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Review

Fire Effects on Soils in Lake States Forests: A Compilation of Published Research to Facilitate Long-Term Investigations

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Abstract: Fire-adapted forests of the Lake States region are poorly studied relative to those of the western and southeastern United States and our knowledge base of regional short- and long-term fire effects on soils is limited. We compiled and assessed the body of literature addressing fire effects on soils in Lake States forests to facilitate the re-measurement of previous studies for the development of new long-term datasets, and to identify existing gaps in the regional knowledge of fire effects on forest soils. Most studies reviewed addressed fire effects on chemical properties in pine-dominated forests, and long-term (>10 years) studies were limited. The major gaps in knowledge we identified include: (1) information on fire temperature and behavior information that would enhance interpretation of fire effects; (2) underrepresentation of the variety of forest types in the Lake States region; (3) information on nutrient fluxes and ecosystem processes; and (4) fire effects on soil organisms. Resolving these knowledge gaps via future research will provide for a more comprehensive understanding of fire effects in Lake States forest soils. Advancing the understanding of fire effects on soil processes and patterns in Lake States forests is critical for designing regionally appropriate long-term forest planning and management activities.

Keywords: Lake States; fire effects; soil; forest; Michigan; Minnesota; Wisconsin; New York; Ontario; Manitoba

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1. Introduction

Fire is an important mineralizing agent in nutrient cycles of moisture-limited ecosystems but may also contribute to decreased nutrient availability in the longer term by consuming soil organic matter and decreasing microbial processes responsible for nutrient turnover [1]. Severe fires may alter soil structure, wettability and porosity in ways that impact water holding capacity, potential for erosion and forest regeneration [1]. Understanding fire effects on soil processes and patterns is critical for long-term forest planning and management. In particular, knowledge of fire impacts on sandy, organic matter-poor soils typical of fire-prone forests is important because of the potential for persistent negative effects on soil fertility and site productivity, especially when fires occur with a frequency or severity outside of the historic range of variation. Similarly, effects on the more organic matter-rich soils of forests in which fire occurs relatively infrequently (such as peatlands) or is an uncharacteristic disturbance (such as northern hardwood forests) may be greater or more persistent than in forests where recurrent fire is common. Although the implications of changing patterns in temperature and precipitation under future climate scenarios are not well understood, increases in fire frequency or severity are likely to exacerbate nutrient losses and shifts in forest structure or composition beyond those that occur from fires of frequency and severity more similar to the pre-EuroAmerican settlement period. Long-term studies of fire effects on a range of forest soils are critical for understanding immediate, delayed and persistent effects of fire.

The Lake States Fire Science Consortium (LSFSC) is funded by the Joint Fire Science Program [2] to promote fire science knowledge exchange within ecologically defined geographic regions (Figure 1). The geographic region covered by the LSFSC (portions of New York, Ohio, Michigan, Minnesota, Wisconsin, Ontario and Manitoba) supports a wide variety of forest types, including forests where fire was a common historical natural disturbance that was mediated by climate, fuels, other biotic and abiotic disturbance agents, and physiography to produce a range of effects (Figure 1, Table 1) [3,4]. Forests in this region therefore represent a range of historic fire regimes, such as the infrequent, high-severity crown fires characteristic of jack pine (*Pinus banksiana* Lamb.) forests, relatively frequent, low- to moderate-severity surface fires characteristic of mixed-pine forests, and infrequent, low- or high-severity fires in northern hardwood forests [5–7].

Figure 1. Map of the fourteen existing Regional Consortia funded by the Joint Fire Science Program [2]. The Lake States Fire Science Consortium covers the northern portions of Minnesota, Wisconsin and Michigan, and includes portions of Ohio, New York and the provinces of Manitoba and Ontario (not shown).

Table 1. Current forest area and percent of area by forest type for Michigan, Minnesota, New York and Wisconsin as representation of forest area and composition in the Lake States region. Data from Shifley *et al.* (2012) [8].

State	Forest area	Oak-hickory	Maple-beech-birch	Aspen-birch	Spruce-fir	Elm-ash-cotton wood	White-red-jack pine	Oak-pine	Other [1]
	(1000 ha)	*Percent of forest area*							
Michigan	7910	16	32	16	13	7	10	3	2
Minnesota	6633	9	10	40	23	9	6	2	2
New York	7555	21	54	4	3	4	7	3	3
Wisconsin	6586	23	26	20	9	9	9	4	1

[1] Includes non-stocked forest land.

Climate and physiography were the major influences on stand-replacing and stand-maintaining fire in pre-settlement northern forests [9,10], whereas an early assessment of the role of fire in the virgin hardwood forests of northern Wisconsin concluded that historic fires "were not conflagrations of catastrophic proportions which destroyed the primeval forest and changed its climax formations into subclimax types of the present era, but rather periodic and ecologically normal events in the life of the forest…it has been and is, from a broad ecological viewpoint, a normal, beneficial and necessary factor in the perpetuation of virgin forest" [11]. Fire was also used by native peoples in portions of the Lake States region prior to EuroAmerican settlement and it is sometimes difficult to separate the importance of this anthropogenic fire from natural fire as a driver of forest dynamics [12–14].

Today, patterns of drought and precipitation influence fire occurrence in Lake States forests, and most ignitions occur as a result of human activity [15]. Major land-use changes that occurred in the early 1900s dramatically altered fire frequency and extent, forest structure and composition, and the extent of contiguous forest cover on the landscape [4,16–19]. Prescribed fire is used as a management tool in northern forests to manage invasive plant species, restore forests to more historical structure or function [20,21], or to prepare seedbeds for forest regeneration [22,23], although competition control and slash reduction are the primary purposes of prescribed fire in this region [24]. In general, prescribed fire is considered to be a positive influence on an ecosystem, and is used to achieve the management objectives identified above. However, fire may also have a negative influence on ecosystem structure and function, and can potentially have detrimental effects on soils. For example, severe fire may consume a large proportion of soil organic matter—thereby reducing critical nutrient pools—or may sterilize the soil environment [1,25]. Fires that occur outside of the natural range of variability, such as stand-replacing fires in jack pine forests that occur before trees reach reproductive age, often limit nutrient input to forest soils by eliminating the aboveground forest and associated litterfall [26,27].

Examples of persistent detrimental effects of fire in eastern forests exist where frequent or severe fires that followed extensive logging of the early settlement period have degraded Lake States pine forests into low-productivity, barren-like or scrub-oak environments (e.g., [28–31]). This suggests that fire outside the natural range of variation may dramatically alter vegetation structure and composition and ecosystem processes associated with nutrient availability in soil in ways that exceed typical effects [5,32,33]. In some instances, studies outside of the northern Lake States have shown that these changes to natural disturbance regimes and soils may lead to "landscape traps", in which conditions are modified to the point where entire landscapes are shifted into an undesirable and potentially irreversible state [34].

Several recent meta-analyses have indicated that regional effects of fire in temperate forests may differ from broader national trends. For example, mineral soil C storage decreases following fire in forests of the northwestern United States, whereas there are no effects in forests of either the southeastern or northeastern regions [35]. Other authors have reported initial increases in forest floor C storage following prescribed fire in western forests, and close to no effect in forests of the southeastern United States [36]. Prescribed fire causes 71% greater losses of forest floor N pools in western forests than in forests of the southeastern United States [37]. Given the differences that exist between fire effects in western and eastern forest soils, it is likely that differences also exist among regions within the eastern United States, and among forest types within regions. We argue that evaluating differences in fire effects between vast geographic regions such as the broadly defined western or eastern United States does not provide the information that is necessary for understanding the magnitude and duration of response to fire disturbance at more specific geographic scales. We suggest that major differences in forest community composition, physiography (glacial geomorphology), soil type (mineralogy and degree of weathering) and climate (temperature, precipitation, growing season length) [38] between the Lake States and other regions in the eastern U.S. may influence fire effects and post-fire recovery, and that dependence on fire effects information from other regions is in most instances inappropriate for local management decisions. Information from the Lake States region has been underrepresented in recent literature syntheses, and this limits access to research that is most appropriate for informing local or regional management. For example, a synthesis of the ecological effects of prescribed fire seasonality relied primarily on studies from the southeastern United States to represent "eastern" forest types [39], and information on wetland soils was the only representation from Lake States ecosystems presented in a synthesis of fire effects on soil [1]. Consequently, a quantitative review of the current state-of-knowledge of fire effects in the Lake States region is needed to increase the resolution of information that has traditionally been presented broadly as "eastern" fire effects information. This information is needed as a critical first step in assessing differences in fire effects among geographic regions.

Further, most studies of fire effects on soils report immediate or short-term (one to three years) results in spite of growing emphasis on the value of long-term ecological research for appropriately evaluating ecosystem response. Because the duration of ecological research studies are typically limited by funding cycles, even studies that establish infrastructure to support long-term evaluations may become inactive in subsequent funding cycles as a result of changing funding priorities at the national level. Re-measurement of previous study sites therefore provides an alternative approach for developing long-term datasets [40].

Here, we compile the body of published (peer-reviewed) literature addressing fire effects on forest soils in the Lake States region, and synthesize the existing data to increase awareness of regional fire effects information. Increased knowledge of locations used for previous research may facilitate the re-measurement of previous study locations and thereby develop new long-term fire effects datasets. Information on the range of observed fire effects within the Lake States region provides important baseline data for monitoring effects of future fires. This baseline data will be particularly important for evaluating effects of severe fires, which may become increasingly common if recent patterns of severe and/or prolonged regional drought persist [41]. We present this review as part of a broader effort by the Lake States Fire Science Consortium to compile and synthesize literature relevant to the fire ecology and management of Lake States ecosystems and to identify gaps in existing knowledge. Increased research efforts to develop regional fire-effects information will facilitate integration of Lake States ecosystems in broader regional or continental-scale assessments and fill major gaps in national syntheses of fire literature.

2. Experimental Section

We performed a keyword search of all years in all databases cataloged by the *Web of Knowledge* using combinations of the following search terms: *fire, burn, wildfire,* refined by *soil* and *forest*, and further refined by *Michigan, Minnesota, Wisconsin, New York, Ohio, Ontario*, *Manitoba, Great Lakes,* or *Lake States.* Geographic refinements were included as the final part of the search string. The literature search returned more than 600 results. Each publication returned was checked to confirm study location and relevance. Additional publications that were not captured in these searches were included based on the knowledge of the authors and a review of citations used in previously identified publications, and these included three agency or agricultural research station publications [42–44]. Ultimately, 63 of the publications that met our keyword and location criteria presented primary data from field studies conducted within or adjacent (within approximately 150 km) to the LSFC region, and we reviewed and summarized key information from these 63 publications. We provide an index to publication summaries by forest type, fire type, study duration, soil layer and soil properties addressed in Table 2. We present summaries for individual studies in alphabetical order by author name in Supplementary Information.

Table 2. Index to citation numbers for studies addressing fire effects on soils in the Lake States region. Full citations are given in References. Summary tables for studies indexed in this table are presented in alphabetical order by author last name in Supplementary Information.

Topic	Citation numbers
Forest type	
Pine-dominated	[5,26,27,40,43–70]
Boreal mixedwood	[42,71–84]
Deciduous	[40,59,85–99]
Fire type	
Prescribed	[47,48,56,57,61,62,69,70,72,87–96,98]
Prescribed following harvest	[43,44,49–54,58,64,65,89,97]
Wildfire	[5,42,46,55,60,66–68,71,73,75,77–86,100]
Both	[26,27,45,59,63,74,76,99]
Unspecified	[40]
Study duration	
Repeated measurements over ≥5 y	[40,52,57,71,76,85]
Measurements >10 y post-fire	[5,26,27,40,46,51,52,59,63,66,68,75,76,82–84,89,95,99]
Chronosequence	[5,46,59,63,66,68,82,89,97,99]
Soil layer	
Organic soil	[26,27,54,55,61,69,70,78,91]
Mineral soil	[42,47,50,51,56,71,74,85–88,93–99]
Both	[5,40,43–46,48,49,52,57–60,64–68,72,73,75–77,79–84,89,90,92,100]
Other	[53,62,63]
Soil properties	
Chemical	[5,27,40,42–48,57,59,60,66–68,71–73,76–81,83–86,88–90,92–96,98,100]
Physical	[26,43–47,52,55,59,61,66,68–71,73,74,80–82,90,92–94,96–98]
Biological	[26,27,42,46,49–51,53,54,56,58,62–68,75,82,84,87–91,93–95,97,99]

Because the available regional data on fire effects on forest soils is limited and addresses disparate topics, a meta-analytical approach is not currently feasible for identifying overarching patterns in soil effects. Here, we provide a baseline quantitative assessment of the range of variability in regional fire effects. We calculated the magnitude and direction (positive or negative) of effect for all publications that reported soil chemical, physical and biological properties from burned treatments and unburned reference areas. We considered pre-fire measurements, adjacent unburned areas, or—for chronosequence studies—mature stands as reference areas. To standardize for the variety of measurement methods reported in the literature, we calculated percent change from data reported from burned and unburned areas for each publication. We also grouped variables reported in the literature into more general groups (for example, we grouped reports of soil total C mass and concentration as Total C). We considered nutrient pools or concentrations as chemical properties, whereas we considered nutrient fluxes (such as N mineralization rates) as biological properties. Here, we report the number of observations (including multiple observations reported in individual publications) and mean, minimum and maximum percent change (relative to reference areas) for major soil chemical (Tables 3 and 4), physical (Table 5) and biological (Tables 6 and 7) properties, by soil layer (organic, mineral, or organic + mineral combined, as reported in each publication), forest type (pine-dominated, deciduous, or boreal mixedwood), and time since fire (<5 years, 5–10 years, or >10 years).

A comprehensive evaluation of regional fire effects in relation to the large body of literature from western forests, or a detailed discussion of the underlying mechanisms that drive fire effects on forest soils, are beyond the scope of this review.

Table 3. Size and direction of fire effect on soil C, N and P in Lake States forests by soil layer, forest type, and time since fire. Shown are number of observations in the literature that reported measurements from burned and reference (unburned) areas, and mean, minimum and maximum percent change relative to reference areas. Categories for which no data were reported for burned and reference areas are indicated by --. Values shown in rows for each variable, soil layer, and forest type major categories were calculated across all included subcategories.

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Total C				94	−6	−90	180
	Organic layer			45	−19	−90	180
		Pine-dominated		21	−43	−90	4
			<5 years	10	−43	−89	−11
			5−10 years	3	−29	−36	−19
			>10 years	8	−49	−90	4
		Deciduous		--	--	--	--
		Boreal mixedwood		24	2	−74	180
			<5 years	16	−47	−74	−10
			5–10 years	--	--	--	--
			>10 years	8	100	12	180
	Mineral layer			37	6	−60	78
		Pine-dominated		25	16	−11	78
			<5 years	7	10	−11	30
			5–10 years	4	−1	−7	13
			>10 years	14	23	−8	78
		Deciduous		4	−14	−26	−3
			Time not specified	4	−14	−26	−3
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		8	−16	−60	33
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	8	−16	−60	33
	Organic + mineral combined [1]			12	6	−15	31
		Pine-dominated		12	6	−15	31
			<5 years	1	15	15	15
			5–10 years	4	3	−15	20
			>10 years	7	6	−12	31
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 3. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Organic C				29	−20	−66	85
	Organic layer			12	−13	−56	21
		Pine-dominated		--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		12	−13	−56	21
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	12	−13	−56	21
	Mineral layer			17	−25	−66	85
		Pine-dominated		--	--	--	--
		Deciduous		3	−4	−9	0
			<5 years	3	−4	−9	0
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		14	−30	−66	85
			<5 years	2	12	−61	85
			5–10 years	--	--	--	--
			>10 years	12	−37	−66	−10
Total N				119	−3	−89	200
	Organic layer			43	−27	−89	67
		Pine-dominated		34	−26	−89	67
			<5 years	16	−21	−89	67
			5–10 years	6	−26	−81	44
			>10 years	12	−32	−88	14
		Deciduous		6	−48	−86	−13
			Time not specified	2	−21	−29	−13
			<5 years	4	−61	−86	−36
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		3	2	0	6
			<5 years	3	2	0	6
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
	Mineral layer			52	8	−28	41
		Pine-dominated		38	11	−5	41
			<5 years	23	10	−5	28
			5–10 years	7	10	−2	21
			>10 years	8	13	−3	41
		Deciduous		14	1	−28	36
			Time not specified	8	−16	−28	2
			<5 years	6	24	14	36
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		--	--	--	--
	Organic + mineral combined [1]			24	15	−50	200
		Pine-dominated		24	15	−50	200
			<5 years	5	42	−14	100
			5–10 years	6	35	−21	200
			>10 years	13	−5	−50	17
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 3. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Inorganic N				41	−78	−2656	338
	Organic layer			--	--	--	--
	Mineral layer			32	−86	−2656	338
		Pine-dominated		--	--	--	--
		Deciduous		16	−223	−2656	38
			Time not specified	6	−54	−84	−28
			<5 years	10	−324	−2656	38
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		16	50	−25	338
			<5 years	8	79	−25	338
			5–10 years	8	21	−20	100
			>10 years	--	--	--	--
	Organic + mineral combined [1]			9	−46	−83	33
		Pine-dominated		9	−46	−83	33
			<5 years	1	−36	−36	−36
			5–10 years	2	−78	−83	−72
			>10 years	6	−37	−75	33
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Organic N				18	−19	−80	46
	Organic layer			--	--	--	--
	Mineral layer			--	--	--	--
	Organic + mineral combined [1]			18	−19	−80	46
		Pine-dominated		18	−19	−80	46
			<5 years	2	−41	−73	−10
			5–10 years	4	−37	−80	−3
			>10 years	12	−9	−37	46
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Soluble N				9	−20	−49	18
	Organic layer			--	--	--	--
	Mineral layer			--	--	--	--
	Organic + mineral combined [1]			9	−20	−49	18
		Pine-dominated		9	−20	−49	18
			<5 years	1	−33	−33	−33
			5–10 years	2	−46	−49	−44
			>10 years	6	−10	−45	18
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 3. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Total P				5	5	−13	30
	Organic layer			5	5	−13	30
		Pine-dominated		--	--	--	--
		Deciduous		2	−12	−13	−11
			Time not specified	2	−12	−13	−11
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		3	16	0	30
			<5 years	3	16	0	30
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
	Mineral layer			--	--	--	--
Extractable P				106	63	−77	600
	Organic layer			--	--	--	--
	Mineral layer			69	72	−77	600
		Pine-dominated		29	116	−25	500
			<5 years	21	104	−25	400
			5–10 years	6	169	−17	500
			>10 years	2	85	51	120
		Deciduous		24	26	−55	94
			Time not specified	2	−36	−55	−18
			<5 years	22	32	−9	94
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		16	60	−77	600
			<5 years	4	149	−60	600
			5–10 years	4	154	100	257
			>10 years	8	−31	−77	44
	Organic layer			21	41	−69	275
		Pine-dominated		21	41	−69	275
			<5 years	14	67	−28	275
			5–10 years	4	−22	−69	0
			>10 years	3	5	−39	34
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			--	--	--	--
	Organic + mineral combined [1]			16	51	−40	193
		Pine-dominated		16	51	−40	193
			Time not specified	1	0	0	0
			<5 years	3	71	0	193
			5–10 years	5	21	−40	56
			>10 years	7	71	−9	138
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

[1] Indicates data reported from combined organic + mineral layers and from the organic-mineral transition.

Table 4. Size and direction of fire effect on soil pH, Ca, K and Mg in Lake States forests by soil layer, forest type, and time since fire. Shown are number of observations in the literature that reported measurements from burned and reference (unburned) areas, and mean, minimum and maximum percent change relative to reference areas. Categories for which no data were reported for burned and reference areas are indicated by --. Values shown in rows for each variable, soil layer, and forest type major categories were calculated across all included subcategories.

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
pH				85	7	−15	23
	Organic layer			17	16	5	23
		Pine-dominated		17	16	5	23
			<5 years	14	17	5	23
			5–10 years	3	13	11	14
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			55	4	−15	21
		Pine-dominated		35	5	−12	15
			<5 years	24	5	0	15
			5–10 years	5	2	−12	12
			>10 years	6	10	2	15
		Deciduous		4	13	9	17
			Time not specified	4	13	9	17
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		16	0	−15	21
			<5 years	4	1	−12	14
			5–10 years	4	3	−6	21
			>10 years	8	−1	−15	10
	Organic + mineral combined [1]			13	4	−3	10
		Pine-dominated		13	4	−3	10
			<5 years	3	3	0	8
			5–10 years	4	6	0	10
			>10 years	6	3	−3	7
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Ca				98	20	−73	251
	Organic layer			24	0	−33	82
		Pine-dominated		21	1	−33	82
			<5 years	14	3	−33	82
			5–10 years	4	−19	−33	0
			>10 years	3	17	−32	58
		Deciduous		--	--	--	--
		Boreal mixedwood		3	−4	−6	0
			<5 years	3	−4	−6	0
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
	Mineral layer			67	29	−73	251
		Pine-dominated		29	30	−40	144
			<5 years	21	47	−2	144
			5–10 years	6	−20	−40	15
			>10 years	2	6	5	7

Table 4. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
		Deciduous		22	29	−12	251
			<5 years	22	29	−12	251
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		16	28	−73	140
			<5 years	4	67	17	140
			5–10 years	4	60	−13	113
			>10 years	8	−6	−73	100
	Organic + mineral combined [1]			7	2	−7	25
		Pine-dominated		7	2	−7	25
			Time not specified	1	−6	−6	−6
			<5 years	2	13	0	25
			5–10 years	3	−3	−7	0
			>10 years	1	3	3	3
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
K				106	41	−69	900
	Organic layer			30	4	−69	233
		Pine-dominated		25	−10	−69	157
			<5 years	14	−23	−69	45
			5–10 years	4	−27	−63	14
			>10 years	7	26	−69	157
		Deciduous		--	--	--	--
		Boreal mixedwood		5	70	0	233
			<5 years	5	70	0	233
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
	Mineral layer			69	58	−39	900
		Pine-dominated		29	20	−11	48
			<5 years	21	20	−11	48
			5–10 years	6	26	6	45
			>10 years	2	5	−9	19
		Deciduous		22	127	−39	900
			<5 years	22	127	−39	900
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		18	35	−34	167
			<5 years	6	39	−34	131
			5–10 years	4	79	42	167
			>10 years	8	9	−21	46
	Organic + mineral combined [1]			7	36	−29	233
		Pine-dominated		7	36	−29	233
			Time not specified	1	233	233	233
			<5 years	2	28	15	40
			5–10 years	3	−10	−29	3
			>10 years	1	−8	−8	−8
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 4. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Mg				89	11	−88	188
	Organic layer			24	3	−41	111
		Pine-dominated		21	2	−41	111
			<5 years	14	−9	−33	33
			5–10 years	4	3	−38	33
			>10 years	3	51	−41	111
		Deciduous		--	--	--	--
		Boreal mixedwood		3	12	0	29
			<5 years	3	12	0	29
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
	Mineral layer			59	15	−88	188
		Pine-dominated		29	11	−88	81
			<5 years	21	22	−33	81
			5–10 years	6	−29	−88	0
			>10 years	2	23	5	40
		Deciduous		22	28	−16	188
			<5 years	22	28	−16	188
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		8	−8	−56	100
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	8	−8	−56	100
	Organic + mineral combined [1]			6	−1	−9	7
		Pine-dominated		6	−1	−9	7
			<5 years	2	0	0	0
			5–10 years	3	−5	−9	0
			>10 years	1	7	7	7
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

[1] Indicates data reported from combined organic + mineral layers and from the organic-mineral transition.

Table 5. Size and direction of fire effect on soil physical properties in Lake States forests by soil layer, forest type, and time since fire. Shown are number of observations in the literature that reported measurements from burned and reference (unburned) areas, and mean, minimum and maximum percent change relative to reference areas. Categories for which no data were reported for burned and reference areas are indicated by --. Values shown in rows for each variable, soil layer, and forest type major categories were calculated across all included subcategories.

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Bulk density				4	−2	−9	6
	Organic layer			--	--	--	--
	Mineral layer			3	0	−3	6
		Pine-dominated		--	--	--	--
		Deciduous		3	0	−3	6
			<5 years	3	0	−3	6
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 5. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
	Organic + mineral combined [1]			1	−9	−9	−9
		Pine-dominated		1	−9	−9	−9
			<5 years	1	−9	−9	−9
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Organic layer depth				4	−44	−57	−32
		Pine-dominated		4	−44	−57	−32
			<5 years	4	−44	−57	−32
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Organic layer mass				33	−55	−100	38
		Pine-dominated		30	−58	−100	38
			Time not specified	24	−71	−100	−37
			<5 years	4	−23	−38	−7
			5–10 years	--	--	--	--
			>10 years	2	32	26	38
		Deciduous		3	−28	−41	−7
			<5 years	3	−28	−41	−7
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		--	--	--	--
Surface litter cover				4	−47	−60	−39
	Organic layer			4	−47	−60	−39
		Pine-dominated		--	--	--	--
		Deciduous		4	−47	−60	−39
			Time not specified	4	−47	−60	−39
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			--	--	--	--
Temperature				8	−2	−36	23
	Organic layer			5	−12	−36	7
		Pine-dominated		--	--	--	--
		Deciduous		5	−12	−36	7
			Time not specified	4	−15	−36	7
			<5 years	1	0	0	0
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			3	13	6	23
		Pine-dominated		--	--	--	--
		Deciduous		3	13	6	23
			<5 years	3	13	6	23
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 5. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Mineral soil texture				30	−2	−42	100
Percent clay				9	−3	−14	16
		Pine-dominated		9	−3	−14	16
			<5 years	9	−3	−14	16
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Percent silt + clay				21	−1	−42	100
		Pine-dominated		21	−1	−42	100
			<5 years	4	−1	−22	22
			5–10 years	4	23	−33	100
			>10 years	13	−9	−42	11
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Soil water				14	9	−43	98
Overland flow volume				3	56	28	98
	Organic layer			3	56	28	98
		Pine-dominated		--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		3	56	28	98
			<5 years	3	56	28	98
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
Soil moisture content				8	−9	−43	16
	Organic layer			3	−13	−18	−5
		Pine-dominated		3	−13	−18	−5
			<5 years	3	−13	−18	−5
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			2	−31	−43	−18
		Pine-dominated		--	--	--	--
		Deciduous		2	−31	−43	−18
			Time not specified	2	−31	−43	−18
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		--	--	--	--
	Organic + mineral combined [1]			3	8	0	16
		Pine-dominated		3	8	0	16
			<5 years	3	8	0	16
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 5. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Soil water volume				3	10	2	21
	Mineral layer			3	10	2	21
		Pine-dominated		--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		3	10	2	21
			<5 years	3	10	2	21
			5–10 years	--	--	--	--
			>10 years	--	--	--	--

[1] Indicates data reported from combined organic + mineral layers and from the organic-mineral transition.

Table 6. Size and direction of fire effect on litter decomposition, soil respiration, N dynamics, and enzyme activities in Lake States forests by soil layer, forest type, and time since fire. Shown are number of observations in the literature that reported measurements from burned and reference (unburned) areas, and mean, minimum and maximum percent change relative to reference areas. Categories for which no data were reported for burned and reference areas are indicated by --. Values shown in rows for each variable, soil layer, and forest type major categories were calculated across all included subcategories.

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Litter decomposition				34	−2	−35	22
	Organic layer			34	−2	−35	22
		Pine-dominated		24	1	−15	15
			<5 years	12	1	−15	15
			5–10 years	--	--	--	--
			>10 years	12	0	−7	7
		Deciduous		6	−9	−35	22
			Time not specified	6	−9	−35	22
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		4	−7	−24	1
			<5 years	4	−7	−24	1
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
	Mineral layer			--	--	--	--
Respiration				30	−2	−59	127
	Organic layer			3	−9	−22	0
		Pine-dominated		3	−9	−22	0
			<5 years	3	−9	−22	0
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 6. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
	Mineral layer			4	9	−59	127
		Pine-dominated		4	9	−59	127
			<5 years	4	9	−59	127
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Organic + mineral combined [1]			23	−2	−20	27
		Pine-dominated		23	−2	−20	27
			<5 years	2	−13	−14	−12
			5–10 years	1	−20	−20	−20
			>10 years	20	−1	−11	27
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
N dynamics							
N immobilization				2	−3	−15	8
	Organic layer			--	--	--	--
	Mineral layer			--	--	--	--
	Organic + mineral combined [2]			2	−3	−15	8
		Pine-dominated		2	−3	−15	8
			<5 years	2	−3	−15	8
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
N mineralization				64	−22	−95	326
	Organic layer			11	−56	−95	25
		Pine-dominated		11	−56	−95	25
			<5 years	3	−67	−93	−41
			5–10 years	1	−90	−90	−90
			>10 years	7	−46	−95	25
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			39	−7	−89	326
		Pine-dominated		20	23	−60	326
			<5 years	5	75	−51	326
			5–10 years	2	41	1	82
			>10 years	13	−1	−60	74
		Deciduous		19	−38	−89	67
			Time not specified	8	−61	−82	−36
			<5 years	5	18	−37	67
			5–10 years	--	--	--	--
			>10 years	6	−55	−89	−29
		Boreal mixedwood		--	--	--	--

Table 6. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
	Organic + mineral combined[2]			14	−36	−79	21
		Pine-dominated		14	−36	−79	21
			<5 years	6	−26	−63	6
			5–10 years	1	−65	−65	−65
			>10 years	7	−41	−79	21
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Nitrification				12	412	−175	2775
	Organic layer			2	−64	−64	−64
		Pine-dominated		2	−64	−64	−64
			<5 years	1	−64	−64	−64
			5–10 years	--	--	--	--
			>10 years	1	−64	−64	−64
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			7	442	−175	2775
		Pine-dominated		2	1721	667	2775
			<5 years	1	667	667	667
			5–10 years	--	--	--	--
			>10 years	1	2775	2775	2775
		Deciduous		5	−70	−175	140
			<5 years	1	140	140	140
			5–10 years	--	--	--	--
			>10 years	4	−123	−175	−40
		Boreal mixedwood		--	--	--	--
	Organic + mineral combined[2]			3	662	1	1625
		Pine-dominated		3	662	1	1625
			<5 years	2	180	1	360
			5–10 years	--	--	--	--
			>10 years	1	1625	1625	1625
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Microbial enzyme activity				20	−9	−75	45
Acid phosphatase activity				2	−42	−50	−35
	Organic layer			1	−50	−50	−50
		Pine-dominated		1	−50	−50	−50
			<5 years	1	−50	−50	−50
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			1	−35	−35	−35
		Pine-dominated		1	−35	−35	−35
			<5 years	1	−35	−35	−35
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 6. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Alkaline phosphatase activity				2	−38	−75	0
	Organic layer			1	−75	−75	−75
		Pine-dominated		1	−75	−75	−75
			<5 years	1	−75	−75	−75
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			1	0	0	0
		Pine-dominated		1	0	0	0
			<5 years	1	0	0	0
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Arylsulfatase activity				2	−21	−67	25
	Organic layer			1	−67	−67	−67
		Pine-dominated		1	−67	−67	−67
			<5 years	1	−67	−67	−67
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			1	25	25	25
		Pine-dominated		1	25	25	25
			<5 years	1	25	25	25
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Proteolytic activity				14	1	−30	45
	Organic layer			--	--	--	--
	Mineral layer			--	--	--	--
	Organic + mineral combined [2]			14	1	−30	45
		Pine-dominated		14	1	−30	45
			<5 years	3	−7	−30	27
			5–10 years	2	39	32	45
			>10 years	9	−5	−30	42
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

[1] Indicates data reported from combined organic + mineral layers, from the organic-mineral transition, and measurements taken from sampling chambers placed on the surface of the forest floor that captured respiration from the underlying mineral and organic layers; [2] Indicates data reported from combined organic + mineral layers and from the organic-mineral transition.

Table 7. Size and direction of fire effect on soil organisms in Lake States forests by soil layer, forest type, and time since fire. Shown are number of observations in the literature that reported measurements from burned and reference (unburned) areas, and mean, minimum and maximum percent change relative to reference areas. Categories for which no data were reported for burned and reference areas are indicated by --. Values shown in rows for each variable, soil layer, and forest type major categories were calculated across all included subcategories.

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Microbial biomass C				1	−39	−39	−39
	Organic layer			--	--	--	--
	Mineral layer			--	--	--	--
	Organic + mineral combined [1]			1	−39	−39	−39
		Pine-dominated		1	−39	−39	−39
			<5 years	1	−39	−39	−39
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Actinomycete abundance				20	80	−56	465
	Organic layer			12	49	−56	328
		Pine-dominated		--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		12	49	−56	328
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	12	49	−56	328
	Mineral layer			8	126	−38	465
		Pine-dominated		--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		8	126	−38	465
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	8	126	−38	465
Bacteria abundance				29	186	−78	1046
	Organic layer			16	135	−63	484
		Pine-dominated		4	27	−50	210
			<5 years	4	27	−50	210
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		12	171	−63	484
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	12	171	-63	484

Table 7. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
	Mineral layer			8	406	−34	1046
		Pine-dominated		--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		8	406	−34	1046
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	8	406	−34	1046
	Organic + mineral combined [1]			5	−4	−78	60
		Pine-dominated		5	−4	−78	60
			<5 years	5	−4	−78	60
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Fungi abundance				35	61	−89	338
	Organic layer			16	66	−35	333
		Pine-dominated		4	93	−35	333
			<5 years	4	93	−35	333
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		12	58	−19	239
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	12	58	−19	239
	Mineral layer			10	120	−44	338
		Pine-dominated		2	47	5	90
			<5 years	2	47	5	90
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		8	138	−44	338
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	8	138	−44	338
	Organic + mineral combined [1]			9	−15	−89	38
		Pine-dominated		5	−36	−89	−15
			<5 years	5	−36	−89	−15
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		4	11	−2	38
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	4	11	−2	38

Table 7. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
Streptomycete abundance				8	61	−53	332
	Organic layer			4	2	−53	55
		Pine-dominated		4	2	−53	55
			<5 years	4	2	−53	55
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			--	--	--	--
	Organic + mineral combined [1]			4	119	−40	332
		Pine-dominated		4	119	−40	332
			<5 years	4	119	−40	332
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Vascular plant seed density				1	−6	−6	−6
	Organic layer			--	--	--	--
	Mineral layer			--	--	--	--
	Organic + mineral combined [1]			1	−6	−6	−6
		Pine-dominated		1	−6	−6	−6
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	1	−6	−6	−6
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Carabid beetle diversity				3	32	−5	75
	Organic layer			3	32	−5	75
		Pine-dominated		3	32	−5	75
			<5 years	3	32	−5	75
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Ectomycorrhizal diversity				2	−14	−18	−11
	Forest floor surface			1	−18	−18	−18
		Pine-dominated		--	--	--	--
		Deciduous		1	−18	−18	−18
			Time not specified	1	−18	−18	−18
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		--	--	--	--

Table 7. *Cont.*

Variable	Soil layer	Forest type	Time since fire	N	Mean (%)	Min (%)	Max (%)
	Plant root tips			1	−11	−11	−11
		Pine-dominated		--	--	--	--
		Deciduous		1	−11	−11	−11
			Time not specified	1	−11	−11	−11
			<5 years	--	--	--	--
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Boreal mixedwood		--	--	--	--
Microbial community diversity				8	−9	−26	−1
	Organic layer			4	−4	−7	−1
		Pine-dominated		4	−4	−7	−1
			<5 years	3	−4	−7	−1
			5–10 years	1	−2	−2	−2
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			4	−13	−26	−4
		Pine-dominated		4	−13	−26	−4
			<5 years	3	−16	−26	−4
			5–10 years	1	−6	−6	−6
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
Microbial community evenness				4	−2	−4	0
	Organic layer			2	−1	−2	0
		Pine-dominated		2	−1	−2	0
			<5 years	2	−1	−2	0
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--
	Mineral layer			2	−3	−4	−2
		Pine-dominated		2	−3	−4	−2
			<5 years	2	−3	−4	−2
			5–10 years	--	--	--	--
			>10 years	--	--	--	--
		Deciduous		--	--	--	--
		Boreal mixedwood		--	--	--	--

[1] Indicates data reported from combined organic + mineral layers and from the organic-mineral transition.

3. Results and Discussion

3.1. Existing Research

Publication dates of the 63 publications that met our criteria as described above spanned from 1959 to 2012. One study was published in the 1950s, two in the 1960s, 16 in the 1970s, nine in the 1980s, 12 in the 1990s, 16 in the 2000s, and seven studies were published between 2010 and 2012. Thirty-three

(52%) of the publications focused on pine-dominated forests (Table 2). Of these, 26 (41%) were conducted in jack pine forests or barrens, and five (8%) in mixed pine or red pine (*P. resinosa* Ait.) forests, including one (2%) in a red pine plantation. A total of sixteen (25%) studies focused on deciduous forest types (Table 2), and the majority (10 studies or 16%) of these were conducted in oak (*Quercus*)-dominated ecosystems whereas three studies (5%) were conducted in northern hardwood ecosystems (one in mesic hardwoods, two in aspen (*Populus*) woodland, and one in a recently clearcut and burned stand that represented an early successional stage along an eastern hemlock (*Tsuga Canadensis* (L.) Carrière)-northern hardwood chronosequence). Fifteen studies (24%) were conducted in boreal forest types, which often include a mixture of coniferous and deciduous species (Table 2). Half (32 studies, or 51%) of the publications focused exclusively on prescribed fire or prescribed fire following forest harvest, whereas 22 studies (35%) evaluated wildfire effects and eight studies (13%) used a combination of wildfire and prescribed fire locations (Table 2).

The majority (44 studies, or 70%) of the publications reported studies conducted ≤10 y post-fire. Nineteen studies (30%) reported data from measurements taken >10 y after a fire event (Table 2). The longest-term continuous study reported on soil temperatures over a 17 year period following wildfire [52]. Most long-term studies reported data from older wildfires or harvested and burned locations. Several authors (ten studies or 16% of publications) assembled chronosequences to evaluate the effect of time since fire on soil properties (Table 2).

Fifty-two percent of the publications (33 studies) reported information on both organic and mineral soil layers, whereas 29% (18 studies) focused on mineral soil only and 14% (nine studies) focused on organic soil only (Table 2). The majority of studies (40 or 63%) reported fire effects on soil chemical characteristics such as soil pH, or nutrient pools (Tables 2–4). Twenty-six studies (41%) reported data on soil physical characteristics, including soil texture, moisture content, or temperature (Tables 2 and 5). Thirty-one publications (49%) addressed fire effects on soil biological characteristics such as microbial activity, or rates of nutrient transformations, or microbial community diversity (Tables 2, 6 and 7).

On average, fire decreased total C in organic soil by 19%, whereas a 6% increase occurred in mineral soil (Table 3). The decrease in total C in organic soil was attributed to large (29% to 49%) decreases observed in pine-dominated forests; fire decreased total C in mixed forests <5 years post-fire, although 100% increases relative to unburned areas were observed among studies conducted >10 years since fire. Fewer observations of organic C were reported than for total C, and 48% of observations occurred in boreal mixed forest types. All studies of fire effects on organic C were conducted <5 years or >10 years following fire, and the observations reported from >10 years post-fire suggest that major decreases in organic C persist through time (Table 3).

The effect of fire on total soil N was more negative and showed a wider range of effects in organic soil than in mineral soil (Table 3). Effects on organic soil in pine-dominated forests ranged from −89% to 67%, whereas effects on deciduous forest organic soil were consistently negative. All longer-term observations were limited to mineral soil in pine-dominated forests (Table 3). Fire effects on soil inorganic N (pools and concentrations) were more strongly negative, and this was driven by effects reported in deciduous forests. Fire increased inorganic N in boreal mixedwood forests, and the range between the minimum and maximum effect was much smaller than in deciduous forests. The absence of data on fire effects on inorganic N pools in pine-dominated forests indicates a strong need for this information in the Lake States region. Similarly, no data on longer-term effects on inorganic N in deciduous forests were identified in this review (Table 3). Reports of fire effects on organic N and soluble N exist for pine-dominated forests only, whereas data on total P exist for relatively short-term observations from organic soil in deciduous and boreal mixedwood forests only. The mean effect of fire on extractable P is positive for organic soil in conifer forests and in mineral soil in all forest types; no data exist on organic soil in deciduous or boreal mixedwood forests (Table 3).

The overall mean responses of all soil C and N variables were negative, whereas the effects of fire on soil P were positive. Similarly, the overall mean responses of soil pH, Ca, K and Mg were positive (Table 4). In general, mean fire effects on soil pH are minor (<41% increase), although K increased by 900% in deciduous forest mineral soil <5 years following fire (Table 4). Data on intermediate- to long-term responses of cations to fire in deciduous forests are lacking (Table 4).

Few observations of regional fire effects on soil physical properties exist, and nearly all occurred <5 years following fire or at an unspecified time since fire (Table 5). Overall mean effects of fire on soil physical properties were minor (≤10% change relative to reference areas) for all variables except organic layer depth, mass and surface litter cover (effects ranged from 100% losses to increases of 38%) (Table 5). No data exist that indicate whether or not these small changes in physical properties persist through time, and this gap in knowledge may be particularly important for monitoring ecosystem recovery following more severe fires—such as are common in jack pine-dominated forests in this region—that cause the greatest impact to forest soil [1,55].

In general, fire decreased soil biological processes (Table 6). Fire decreased litter decomposition (mass loss) in deciduous and boreal mixedwood forests by <10%, and the positive effect in pine-dominated forests was minimal (Table 6). Two observations of fire effects on N immobilization suggest relatively minor (−15% to 8%) effects in pine-dominated forests. A greater number of observations of N mineralization indicate a wider range of variability in the response of this variable (−95% to 326%); no data exist from boreal mixedwood forests, and data from deciduous forests are limited to the mineral soil layer (Table 6). Nitrification was the only soil process that showed an overall increase following fire, and this was driven by major increases reported from mineral and combined organic + mineral soil in pine-dominated forests (Table 6). The limited reported data suggest that nitrification in conifer forests increases with time since fire, whereas the opposite trend was evident in deciduous forests (Table 6).

Fire had an overall negative effect (−9%) on soil exoenzyme activities, although arylsulfatase and proteolytic enzyme activities showed negative as well as positive responses (Table 6). For arylsulfatase, a single observation of negative effects was reported from organic soil, and a single observation of positive effects was reported in mineral soil. The response of soil enzymes to fire in this region is a major gap in our current understanding of fire effects on ecosystem processes. The limited data that exist suggest that fire has overall negative effects on nutrient transformations and organic matter cycling in the Lake States region.

Fire decreased soil microbial biomass C and the density of vascular plant seeds in pine-dominated forests, and no information from deciduous or boreal mixedwood forests were located for either variable. Fire increased the overall abundance of actinomycetes, streptomycetes, bacteria, and fungi, with maximum increases observed for bacteria in the mineral layer of deciduous forests (1046%) (Table 7). Our literature search did not locate any studies of bacterial abundance in mineral soil of pine-dominated forests, nor studies of microbial abundance in pine-dominated forests conducted ≥5 years following fire (Table 7).

Fire increased carabid beetle diversity in pine-dominated forests <5 years following fire (Table 7), whereas ectomycorrhizal diversity and overall microbial community diversity and evenness decreased following fire. No studies were located that reported fire effects on soil organism communities >10 years following fire, and the data that exist from shorter post-fire time periods are very limited (Table 7).

3.2. Trends

The literature we reviewed showed that studies of fire effects on soil in the Lake States region are limited primarily to reports of chemical characteristics in organic and upper mineral soil horizons, and that most studies focus on a relatively short-term response to fire. There is a clear need for investigations of longer-term effects of fire on soil (Tables 2–7). No studies reported major or persistent effects on mineral soil physical properties (Table 5). In general, fire increases soil cations, pools of extractable P, and nitrification rates, and decreases litter decomposition, N mineralization, and soil exoenzyme activities (Table 3, 4 and 6). However, persistent increases in mineral soil N, P and K have been reported by repeated measurements over ten years following experimental burning in immature jack pine in the Lake States region [57]. Fire-caused increases in soil nutrients (such as inorganic N forms) may increase nutrient losses due to leaching, although studies of wildfire effects in mixed-conifer forest in the Boundary Waters Canoe Area showed that these effects also decreased with time since fire and were not large enough to cause lake eutrophication [77,80]. However, our calculations of overall mean effect size showed that fire increases soil P (total and extractable) and cations (Ca, K and Mg) and decreases soil total, inorganic, organic, and soluble N forms.

The species composition of a regenerating forest may influence post-fire recovery of mineral soil C [40], suggesting that the ecosystem response to fire may be affected by unique interactions between fire events and forest type. Mineral soil C pools recovered over time since fire in a northern hardwood forest [89], whereas the opposite trend was reported for post-fire jack pine stands [5]. In jack pine, an accumulation of C occurred in the organic soil (forest floor) layer [5], and a study of multiple forest types in the Boundary Waters Canoe Area reported that forest floor C mass 23 years after wildfire exceeded pre-fire levels [83]. Species composition also influences environmental conditions following fire and is likely to have an important influence on soil nutrient dynamics [27]. For example, litter mass and chemistry as well as percent cover by surface vegetation and the soil surface temperature are likely to differ strikingly between regenerating stands dominated by hardwood species and those dominated by jack pine.

Fire frequency influences forest structure and composition and, in turn, soil characteristics. For example, shrub and tree density decreased with increasing fire frequency at Cedar Creek Natural History Area in northern Minnesota [98]. Soil N and P availability and N mineralization rates were negatively related to fire frequency at this study site [87,90,94]. Fire severity also affects properties of forest soils. Reports of high fire severity included fires that consumed the entire organic layer or left only a layer of ash [73] as well as those that resulted in minimal impact to soil where the organic layer was not consumed [55]. Within-fire severity level has a measureable influence on soil properties; for example, soil pH was greater in areas of high fire severity than in areas of lower severity in a boreal forest [73]. The specific effects of fire as a function of severity level have not been well-investigated in the fire effects literature regardless of regional location.

Few studies addressed fire effects on soil organisms or ecosystem processes, and the existing data represent pine-dominated forests; little information exists from deciduous and boreal mixedwood forests (Tables 2, 6 and 7). An early study of soil microorganisms showed that burning reduced microbial numbers and activity up to three growing seasons following fire, however, these effects were minor and were reduced by precipitation events [58]. Litter decomposition increased over the short term (two weeks) following the 1976 wildfire at Seney National Wildlife Refuge [42], whereas no effects were reported following the 1971 Little Sioux Fire in the Boundary Waters Canoe Area [78]. The effects of fire on soil microorganisms may differ among plant species. For example, colonization by ectomycorrhizae was positively correlated with fire intensity for eastern white pine (*P. strobus* L.) seedlings but not for red pine seedlings planted in a burned jack pine clearcut [56]. The existing data provide very limited insight into fire effects on soil ecosystem processes in the Lake States region, and the need to resolve these gaps is clear.

In general, the types of soil responses to fire reported in the regional literature are consistent with the types of effects reported for other eastern and western systems, which include positive and negative responses to fire [1,35,37,101]. The magnitude of fire effect may be largely driven by fire severity. For example, soil organic C in Virginia table mountain pine (*Pinus pungens* Lamb.) stands was decreased more by high-severity fire than by low-severity fire [102]. A meta-analysis of fire effects on soil C and N storage showed that wildfires cause greater losses in soil C and N pools than prescribed fires, and this was attributed to differences in fire severity [35]. Recent meta-analyses of fire effects on soil properties in eastern (focused primarily on southeastern US forests) and western forests have shown that responses are highly variable, may be site-specific, and include increases as well as decreases in soil and forest floor C stocks [36], although a multivariate analysis of overall soil properties indicated a clear separation between western and eastern sites [101].

Although general effects of fire—such as increases or decreases in measured variables—may be similar across diverse regions, the magnitude and duration of effect is perhaps more ecologically important. An early study of fire in the Lake States region emphasized that "each combination of region, climate, forest tree association, soil type and plant species must be considered individually," especially when other environmental factors that influence fire behavior (and consequently, fire effects)—such as forest composition, physiography, soil type and climate—may differ greatly between regions [103]. This early warning emphasizes the importance of developing regionally-specific understanding of fire effects on ecosystem characteristics and processes—a task that remains important today for appropriately informing regional and local land management decisions.

3.3. Future Directions

The limited number of studies addressing fire effects on soils in Lake States forests creates difficulty in comparing effects among contrasting forest types within the region, especially in light of potential "mesophication" of these forests [104]. Only three studies investigated fire effects in multiple forest types [40,59,83] and a strategic approach is needed to be able to compare the magnitude and duration of fire effects on soils across forest types within the Lake States region. Our results indicate that several key areas of opportunity exist to expand our current knowledge of fire effects in the Lake States region. Few of the reviewed publications reported fire temperatures [48,50,58,96], and the level of detail provided for fire behavior information varied from qualitative statements that a fire was "severe" or "intense" to plot-specific measurements of fire intensity and forest floor reduction [57] or field-based assessments of fire severity [55]. Detailed measurements of fire temperature, behavior and severity or fuel consumption must be included in future studies to accurately interpret fire effects on soil or other ecosystem components (e.g., [105]). Modeling fire behavior for specific fire locations and dates may help interpret fire effects at a coarse scale by using pre-fire estimates of forest structure and composition and known fire-weather information. Resources to support this general approach include LANDFIRE [106] and the Fuel Characteristics Classification System [107], among others, although the current level of specificity provided by these tools is limited. The Monitoring Trends in Burn Severity program [108] is currently in progress and will provide fire perimeter and within-fire burn severity maps for fires that occurred from 1984 to 2010 across the entire United States. These maps will allow field sampling to be stratified by fire severity level, thereby increasing the understanding of fire effects by the level of impact on a forest stand.

Controlled and replicated studies are also essential for accurately interpreting fire effects, especially when no pre-fire data exist. Two of the publications we reviewed presented uncontrolled studies from an assemblage of jack pine stands that lacked a clear gradient of fire type and time since fire [26,27]; this approach limits the ability to make clear conclusions about fire effects. Actively managed research locations provide the greatest opportunity for multiple investigations; e.g., seven of the 63 studies we reviewed were conducted at the Cedar Creek Natural History Area in Minnesota, and four studies were conducted at the Petawawa National Forestry Institute near Chalk River, Ontario. Well-established wildfire study locations similarly support multiple investigations, such as the 1971 Little Sioux wildfire in the Boundary Waters Canoe Area of Minnesota which has been used in used in five studies.

Jack pine forests, historically characterized by relatively frequent, stand-replacing crown fires, were the most studied forest type in the region. More information is needed on fire effects on soils in forest types that represent a wider range of fire regimes, e.g., northern hardwood, mixed-pine and boreal forest types. Studies that investigated the effects of varying fire frequencies were limited to oak-dominated ecosystems and none were located for pine-dominated forest types. Although soil chemistry was the most well-studied topic area and many studies presented data on soil organic matter content, no studies examined fire effects on organic matter composition. For example, the influence of fire on pyrogenic C content in forest soils of the region has not yet been investigated. Most studies reported soil nutrient stocks rather than nutrient fluxes or estimations of recovery rates for nutrient pools; this latter data would be valuable for understanding impacts on ecosystem processes that contribute to long-term forest productivity. Nutrient flux data would also be complemented by data on microbial community composition to allow evaluation of relationships between soil ecosystem structure and function by forest type; however, only one study presented both types of information [58]. Of the 63 publications reviewed, only one investigated fire effects on soil macrofauna [53].

Re-measuring locations used in earlier studies can enhance the value of new research by linking new data with an existing body of knowledge, allowing physical, chemical or biological properties to be evaluated over a longer period of time than is possible within the duration of a single funding award, by contributing to the site-specific knowledge held by the local management agency personnel, or by reducing costs involved with locating new sites or implementing new experimental treatments. Several challenges also exist for efforts to establish new studies at previous research locations, such as locating study sites when detailed maps or spatial location have not been published. In the Lake States region, many of the locations used for studies presented in Table 1 may have been impacted in ways that prohibit direct comparisons across time. For example, harvesting and site preparation would disrupt soil and confound long-term datasets. Differences in methods between early and late measurements also create challenges that may or may not allow comparisons across time. For example, the authors of one study [40] constructed a long-term comparison by calculating soil organic matter content from two earlier studies at their site that reported organic matter concentrations. In this example, the analysis relied on original data from published appendices and from archived soil samples from two earlier and well-documented studies. Clear communication with previous or current researchers is essential to ensure that existing studies are not disrupted, and formal collaboration may be necessary for data-sharing. The potential synergy, however, will be valuable for developing long-term or interdisciplinary data that greatly increase our understanding of fire-mediated ecological processes.

One challenge facing fire researchers in the Lake States is the lack of a comprehensive database of wildfire locations. Individual researchers have identified wildfire locations that allow chronosequence studies of wildfire-regenerated jack pine sites in northern lower Michigan [5,66–68], or have used a time series of aerial imagery and photographs to map fire extent and pattern at known locations [109]. A spatially explicit database of fires in the Lake States between 1985 and 1995 has been developed based on state (Minnesota, Wisconsin and Michigan Departments of Natural Resources) and federal (USDA Forest Service) agency records of fire origin [15], although these authors did not use individual fire perimeters. Records of fires on land managed by the National Park Service and U.S. Fish and Wildlife Service as National Wildlife Refuges would further increase our knowledge of fire occurrence and ecological effects. Agency records of fire locations that are currently available commonly provide Public Land Survey System (PLSS) township, range and section, as digital fire perimeter maps are available only for the most recent fires. Maps for older fires may exist only as hard-copy maps in agency files, and digitization of these existing hard-copy information resources would increase research opportunities. Maps for many fires simply do not exist. Thus, a spatial database of known fire locations would have significant value as a resource when establishing future research projects to document long-term fire effects. Many of the studies located through this review included general fire location information only, which limits the ability to re-examine these locations in later years. We encourage investigators to make detailed site location, forest type, treatment, and methods information available after a study is completed, as no single entity currently supports an archive of study locations. Physical archival of field samples would also promote re-measurement and the development of more comprehensive databases for specific locations.

4. Conclusions

This review compiles published studies of fire effects on soils in Lake States forests. Understanding differences in fire effects among geographic or ecological regions—as well as among contrasting forest types—within the eastern United States is critical for implementing appropriate forest management activities and for evaluating past and current effects in light of changing climate patterns. Our results identify previous studies conducted in the Lake States region and provide an assessment of the current state of knowledge of fire effects on these forest soils. This baseline assessment of the range of variability in fire effects will promote greater resolution in future regional and national-level syntheses of fire effects information. These activities are necessary for adequately informing fire and forest management policy decisions that influence long-term forest health.

Most of the studies of fire effects on Lake States forest soils were relatively short-term (<5 years) investigations, clearly indicating a need for longer-term research. The limited number of long-term studies is a pattern that is not unique to this region. Because typical funding cycles for ecological research generally support short-term rather than long-term studies, we hope that this work will facilitate the re-measurement of existing study locations and the development of long-term datasets that allow fire effects to be evaluated at multiple time scales. However, re-measurement is complicated when authors of published studies have omitted detailed site location and fire information. We recommend that new authors provide specific location information to facilitate multi-disciplinary investigations at individual sites, including re-measurement beyond the career length of individual researchers. The results of our review indicate that the major gaps in knowledge of fire effects on soils include: (1) information on fire temperature and behavior information that would enhance interpretation of fire effects; (2) underrepresentation of the variety of forest types in the Lake States region; (3) information on nutrient fluxes and ecosystem processes, and (4) fire effects on soil organisms. Through this review and other ongoing syntheses, the LSFSC is working to facilitate fire science knowledge exchange to advance the regionally-specific understanding of fire effects and support informed management of forests in the Lake States region.

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Conflict of Interest

The authors declare no conflict of interest. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of their respective organizations.

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