' wind-dispersed seed or successful seedling establishment in high-light environments (e.g., marsh thistle [*Cirsium palustre*] [Gucker 2009*a*], swallow-worts [*Cynanchum louiseae* and *C. rossicum*] [Stone 2009*a*], giant hogweed [*Heracleum mantegazzianum*] [Gucker 2009*c*], silkreed [Stone 2010], and white poplar [*Populus alba*] [Gucker 2010*b*]). These reviews described the species as having high potential for establishment in the postfire environment if a seed source is nearby. Gucker's (2010*a*) review describes cypress spurge (*Euphorbia cyparissias*), with its typically hard seed coat and persistent seed bank, as potentially regenerating from seed after fire. Inferences such as these should be applied to management issues with caution until observations from test plots or monitoring indicate whether the species responds as expected.

Geographic Scope of Information

We found the geographic scope of observation-based information on fire to be limited for most species reviews. Field observations from a variety of ecosystems are essential for identifying patterns in invasion ecology, because successful invasions depend not only on species characteristics (invasiveness) but also on site and plant community characteristics (invasibility) (e.g., Sakai *et al*. 2001, Simberloff 2003, Rejmánek *et al*. 2005). Additionally, the geographic distributions of invasive species are not always stable, and the ranges of many invasives are expanding in the United States, increasing the need for information from a variety of locations. Unfortunately, responses to fire for most invasive species have been studied in only a small portion of their US range, so the applicability of reported patterns to other areas is largely unknown. For reviews on giant hogweed (Gucker 2009*c*) and Chinese silvergrass (*Miscanthus sinensis*) (Waggy 2011), observation-based fire information was available only from the species' native ranges. How well their responses to fire in their native ranges resemble those in their nonnative ranges is unknown. Review authors hedged this information by describing the geographic scope of the information presented, and the information should be applied with caution in other plant communities and locations.

CONCLUSIONS

Ideally, the knowledge base available for management of fire and invasive plants should include observation-based information related to all aspects of fire including fuels, fire regimes, immediate responses to fire, and postfire responses over long periods. This information would come from a large proportion of the species' range and would compare the effects of varying fire severities, frequencies, and seasons. Our analysis shows that information on fire and invasive plants in the eastern United States is generally lacking in quantity, quality, and geographic scope. This is reflected in all of our analyses, especially that regarding reported changes in postfire abundance, which was insufficient for confidently predicting potential postfire changes in invasive plant populations for the majority of species reviewed. While biological and ecological information was more abundant and of generally higher quality than fire information for most species reviewed, even this fundamental information was unavailable for many of the invasive plant species of concern to eastern wildland managers. The information gaps and shortcomings described here have implications for field scientists, those who synthesize information, and wildland managers working with fire and invasive species.

Implications for Scientists

Greater understanding of plant invasions and the invasibility of plant communities is needed, and this understanding needs to cover a large portion of the invasive species' range. More applied research is needed on plant invasions (Baskin 1997, Moss 2008, Esler *et al.* 2010), and our analysis suggests that the need is especially great with regard to fire relationships. Studies on fire should consistently report burning conditions and fire behavior using standard terminology (e.g., National Wildfire Coordinating Group, Incident Operations Standards Working Team 1996). Whenever possible, studies should examine the effects of varying fire severity, season, and frequency. Statistical comparisons of invasive plant abundance data from before and after fire or on burned and unburned plots are needed, and long-term studies, extending over decades rather than months or years, are badly needed. Finally, research publications need to clearly articulate the basis and scope of inference for the information reported. To apply this information appropriately, managers need to know if it is based on field observation, years of accumulated experience, speculation, or inference.

Information on the basic biology of invasive plants is just as important as information on fire effects, because biological information may be used to make inferences regarding fire responses in ecosystems where fire research is unavailable. Details such as descriptions of a plant's underground morphology and the type of regeneration after disturbance (seedlings or sprouts) are sometimes critical for informed management. Review authors in this project found that many studies failed to provide basic information even though it could have been observed in the field (and probably was) and reported with minimal additional effort.

Collaboration between scientists and managers, and data sharing, may help improve understanding of invasive species' relationships to fire. Managers may tend to ask more complex, interdisciplinary questions than scientists (Shaw *et al.* 2010), so their early involvement in research could optimize the scope and applicability of the resulting projects. A survey of researchers and managers working with invasive plants in the Midwest showed that both groups favored opportunities to collaboratively develop research-based projects at land managers' sites (Renz *et al.* 2009). While it is obviously desirable to increase the applicability of new research to management questions, it is also important to ensure that data from primary research are available as a resource for increasing understanding. Referring to the potential for publishing primary data via online data centers, Costello (2009) points out that "[c]omparing new data with other data collected in the same or different places and times may reveal previously unknown patterns over larger areas and timescales" and "maximizes the potential return on the investment in research." The sharing of management reports and monitoring data may also contribute to greater understanding of complex ecological issues, including relationships between fire and invasive species.

Implications for Authors of Syntheses

Managers typically state that too little time and inadequate access to resources are barriers for finding, reading, and interpreting the scientific literature pertinent to a management issue

(Shaw *et al.* 2010). Syntheses are often developed to condense scientific results and present them more concisely, thus providing a scientific basis for management strategies, but syntheses need to clearly present the scope of inference and applicability of individual research projects (Barbour 2007). Important standards for syntheses that have emerged from this study include:

- Identify patterns and lack of patterns in information, creating new understanding wherever possible. Without such emergent thinking, the product is summary rather than synthesis.
- Organize to address topics of concern to management, identifying absence as well as presence of information.
- Describe how information was obtained (search criteria and scope of search).
- Identify sources of information (by using in-text citations).
- Indicate basis of information (scientific sample, anecdotal observation, inference, speculation, etc.) and identify potential limitations by hedging appropriately.
- Report location and geographic scope of information.

Implications for Managers

Managers are often forced to make decisions amid a great deal of uncertainty because very few plant invasions and invasive species have been studied relative to all that exist (Simberloff 2011). Syntheses can help consolidate information, present it concisely, and identify patterns. They should also inform readers of the limitations of the information—in other words, its uncertainty. This kind of detail provides a context that may be crucial for applying the information appropriately to management issues. Thus, it is important for readers to note not only the general patterns reported in a synthesis but also the information gaps identified, the geographic scope of information, and any hedges or other indications of the nature and quality of the information.

The need for monitoring increases as uncertainty increases (Moir and Mowrer 1995). When a synthesis presents information with hedging and describes limitations to its scope of inference, the need may be greater for managers to network with others, especially those in the same geographic area, to examine previously burned areas, and to test potential treatments on small plots. Monitoring treatment effects is important so that techniques can be adapted over time to better fit the ecosystems being managed. Model simulations suggest that managers could dedicate 50% of their management time to monitoring without risk of accelerating invasions or reducing the impact of their weed management programs (Maxwell *et al.* 2009).

Fire managers need more high-quality information to avoid spreading invasive plants and increasing invasibility of ecosystems. The need for research and information sharing is great, especially in regard to long-term studies and data sets. As knowledge grows, reviews and syntheses can identify patterns (and lack of patterns) in fire response, describe information gaps, and identify limitations of the information available. All of these aspects of information are needed for managers to integrate science-based knowledge with their own experiences and apply it appropriately to specific fire management questions in invaded or invasible ecosystems.

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