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Shifting conceptions of complexity in forest management and silviculture☆

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A B S T R A C T

In the past several decades, a trend in forestry and silviculture has been toward promoting complexity in forest ecosystems, but how complexity is conceived and described has shifted over time as new ideas and terminology have been introduced. Historically, ecologically-focused silviculture has focused largely on manipulation of structural complexity, but often with the functional role of features in mind. Recently there has been a shift toward viewing complexity in an "adaptive" or "resilience" context, with a focus on understanding forests as complex adaptive systems. As new concepts and terminology are introduced it will be essential that silviculture researchers understand their dissemination into silviculture research, experimental design, and treatment implementation. With this goal in mind we set out to better understand: (1) how complexity terminology and ideas have shifted over time in silviculture, (2) how different conceptions of complexity have been incorporated into silviculture experiments and treatments, and (3) how various complexity concepts are being reconciled with each other in practice. We conducted a multi-stage review of the silvicultural literature for the time period 1992–2017 that included: (1) a broad keyword analysis, (2) a detailed review of a narrower subset of publications, and (3) a thorough review of a set of silvicultural experiments that included a focus on complexity in their design. We also developed a set of case studies that illustrate shifts in complexity conceptions in silvicultural experiment design and analysis. Our analysis indicates considerable lags in incorporation of complexity-focused terminology and ideas into silvicultural research and experimental treatment design. Very few silviculture-focused studies have incorporated adaptive complexity concepts explicitly into design or analysis, even though these concepts were introduced nearly a decade ago and are widely discussed in the literature. However, in our case studies we document how silviculture experiments and research programs that were not designed explicitly around complexity concepts have begun to incorporate these ideas into analysis of treatment outcomes. Silviculture researchers should focus on reconciling conceptions of complexity through analysis of existing experiments and with modeling studies, as well as attempting to better understand mechanistic relationships among structural, functional, and adaptive conceptions of complexity.

1. Introduction

Manipulation of forest ecosystem complexity has long been a consideration in forest management and silviculture. However, through much of the history of forestry, management approaches reduced complexity to create a more predictable production system modeled

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after agricultural systems (Puettmann et al., 2009). Production-focused silvicultural systems were often designed to reduce structural and biological complexity, with the consequence of potentially also reducing adaptability and resilience (Drever et al., 2006). More recently, promotion of complexity in forest ecosystems has become a goal of ecologically-focused silviculture and forest management (Carey, 2001; Franklin et al., 2002; Curtis et al., 2004; Peterson and Maguire, 2005; Keeton, 2006; Forrester et al., 2013; Messier et al., 2013). This transition and the implications it has had for silviculture and forestry have been thoroughly reviewed elsewhere (Puettmann et al., 2009). However, the operational and ecological definition of complexity in forest ecosystems has not been consistently defined and may vary widely depending on the goals of treatments and expertise of the research or management group involved (North and Keeton, 2008). Conceptions of what constitutes complexity and what types of complexity are most relevant to meeting forest management goals may have shifted over time, especially in the last couple decades, as new ideas have entered into the forest ecology and silviculture discourse (Messier et al., 2013). In addition, new measurement and analysis tools have become available (Lefsky et al., 1999; Eitel et al., 2016) making possible novel descriptions of complexity (Hardiman et al., 2011; Ehbrecht et al., 2017). Now that the idea of fostering stand or ecosystem complexity has become widely ingrained into silvicultural planning and practice, it is especially important that there be a common basis from which scientists and practitioners can discuss treatment options and outcomes.

The importance and potential positive impacts of forest complexity have long been acknowledged in forest ecology, with the work of MacArthur and Horn (1969) being foundational in characterizing and quantifying these patterns. Although the active promotion of complexity in forestry and silvicultural practice has long been discussed, the incorporation of these ideas into the mainstream of silviculture can be associated with the "ecological forestry" movement of the early 1990 s (Franklin and Spies, 1991; Lindenmayer and Franklin, 1997). The ecological forestry movement started with an explicit focus largely on manipulation and introduction, through active management, of structural and biological complexity - both at the stand and landscape scale (Franklin, 1997). This included a strong focus on biological legacies (now sometimes discussed as "ecosystem memory") and specific habitat features and attributes associated with late-successional forests (Franklin et al., 2002; Palik et al., 2002; Keeton and Franklin, 2005). Silvicultural practices tended to focus on treatments such as variable retention and patch cutting as an alternative to clear-cutting (Franklin, 1997; Lindenmayer and Franklin, 1997; Carey, 2001; Seymour and White, 2002). Through the history of ecological forestry, structural complexity has been characterized in a variety of ways, using single and multi-metric descriptions and both qualitative and quantitative approaches (McElhinny et al., 2005). Many of the original ecological forestry studies and treatments were focused on specific habitat features (such as downed woody debris) utilized by wildlife or characteristic of late-successional forests and thus often framed complexity based on qualitative assessments or presence-based approaches focused on such attributes (e.g., Spies et al., 1988; Spies and Franklin, 1991; Tyrrell and Crow, 1994). More quantitative approaches have also been employed and have focused on factors such as tree spatial arrangement (Pommerening, 2002), canopy structure (Parker and Russ, 2004; Hardiman et al., 2011), biological community complexity (e.g., species and functional trait diversity; Berger and Puettmann, 2000; Finegan et al., 2015), and combinations of factors into synthetic metrics (e.g., Acker et al., 1998; Zenner and Hibbs, 2000; Staudhammer and LeMay, 2001).

Although most ecological silviculture practices have focused on manipulation of structural attributes and complexity in forests, there has also been an implicit focus on the functional importance of these features (Hunter, 1999; Carey, 2001). In recent decades there has been a shift toward more explicit consideration and manipulation of functional complexity in forest ecosystems (e.g., Stanturf et al., 2014; Ford and Keeton, 2017). This may be reflected in a shift in usage from "biological legacies" to a broader view of "ecosystem memory" (Ogle et al., 2015; Johnstone et al., 2016; Bergeron et al., 2017), with more explicit consideration of a wide variety of functions that are retained or promoted through management, including the influence of the retained vegetation on future successional dynamics (Drever et al., 2006; Messier et al., 2013). An example is the promotion of fire through management focused on affecting both ecosystem structure and tree species composition (Stanturf et al., 2014), or maintenance of nutrient uptake capacity in stands through retention of trees that support diverse assemblages of mycorrhizae (Simard et al., 2013). Although the explicit quantification of functional complexity has become a focus of academic research, the degree to which such conceptions of complexity have been (or can be) incorporated into silvicultural planning is not clear.

In recent years there has also been a significant shift toward forward-looking notions of complexity that could be termed "adaptive" or "resilience" complexity. This direction is focused on understanding and promoting the resilience or adaptive capacity of forest ecosystems and draws ideas and nomenclature from literature focused on complex adaptive systems (CAS; Drever et al., 2006; Messier et al., 2013). The work of Puettmann et al. (2009) and others has brought this conception of forest complexity into the mainstream of silvicultural research. The CAS framework focuses on bottom-up control, interconnectedness, and feedback loops of elements and functions in forest ecosystems (Filotas et al., 2014). This framework prompts silviculture researchers and practitioners to view treatments as manipulating both ecosystem elements and how they interact, and that the resulting response is an emergent property driven by changes in elements, interactions and feedback loops (Drever et al., 2006; Churchill et al., 2013; Messier et al., 2013). "Adaptive complexity" could therefore be characterized as aspects of an ecological system that promote a more diverse and resilient array of potential ecosystem responses to perturbations (Filotas et al., 2014). This new conception of how to frame complexity in silviculture has coincided with a realization among scientists and practitioners that a grand challenge for the future of forest management will be understanding and preparing for the response of managed forests to current and future environmental changes and stressors (e.g., climate change, invasive pests; Millar et al., 2007; Messier et al., 2013).

These different views of complexity are certainly not mutually exclusive and are often considered concurrently, but the emphasis in academic circles has shifted over time to explicitly include functional and adaptive complexity (Messier et al., 2013). However, there can be lags in the incorporation of concepts into silvicultural practice due to the time needed for dissemination, planning, and implementation. Understanding the timeline for integration of ideas into silvicultural treatment design is important as new concepts (e.g., complex adaptive systems) and metrics/methods (e.g., 3D canopy complexity from terrestrial LiDAR) are introduced and promoted in the academic literature. This is especially true if, as the discussion and messaging from silvicultural researchers shifts, concepts that have been promoted in the past are relegated and the overall incorporation of complexity-based thinking into silvicultural practice risks losing momentum. To most efficiently incorporate new concepts into silviculture, there is likely to be value in building on prior frameworks and understanding how new concepts can be related to existing frameworks in practice.

With these issues in mind we set out to better understand how conceptions of complexity in silviculture have shifted over time and how different conceptions can be reconciled (Fig. 1). Our specific objectives were to: (1) characterize the adoption of complexity terminology and concepts over time in the forestry/silviculture literature, (2) illustrate examples of the incorporation of different conceptions of complexity into silvicultural experiments, and (3) explore strategies for concurrently addressing or implementing multiple conceptions of complexity in silviculture. We discuss how the field of silviculture can most effectively incorporate emerging tools and data on complexity into design and assessment of silvicultural practices. We also discuss the implications of our findings for ecologically-focused forest management and some potential future directions for incorporating a wider variety

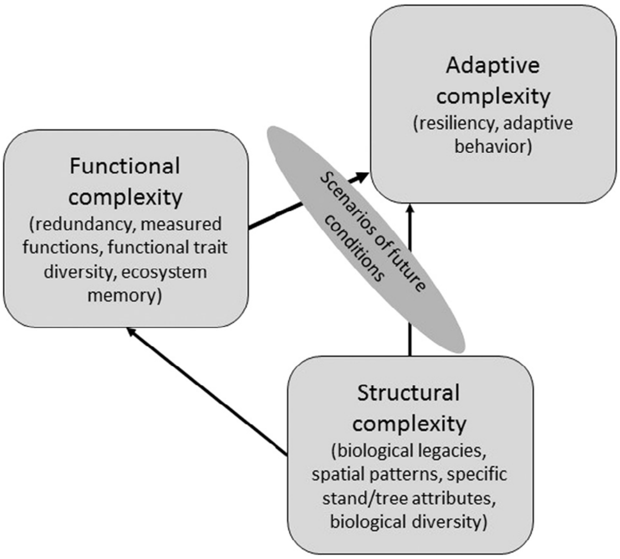

Fig. 1. Conceptual diagram illustrating the relationship between different conceptions of complexity that could be used to analyze or design silviculture treatments.

of views of forest complexity into silviculture.

2. Quantitative and qualitative literature review

We conducted a mixed quantitative and qualitative review of the forestry/silviculture literature. In this review we address the following specific questions: (1) How has the use of complexity terminology changed over time?, (2) How has the incorporation of different complexity conceptions into research and treatment design changed over time?, and (3) How has the adoption of complexity concepts differed among sub-fields within forestry? Details of the search criteria and the list of journals searched are included in the Supplementary Material (Appendix 1).

2.1. Literature review methods

2.1.1. Keyword analysis

To assess the volume of literature focused on complexity in silviculture and forest management we first conducted a keyword search using Web of Science (v. 5.25.1; Clarivate.Analytics, 2017) for papers that included selected terms related to complexity ("complex", "complexity", "heterogeneity", "heterogeneous", "adaptive") in combination with terms that indicated a focus on silviculture or forestry ("silviculture", "silvicultural", "forestry", "forest ecology", "forest management"). We assessed the usage of this selected terminology over time (from 1992 to 2017) in a selection of international and regional forestry journals and related applied ecology and conservation biology journals where forestry and silviculture studies are often published (Supplementary Material – Appendix 3). Our selection of complexity keywords was based around their specificity to the topic and a perception of increased usage over time in the literature. The selection, by necessity, excludes many closely related terms (e.g., "structural" which has a wide array of uses not related to complexity) and consequently some relevant work has likely been omitted. Nevertheless, we believe the analysis is broadly representative of the pattern of diffusion of complexity-focused terminology through the forestry literature.

2.1.2. Detailed literature review

To better understand how different conceptions of complexity have been incorporated into silviculture over time we conducted a detailed review of a subset of publications. We identified all publications (from the same set of journals as above) from the period 1992–2017 that specifically included the terms "complexity" or "heterogeneity" or "adaptive" and "silviculture". We then conducted a detailed review of these manuscripts and categorized publications in three ways. First, we determined how complexity was incorporated into the research and assigned studies to the following "analysis type" categories: (1) complexity was explicitly included in or related to the analysis (rather than just discussed peripherally in the Introduction or Discussion), (2) analysis addressed complexity associated with existing treatments or disturbances, (3) the study utilized explicit treatments designed to manipulate complexity, or (4) the study focused on modeling of complexity. Second, we classified "complexity conceptions" (Fig. 1) used in each publication into categories: (1) qualitative structural complexity, (2) non-spatial quantitative structural complexity, (3) spatial structural complexity, (4) attribute/trait/biological complexity, (5) functional complexity, and (6) adaptive complexity. Third, we categorized each article into sub-disciplines as follows: (1) production forestry, (2) silviculture, (3) ecological forestry, (4) forest ecology, and (5) biological conservation/wildlife management. In each of these categorizations a single paper could be classified into multiple categories. Therefore, we analyzed the proportion of papers that incorporated each "analysis type" and "complexity conception" and how these proportions changed over time in five year increments during the period of interest (1992–2017). We also assessed differences in the frequency of usage for each "analysis type" and "complexity conception" among sub-disciplines. Differences in the frequency of usage of "analysis types" and "complexity conceptions" were compared among sub-disciplines and 5-year time periods using contingency table analysis (using PROC FREQ in SAS v. 9.4).

2.1.3. Review of silvicultural experiments

Finally, we analyzed a set of silvicultural experiments that were intended to promote complexity in managed forests, to attempt to understand how different conceptions of complexity have been incorporated into treatment design and implementation. We focused primarily on operational-scale experiments and those with a specific focus on silviculture and forestry outcomes (i.e., not purely ecology-focused experiments). We also limited the scope of the sample by only evaluating experiments implemented in the US, where we are most familiar with the forest types and discourse around silviculture and forest management. For each experiment we analyzed an initial publication that detailed ideas and goals underpinning the experimental design, expected outcomes and methods for assessing these, silvicultural systems and treatments employed or modified for use in the project, and specific on-the-ground experimental design and implementation. Based on this review we developed a list of strategies that have been employed to incorporate complexity into forest management (Table 1) and attempted to identify which strategies were utilized in each of the experiments. We also assessed which of the "conceptions of complexity" (Section 2.1.2) were considered in the design and implementation of the experiments. In many cases subsequent studies or analyses have addressed conceptions not originally included in the experimental design. We have focused on the framing of the original intent of the projects, but include discussion of subsequent studies that have built new conceptions of complexity onto existing frameworks.

2.2. Literature review results

2.2.1. Keyword analysis

The use of complexity-related terminology in the forestry literature exhibited an upward trend over time during the study period (1992–2017). The keyword search revealed a set of 5230 papers that included the selected complexity and forestry keywords, which represented 12.3% of all articles published in the forestry literature (as defined by a search of the same journals for only the forestry-related keywords) during the study period. The use of complexity terminology increased greatly over time (Fig. 2), both in terms of number of papers

Table 1
Methods for incorporating complexity into silviculture treatments or systems that were identified through review of publications detailing design and analysis of silvicultural experiments focused on manipulation of complexity.

Number^	Type of complexity-focused management	# of Experiments*
1	Traditional silvicultural systems applied outside normal study system	3
2	Traditional silvicultural systems applied in spatially heterogeneous fashion	15
3	Traditional silvicultural systems applied in temporally heterogeneous fashion	4
4	Variable density thinning and other alternative intermediate stand treatments	4
5	Green tree retention and other clear-cutting alternatives	6
6	Irregular and other shelterwood variants	4
7	Multi-cohort management	5
8	Gap-based management	10
9	Natural disturbance emulation	9
10	Legacy retention or creation	8
11	Size structure-based structural complexity enhancement	3
12	Structural complexity enhancement based on spatial pattern manipulation	11
13	Structural complexity enhancement based on canopy manipulation	1
14	Species diversity manipulation/maintenance/enhancement	12
15	Functional trait diversity manipulation/maintenance/enhancement	7
16	Manipulation targeted at specific ecosystem function(s)	6
17	Manipulation targeted at specific habitat feature(s)	6
18	Direct manipulation of resilience	3
19	Transition	3

^ For reference in "Management frameworks" column in Table 2.

* Number of silvicultural experiments reviewed in Table 2 that included each strategy in initial design and framing.

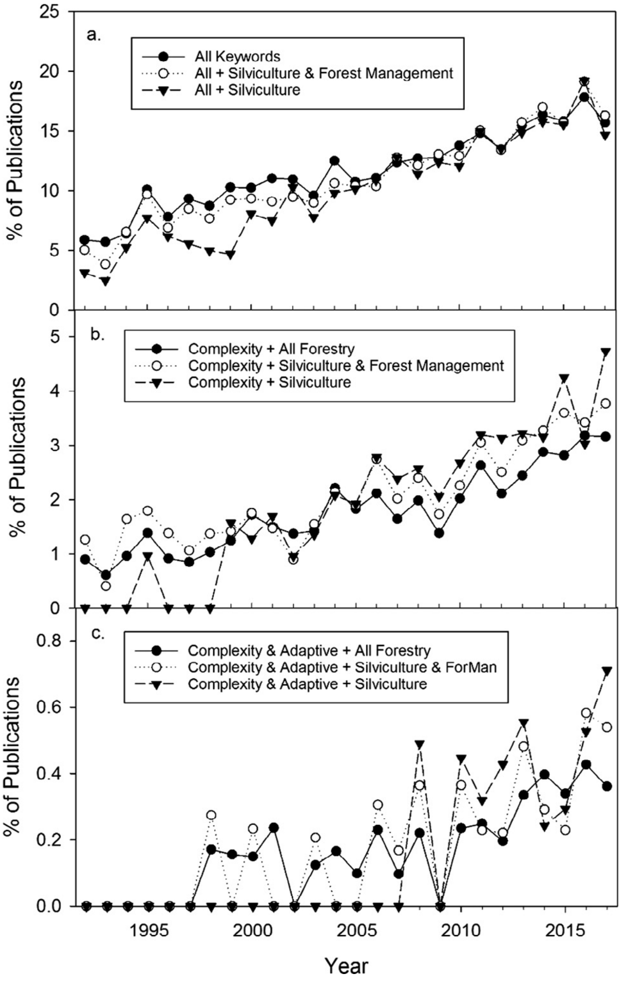

Fig. 2. Percent of articles that used selected complexity-focused keywords over the period 1992–2017 in forestry (and related) journals. Silviculture and Forest Management category in each panel includes only papers with specific keywords "silviculture", "silvicultural", or "forest management". Silviculture category in each panel does not include the term "forest management". Panel b includes only "complexity" and "complex" as keywords, panel c includes only publications that had both "complexity" or "complex" and "adaptive" as keywords.

(46 in 1992 vs. 376 in 2016) and in the proportion of papers published (5.9% in 1992 vs. 17.9% in 2016). The trends were relatively similar when a restricted set of forestry keywords were assessed, such as for papers that included only "silviculture" or "silvicultural" as keywords (Fig. 2). There were some interesting differences when the complexity-focused keyword search was restricted to specific terms. For the set that included only the term "complexity", there was a distinct lag of silviculture-specific articles (as indicated by the specific inclusion of the terms "silviculture" or "silvicultural"), with almost no publications prior to 1998 (Fig. 2b). There were no articles that included all of the terms "silviculture", "complexity", and "adaptive" prior to 2008 (Fig. 2c).

2.2.2. *Detailed literature review analysis*

The starting data set for the detailed review—produced by our keyword search for "complexity" or "heterogeneity" or "adaptive" and "silviculture"—consisted of 986 articles. An initial review of abstracts was used to limit this set to those articles that were potentially relevant to this analysis (i.e., actually focused on silviculture or forest management, and had some relation to measurement of complexity in forests), resulting in a data set of 360 that were fully reviewed. Upon full review, 270 of the publications met the criteria of being primary research articles and having significant content (more than passing references) relating to both complexity and forest management/ecology. The full list of articles reviewed and breakdown by categories is included in the Supplementary Material (Appendices 2 & 5). The number of articles that were classified into the different sub-disciplines differed greatly, with most articles meeting the criteria of including material related to forest ecology (99%), and a large percentage including silviculture (62%) or ecological forestry (52%). In comparison, relatively few articles focused on conservation biology/wildlife management (24%) or production forestry (15%).

Conceptions of complexity varied greatly in the degree to which they have been incorporated into the literature over the study period ($X^2 = 760.3$, df = 5, $p < .001$; Fig. 3a). Qualitative (71% of articles reviewed), quantitative-non-spatial (93%), and attribute/biological (86%) complexity have been much more commonly incorporated than spatial (33%), functional (12%), or adaptive (9%) complexity concepts. The frequency of these conceptions in the various sub-disciplines did not differ significantly statistically ($X^2 = 15.48$, df = 20, $p = .75$), but notably adaptive complexity was not incorporated into any articles in

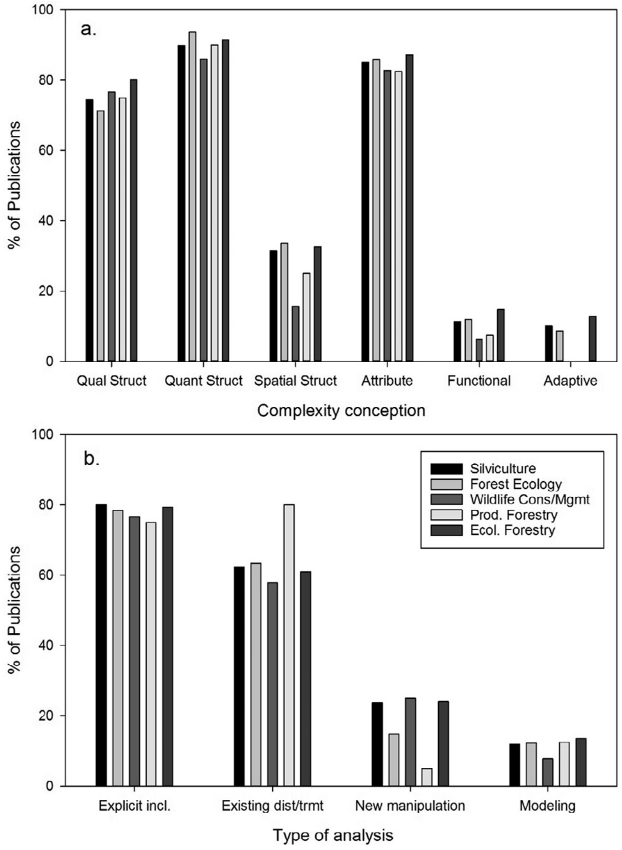

Fig. 3. Percent of publications in the detailed literature review analysis (within sub-disciplines) that included different (a) conceptions of complexity and (b) analysis types.

wildlife/biological conservation or production forestry-focused publications (Fig. 3a). The usage of different analysis types in addressing complexity also varied greatly ($X^2 = 375.1$, df = 3, $p < .001$; Fig. 3b). Many studies directly addressed complexity through their analyses (78%) or analyzed complexity associated with existing treatments or disturbances (63%), but far fewer included new manipulations directly targeting complexity (15%) or conducted modeling to better understand complexity patterns (12%). The intersection of different complexity conceptions and analysis types did not differ significantly from the expected marginal frequencies ($X^2 = 16.14$, df = 15, $p = .37$) among combinations of categories (e.g., “qualitative complexity” and “existing treatments/disturbances”).

The number of articles incorporating complexity as a topic increased greatly over time and at a faster pace than the overall increase in the number of silviculture articles (235% vs. 53% mean increase across time periods). There was an increase in the incorporation of all of the different conceptions of complexity over time (Fig. 4a). There was not a statistically significant difference in the pattern of incorporation of the different conceptions over time ($X^2 = 19.82$, df = 20, $p = .47$), but some variation in temporal patterns was discernable. Qualitative, quantitative-non-spatial, and attribute complexity increased early and have continued to be the most common conceptions utilized in the literature (Fig. 4a). Functional and adaptive complexity are quite rare in the literature, but have both increased in the past ~5 years (i.e., mostly used in 2012–2017). Incorporation of complexity increased greatly over time in each sub-discipline, but the temporal pattern varied among categories (Fig. 4b). Incorporation of complexity into forest ecology and ecological forestry increased quickly and generally continued to increase over the entire time period. Studies focused on silviculture initially increased quickly but have not increased over the past 15 years. Papers focusing on biological conservation also have plateaued recently and those focused on complexity and production forestry have actually decreased in the past ~10 years (Fig. 4b).

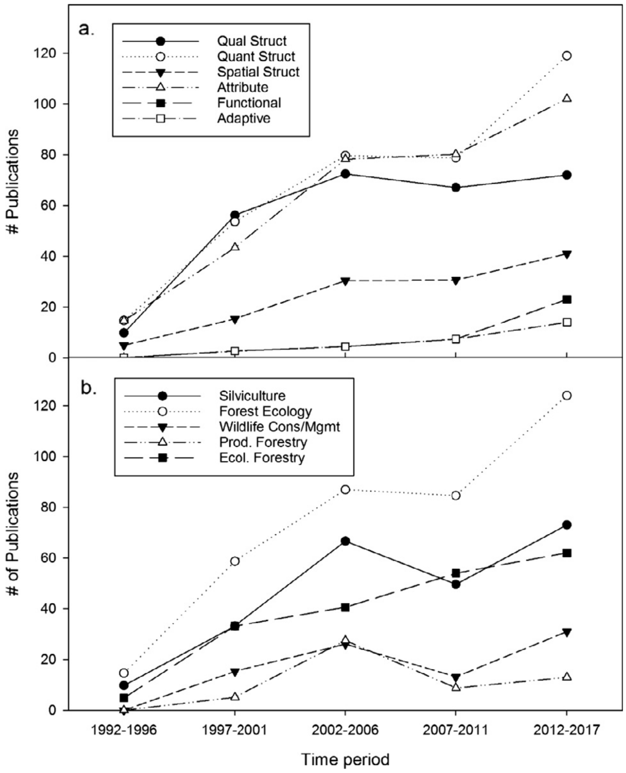

Fig. 4. Analysis of publications in detailed literature review illustrating temporal pattern of (a) incorporation of complexity conceptions and (b) focus on complexity in different sub-disciplines within forestry. To account for overall publication inflation rates over time, counts are scaled based on the number of total publications in each time period (in the selected journals) using the keyword “silviculture” with 2012–2017 as the baseline. Scalars for each period are as follows: 1992–1996 = 4.9, 1997–2001 = 2.55, 2002–2006 = 1.45, 2007–2011 = 1.46, 2012–2017 = 1.0.

2.2.3. Silvicultural experiment review analysis

We identified and analyzed 18 silvicultural experiments implemented between 1995 and 2017. Experiments varied greatly in scale of treatment and inference, but most involved multiple stand-scale replicates (Table 2). Most early experiments were located in the Pacific Northwest (PNW) region and focused on Douglas-fir forests, with some notable exceptions (Table 2). We identified a list of 19 strategies for incorporating complexity into silvicultural treatments/systems that were either included in the planning process for these experiments or have been mentioned in the literature as potential strategies (Table 1). Based on close reading of the cited publications (Table 2), each of the experiments included at least four of these strategies in their planning process. The strategies utilized (or at least discussed) have changed somewhat over time, but also have (often necessarily) varied among different regions/forest types (Table 2). For example, variable density thinning (strategy #4 in Table 1) has been an important strategy in the PNW (although not absent elsewhere), while natural disturbance emulation (#9) is more widely cited as a design factor in Northeast and Great Lakes region forests (Table 2). Manipulation of spatial patterns (#12) has been a much more common strategy (Table 1) for creating structural complexity than direct manipulation of the complexity of size structure (#11) or canopy structure (#13). Strategies focused on specific ecosystem functions (#16) and habitat features (#17) were present in many experiments from the beginning of the study period, but strategies specifically targeting ecosystem resilience (#18) and transition (#19) were not generally discussed as part of experimental design until much more recently (Table 2).

Table 2
List of silvicultural experiments reviewed and relevant publications detailing study design and objectives – ordered by date of treatment implementation ("Start date"). Study acronyms defined in cited publications.

Study	Start date	Region[#]	Size (ha)	Management frameworks*	Complexity conceptions^	Citation
YSTDS	1995	PNW	90	2, 4, 8, 14	QN, S, AB	Davis et al. (2007)
AFERP	1995	NE	90	2, 3, 7, 9, 12, 14	QL, QN, S, AB	Arseneault et al. (2011)
Divide	1995	GL	136	2, 8, 9, 14, 15	QN, S, AB, F	Kern et al. (2014)
DEMO	1996	PNW	468	5, 10, 12, 16, 17	QL, QN, S, AB, F	Aubry et al. (2004)
Ichauway	1997	SE	30	1, 2, 5, 9, 12, 14, 16	QL, QN, S, AB, F	Palik et al. (2003)
DMS	1997	PNW	1069	2, 3, 4, 5, 8, 10, 12, 13, 16, 17	QL, QN, S, AB, F	Cissel et al. (2006)
Capitol	1998	PNW	240	1, 2, 6, 7, 8, 12, 17	QL, QN, S	Curtis et al. (2004)
YB Legacy-tree	2003	GL	235	2, 8, 9, 10, 12, 14, 15	QN, S, AB, F	Shields et al. (2007)
Chippewa	2003	GL	64	2, 5, 9, 12, 14, 16	QL, QN, S, AB, F	Palik et al. (2014)
FEMDP/SCE	2003	NE	20	2, 8, 9, 10, 11	QL, QN, S, F	Keeton (2006)
Flambeau	2007	GL	300	2, 8, 9, 10, 15	QL, QN, S, AB, F	Forrester et al. (2013)
MOSS	2007	GL	600	2, 6, 7, 8, 10, 14	QL, QN, S, AB	Fassnacht et al. (2015)
ICO	2008	IMW	30	8, 9, 11, 12, 16, 17	QN, F, AD	Churchill et al. (2013)
HEE	2008	CH	3600	2, 3, 14, 15, 17	QL, AB	Swihart et al. (2013)
ASCC – CEF	2014	GL	200	2, 4, 6, 7, 11, 12, 14, 15, 18, 19	QN, S, AB, F, AD	Nagel et al. (2017)
ASCC – SCG	2017	NE	100	3, 4, 8, 10, 12, 14, 18, 19	QN, S, AB, F, AD	Nagel et al. (2017)
NHSEED	2017	GL	45	1, 5, 6, 7, 9, 14, 15	QL, QN, AB	This paper
ASCC – SJNF	2018?	IMW	NA	2, 5, 10, 12, 14, 15, 16, 17, 18, 19	QN, S, AB, F, AD	Nagel et al. (2017)

[#] PNW = Pacific Northwest, NE = Northeast, SE = Southeast, GL = Great Lakes, CH = Central Hardwoods, IMW = Inter-mountain West.

* Numbers reference management strategies listed in Table 1 – based on strategies outlined in cited publications.

^ Complexity conceptions included in analysis focused on each experiment: QL = Qualitative, QN = Quantitative non-spatial, S = Spatial, AB = Attribute/biological, F = Functional, AD = Adaptive.

3. Case studies

We present a series of four case studies that illustrate how various conceptions of complexity have been incorporated into design of selected, recent silvicultural experiments in different forest types and regions. We link the development of these specific studies and experiments to shifting views on complexity and changing management goals. We characterize techniques used to promote or manipulate different types of complexity, and data and analysis frameworks used in design and assessment. Each also includes existing or potential strategies for reconciling different complexity concepts within established frameworks.

3.1. Gap and legacy-based management in Great Lakes region northern hardwood forests

Management of northern hardwood forests in the Great Lakes region has tended towards simplification, with a focus on creating productive near-monocultures of economically important saw-timber and veneer species (largely sugar maple; *Acer saccharum*). Widespread focus on this management outcome has led to reduced ecological complexity and resiliency. Specifically, management in this region has relied to a large extent on silvicultural systems that favor increased dominance by shade-tolerant maples, such as single-tree selection (Metzger and Tubbs, 1971; Crow et al., 2002; Schuler, 2004; Neuendorff et al., 2007). Until recently, the high economic value of these stands tended to favor conceptualizations of complexity focused purely on structural features (e.g., variability in tree size) rather than species and functional diversity, biological legacies, spatial scale and patterning, or resiliency and adaptive capacity. However, projections of sugar maple decline in this region under climate change (Iverson et al., 2008), and declining efficacy of dominant silvicultural systems in the face of biotic and abiotic stressors (Bal et al., 2015; Kern et al., 2017) are shifting how complexity is conceptualized in these forests. Researchers and managers are increasingly exploring ways to maintain and restore complexity, with the objective of providing opportunities for sustainable timber harvest (Keeton, 2006), enhancing habitat quality for late-successional biodiversity (Dove and Keeton, 2015) and providing ecosystem services, such as riparian functionality (Warren et al., 2016) and high levels of carbon storage (Ford and Keeton, 2017).

Increasingly, silvicultural experiments are being implemented that reflect a broadened view of complexity in northern hardwoods forests. A number of recent projects have focused on gap-based silvicultural systems and on expanding the types of variables being studied and outcomes being sought. Gap creation influences the resource environment for tree seedling establishment and growth, such that species partition various niches within or among gaps (Grubb, 1977). One approach to adding complexity into silvicultural systems is to emulate the frequency, distribution, and size of canopy gaps that result from natural disturbance at various stages of stand development (Coates and Burton, 1997; Franklin et al., 2007). In northern Wisconsin, the Divide Gap Study (Table 2) examined a wide array of metrics of complexity across a range of harvest-created gap sizes. In this study, ground-layer plant traits varied with gap position, gap size, and time since harvest, highlighting localized gap effects on the complexity of species and functional trait composition (Kern et al., 2012). Simulations of gap-based management approaches (emulating gap size distributions of natural disturbances) predicted increased species richness and variability in plant traits, highlighting potential stand-level effects of harvest gap size on ground-layer plant community complexity (Kern et al., 2014). In another study, the Yellow Birch Legacy-Tree project (Table 2) incorporated ecosystem memory concepts in maintaining compositional diversity through retention of mature yellow birch (*Betula alleghaniensis*) individuals as the focal point of harvest-created canopy gaps in a maple-dominated forest matrix (Shields et al., 2007; Poznanovic et al., 2014). Across a range of taxa, harvest gaps exhibited distinct communities and/or greater diversity than the surrounding forest matrix (Shields and Webster, 2007; Shields et al., 2007) and high variation in spatial patterning of regeneration associated with legacy-tree retention (Poznanovic et al., 2014).

Based on outcomes of prior gap studies in increasing complexity (Shields et al., 2007; Prevost et al., 2010; Kern et al., 2012, 2014; Poznanovic et al., 2014) and older studies investigating a range of traditional silvicultural systems (Eyre and Zillgitt, 1953; Godman and Krefting, 1960; Tubbs and Metzger, 1969), the Northern Hardwood Silvicultural Experiment to Enhance Diversity (NHSEED) focuses on rediscovering and reconceptualizing the use of even-aged silvicultural systems in northern hardwood forests (Table 2). This experiment was installed in 2017 and investigates novel variations on patch clearcut and shelterwood systems with inclusion of site preparation, deer exclusion, and direct seeding. Specifically, this study examines the role of seed limitation, light limitation, microsite limitation, and browse pressure on the species and functional diversity of tree regeneration.

3.2. Structural retention harvesting in red pine ecosystems; restoring complexity, tree diversity, and adaptability to an unknown future

An early conception of complexity in forests focused on structural conditions resulting from natural disturbance and stand development (MacArthur and MacArthur, 1961; Franklin et al., 2002), including tree size and age distributions, tree morphological characteristics, and decadence and deadwood features. Included in this view of complexity is the arrangement of structural features across a stand, i.e., spatial heterogeneity. Complexity as described here is often managed against in production silvicultural systems. A case in point are red pine (*Pinus resinosa*) forests of the western Great Lakes region of North America. Historically, these forests had disturbance regimes characterized by infrequent heavy, but partial canopy removal from fire, root disease, and wind, along with frequent, but heterogeneous, surface fires (Frelich, 2002; Drobyshev et al., 2008). This disturbance regime resulted in stands with complex age structures, variable tree sizes, heterogeneous canopies, mixed-species composition, and spatially variable understories (Palik and Zasada, 2003). In contrast, contemporary red pine stands are often models of simplicity with: even-aged structure, closed canopies, dominance by red pine, minimal tree size and spatial variation, and dense woody understories dominated by shrubs (especially *Corylus* spp.)

Structural retention harvesting is an approach designed to emulate natural disturbance regimes and promote development of complexity (Roberts et al., 2016). This approach for restoring complexity of red pine ecosystems developed out of an operational-scale experiment on the Chippewa National Forest, Minnesota, USA; The Red Pine Retention Experiment (Table 2; Palik and Zasada, 2003; Roberts et al., 2016). The experiment has a goal of evaluating options for restoration of structural complexity and compositional diversity. Specific objectives are to create two-cohort age structures, enhance spatial heterogeneity of canopy tree and understory shrub communities, and increase tree species diversity. Retention treatments include dispersed, small-gap/aggregate, and large gap/aggregate retention, all combined with manipulation of the woody shrub layer to create spatial heterogeneity; the latter a condition historically maintained by surface fires. A full suite of native tree species are targeted for regeneration. While none of the treatments are perfect emulations of natural disturbance, they are reasonable representations of these dynamics, and resultant structural outcomes.

The newest evolution of this silvicultural approach for managing complexity is incorporated into the Adaptive Silviculture for Climate Change (ASCC) experiment (Nagel et al., 2017). Specifically, the ASCC installation on the Chippewa National Forest in northern Minnesota, USA, includes a resilience treatment aimed at enhancing the adaptive potential of red pine ecosystems to climate change (Table 2). The approach uses retention harvests and variable density thinning to create a heterogeneous mix of environmental conditions so as to favor a mix of native tree species projected to be future-climate adapted. The incorporation of complexity in the two applications described above is largely guided by an understanding of natural developmental models and associated structural conditions (i.e., the original conception of complexity sensu; Franklin et al., 1986). Nonetheless, the functional outcomes and dynamics, including system memory (i.e., legacies) and complexity (structural and functional), also satisfy recent calls for managing forests as complex adaptive systems in the face of future uncertainty (Puettmann et al., 2009).

3.3. Restoring spatial aspects of forest structural complexity in dry forests with the ICO approach

A fine-grained spatial mosaic of individual trees, clumps of closely spaced trees, and openings is an essential component of complexity in dry, frequent-fire pine and mixed-conifer ecosystems (Larson and Churchill, 2012; Clyatt et al., 2016; Rodman et al., 2017). Past land use, timber harvest, and disruption of historical fire regimes have altered stand structure and composition, and consequently compromised ecosystem function and adaptive capacity in many of these forests. Restoration of such fire-prone forest landscapes requires silvicultural approaches that restore and maintain the multi-scaled spatial complexity present in forests with intact disturbance regimes (Hessburg et al., 2015). The individuals, clumps, and openings (ICO) silvicultural and monitoring approach developed by Churchill et al. (2013) responds to this need by providing an operational framework for including information about within-stand spatial patterns in prescriptions, marking guides, and monitoring protocols. The ICO approach was designed to restore pattern-process linkages and the disturbance-stand development cycle by restoring spatial aspects of forest structural complexity (Churchill et al., 2013). ICO is well suited to treatments in previously harvested and fire-excluded sites where there is a need to better align stand structure, composition, and pattern with current and future biophysical conditions and disturbance regimes. Thus, ICO is a useful framework for fuel reduction and restoration treatments, as well as climate change adaptation treatments.

The ICO method provides a way to express complex spatial information in an understandable, efficient way that tree marking crews and equipment operators can implement in on-the-ground treatments (Fig. 5; Churchill et al., 2016). Managers can draw on historical or contemporary reference data from sites with intact frequent fire regimes as a source of spatial pattern information. Such reference data are available for a wide range of dry pine and mixed-conifer forests across the west (Lydersen et al., 2013; Clyatt et al., 2016; Churchill et al., 2017; Rodman et al., 2017). Spatial pattern targets can also be set based on desired functional outcomes and habitat objectives, for example, creation of small and moderate canopy openings to promote snow retention (Schneider et al., 2015); or retention of tree clumps to provide habitat for focal wildlife species, or to provide visual breaks for aesthetic objectives.

An ICO prescription expresses the desired post-treatment conditions in terms of the total number of widely spaced individual trees, and the number of small, medium, and large clumps to be retained in the entire unit after treatment. Prescription targets are intentionally not described in terms of averages or per hectare tree or clump densities. This gives the marking crew or machine operator the freedom to tailor marking and implementation to fine-scale differences in tree condition and biophysical conditions. For example, areas with shallow soils or low vigor trees can be thinned heavier or left as openings, while high densities and larger clumps can be left on moister microsites. Clear guidelines about trees species priority for retention and removal are also required, with fire and drought-resistant species usually given higher priority for retention in most restoration and climate change adaptation treatments. By focusing on tree and biophysical conditions and the tree neighborhood scale, ICO marking facilitates restoring fine-scale heterogeneity in vegetation (Fig. 5) that is aligned with topographic, edaphic, and vegetation conditions.

3.4. Restoration of complexity in coastal Douglas-fir forests using variable density thinning: implications for adaptability

Old-growth coastal Douglas-fir in the Pacific Northwest (PNW) are perhaps the flagship forest type for addressing complexity in silviculture. The ability of trees to reach massive proportions, in conjunction with a mixed-severity historical disturbance regime, resulted in forests with high levels of vertical and horizontal heterogeneity (Waring and Franklin, 1979; Tappeiner et al., 1997; Franklin et al., 2002; Donato et al., 2012; Tepley et al., 2013). Controversy over the logging of old-growth forests on federal land beginning in the 1980 s led to the paradigm shift in management known now as “ecological

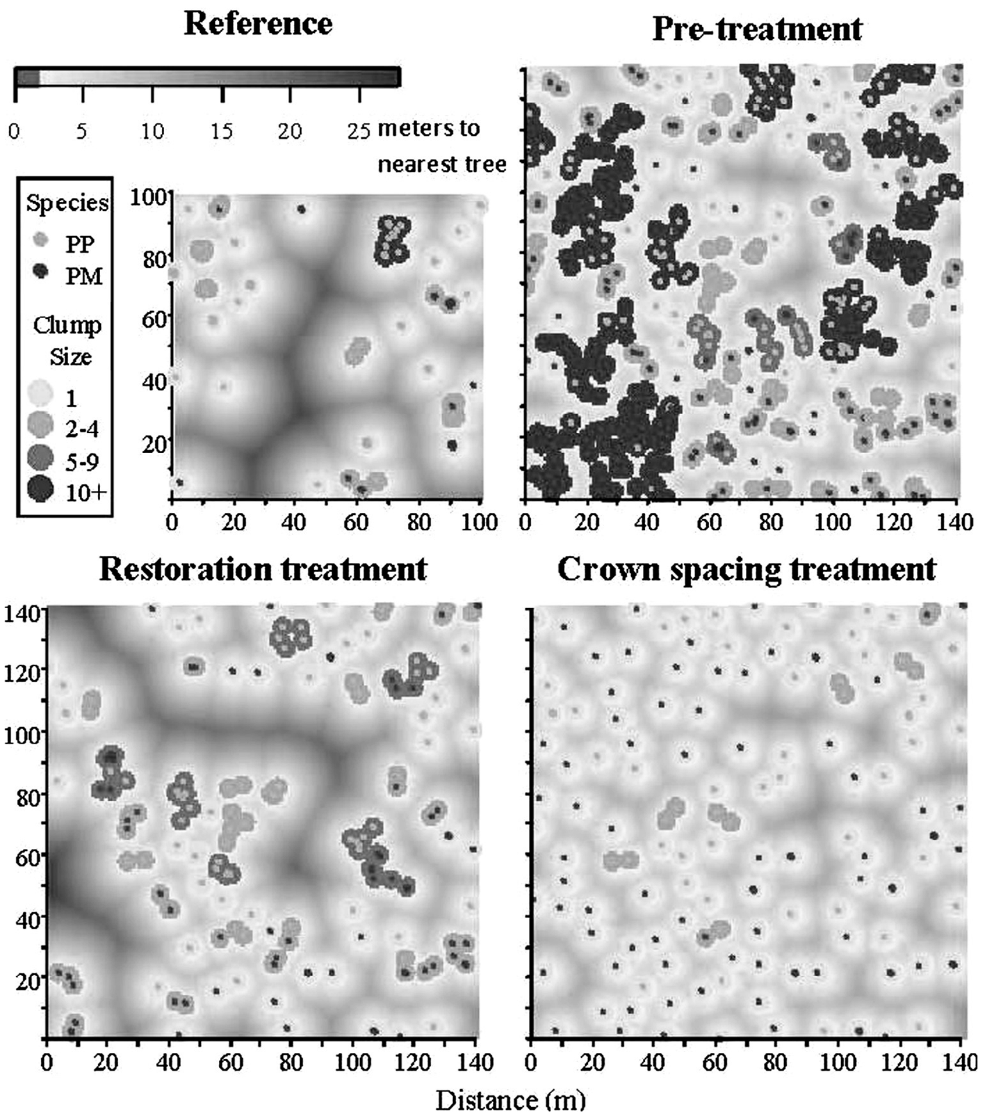

Fig. 5. Tree spatial patterns created when a fire-excluded site (upper left panel "Pre-treatment") is treated with restoration prescription based on the ICO spatial variability metrics (bottom left: 70 TPH, 53.1 cm mean dbh, basal area 16.9 $m^2 ha^{-1}$) compared to a standard spacing-based fuel reduction prescription (bottom right: 65 TPH, 56.6 cm mean dbh, basal area 17.5 $m^2 ha^{-1}$). Compare to local reference tree spatial patterns (upper left panel) which were reconstructed using dendroecological methods to estimate conditions prior to disruption of the historical frequent fire regime. Figure courtesy of Derek Churchill, adapted from Churchill et al. (2013). PP is *Pinus ponderosa*; PM is *Pseudotsuga menziesii*.

forestry" (Thomas et al., 2006; Ruzicka et al., 2013). Following this shift, thinning of homogenous, second-growth even-aged forests became the primary silvicultural practice implemented on federal forestlands in the PNW. In the early 1990 s several large-scale silvicultural experiments were designed to assess the ability of variable-density thinning to accelerate the development of structural complexity and associated ecosystem services (i.e., spotted owl habitat) relative to standard commercial thinning (Table 2; Poage and Anderson, 2007). Among these experiments is the Density Management Study (DMS), which includes three thinning treatments (high, moderate and variable residual tree densities) with leave islands and gaps of three different sizes, and also extends to investigation of management impacts on ecosystem functioning associated with headwater streams (Cissel et al., 2006).

Research conducted on the DMS has effectively addressed original questions related to the restoration of complex forest structures and associated ecosystem services. Additionally, the experiment has taken on new significance as investigators have begun to examine questions related to managing forests as complex adaptive systems in the context of global change. Results show variable density thinning increases structural complexity by accelerating the development of large diameter overstory trees and multiple canopy layers while suspending the process of crown lift. However, these treatments have also reduced density-dependent mortality (i.e., self-thinning), and hence the recruitment of downed wood (Dodson et al., 2012; Puettmann et al., 2016). Overstory responses are also tightly coupled with understory plant community composition and diversity (Ares et al., 2009; Ares et al., 2010), leading to functional trade-offs between ecosystem services, specifically carbon vs. diversity (Burton et al., 2013). In addition, research on the DMS has highlighted how thinning can modulate functional relationships between disturbance and climate change within a complex adaptive systems framework (Puettmann, 2011) using a trait-based approach (Neill and Puettmann, 2013). Here, more open conditions within the variable density thinning promoted the recruitment of early-seral and drought tolerant understory plant species, increasing the adaptability of wildlife habitat to increases in the frequency and severity of droughts associated with climate change (Mote and Salathé, 2010; Neill and Puettmann, 2013). However, investigations that accounted for cross-scale interactions highlighted how a complexity of factors, including interactions and feedback loops, drive vegetation development at multiple scales (Fahey and Puettmann, 2007; Burton et al., 2014; Dodson et al., 2014). Ongoing research builds upon these efforts by developing new trait-based models to project the effects of interactions between alternative silvicultural and climate change scenarios on a range of ecosystem services (Fig. 6; Burton et al., 2017).

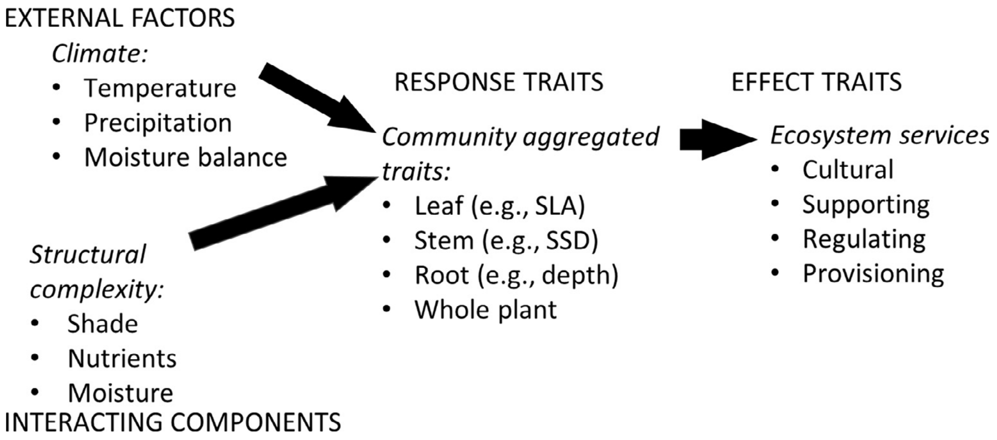

Fig. 6. Modeling forest communities as complex adaptive systems using a response-effect trait approach. Effects of interactions between external factors (climate change) and interacting components (i.e., effects of silviculture on structural complexity) on ecosystem services provided by plant communities can be modeled using a trait-based approach. Plant traits, including leaf (SLA = specific leaf area), stem (SSD = stem specific density), root and whole plant traits, affect the physiological and demographic performance of species, influencing how they respond to changes in structural complexity brought about by forest management and external factors such as climate change (Reich et al., 2003). Trait-based, rather than species-based, models thus provide a mechanistic approach to projecting effects of changes in external factors (i.e., climate) and interacting components (i.e., effects of silviculture or disturbance in general on structural complexity). These processes may influence the provisioning of ecosystem services by the understory (Suding et al., 2008).

4. Discussion

Our analysis of the silvicultural literature supports the view that complexity-focused thinking in silvicultural research has become significantly more prominent over time. There has been a consistent increase in the use of complexity-focused terminology and more widespread incorporation of concepts associated with complexity in the literature and silviculture experiments. However, the analytical focus has generally remained on metrics such as attribute and quantitative non-spatial structural complexity that are both similar to traditional data used in silvicultural planning, and relatively straightforward to directly manipulate through silvicultural treatments. This tendency certainly makes sense, as treatment design generally requires some degree of focus on tangible goals and the direct outcomes of different courses of action. However, although structural and attribute-focused concepts have been most widely adopted, many foundational studies did include a focus on functional or adaptive complexity as well, albeit framed in a slightly different way (e.g., Franklin et al., 1986, 2002; Seymour and White, 2002). Several of these original studies have expanded this focus or incorporated new complexity concepts into research, even though the original goals may not have explicitly included them (e.g., the DMS study outlined above). A further push to promote consideration of functional and adaptive complexity concepts in operational silvicultural planning certainly has merit, but such a shift has not yet widely occurred even in silviculture research and experimental design. In general, there is likely to be value in attempting to reconcile these various conceptions of complexity, especially by better understanding how functional and adaptive complexity emerge from structural and biological aspects of complexity which are more straightforward to directly manipulate through silvicultural treatments.

4.1. Patterns in adoption of complexity concepts over time and across disciplines

Our analysis of the usage of complexity terminology and incorporation of complexity concepts into analysis and design of silvicultural experiments provides some evidence about temporal patterns in the dissemination of ideas into the broader field. Following the ground-breaking work associated with the ecological forestry and natural disturbance-based silviculture movements of the late 1980 s and early 1990s, there was a rapid expansion in the number of publications that both incorporated complexity terminology (Fig. 2) and directly addressed complexity concepts (Fig. 4). In both regards, the effects of the ecological forestry movement and its focus on complexity became readily apparent in the literature in the mid-late 1990s. Around the same time, the first of the complexity-focused silvicultural experiments, that had their genesis in the ecological forestry movement, were implemented (Table 2).

Although there have been many high-impact publications that have certainly affected the expansion of complexity-focused thinking in silviculture, it is hard to specifically tie this pattern to any single publication or group of publications. In North America, seminal publications such as Franklin et al. (1986), Hunter (1990), Franklin and Spies (1991) and later Hunter (1999), Seymour and White (2002), and Franklin et al. (2002) were highly influential (along with many others) on the incorporation of complexity concepts into the silviculture discourse. Exchange of ideas throughout the broader international forestry community was also certainly important, including work on adapting “close-to-nature” forestry in Europe (Schütz, 1999) and management for structural complexity in Australasia (Lindenmayer and Franklin, 1997). Another important milestone in coalescing silvicultural thinking around complexity (at least as evident in the literature) was the 2004 IUFRO “Balancing Ecosystem Values” workshop (Peterson and Maguire, 2005), which included a broad spectrum of authors from across the world and detailed initial results from many of the early complexity-focused silviculture experiments (Table 2). In the case of the recent adoption of concepts focused around complex adaptive systems and adaptive complexity, the influence of Puettmann et al. (2009) seems apparent (Fig. 4a).

Our detailed review indicated that, although the use of complexity-focused terminology has consistently increased over time, the actual incorporation of complexity concepts in analysis/design in silviculture studies may have plateaued in the past decade or more (Fig. 4a). This result may reflect a mismatch between the degree of discussion around complexity in silviculture and the actual implementation of complexity-focused research or treatments. Specifically, discussion around functional and adaptive complexity concepts may not yet be matched by direct inclusion in silviculture research or treatments. Evidence for this trend can be seen in the lag between incorporation of adaptive complexity terminology (Fig. 2c) and the much more recent uptick in incorporation of adaptive complexity in analyses (Fig. 4b). The lag period associated with building impetus for ideas could be an argument against switching over to entirely new frameworks for characterizing or understanding complexity. The field of silviculture as a whole may be best served by focusing on finding commonalities and building new conceptions onto or into existing frameworks.

4.2. Frameworks and strategies for incorporating complexity into silviculture planning

Our analysis of frameworks and strategies for incorporating complexity into design and analysis of silvicultural experiments revealed some interesting distinctions and temporal and regional patterns. The frameworks and strategies that we identified (Table 1) included a mix of adoption of traditional silvicultural treatments and systems into new forest types and spatial configurations (Table 1 - #1–3), as well as adaptation of traditional strategies to new systems and goals (Table 1 - #4–10; Puettmann et al., 2009). Many of these adoption/adaptation strategies have focused on varying the spatial configuration of treatment units at a variety of scales (Table 2), from large, multi-stand treatments deployed at a landscape-scale (HEE, Capitol), to variable retention harvesting at the stand scale (YSTDS, DMS), to tree- and gap-scale removals or retention (DEMO, DMS, Divide, ICO, Yellow Birch Legacy-Tree). There has also been some focus on varying temporal aspects of traditional silvicultural systems to match complexity-focused goals (Arseneault et al., 2011). In many cases the strategy for adaptation of traditional approaches has focused on retention or creation of specific features, often in a biological legacies or ecological memory framework. Many of these alterations have been made with specific goals in mind (e.g., retention or creation of coarse woody debris for wildlife habitat). In more recent studies, functional goals were framed as the specific target of the manipulation (Forrester et al., 2013; Fassnacht et al., 2015), but in reality this shift may be mostly one of emphasis.

There were also many studies that focused on developing strategies for directly affecting different conceptions of complexity through management actions (Table 1 - #11–19). These have been mostly focused on manipulation of the complexity of tree size/age structures (Keeton, 2006), spatial patterns of tree locations (Churchill et al., 2013), or tree species composition and diversity (Fassnacht et al., 2015). All of these conceptions of complexity can be readily manipulated through the application of existing or slightly modified silvicultural treatments or systems and can be assessed using traditional stand/mensuration data. Manipulations designed to directly affect specific ecosystem functions were not especially common, but were present in some studies from the outset. Examples include direct manipulation of water quality through retention of canopy around headwater streams (Cissel et al., 2006) or manipulation of subcanopy/shrub layer structure to affect fire behavior (Churchill et al., 2013) and snow retention (Schneider et al., 2015). Incorporation of resilience or transition goals (in relation to global change drivers) as the direct targets of manipulation in silviculture experiments has only recently become more common, especially with development of the ASCC program and related large-scale experiments (Nagel et al., 2017). However, throughout its history silviculture has targeted resilience (e.g., to pests/disease, natural disturbance) and attempted to transition forests to "future-adapted" states, just not necessarily with global change as the motivation (Messier et al., 2013).

Some general trajectories in incorporation of complexity concepts into management design and data analysis were evident in analysis of silvicultural experiments and case studies. Generally there was an initial focus in the 1990s on spatial heterogeneity and natural disturbance emulation that also included maintenance of biological legacies during treatments (Palik and Zasada, 2003; Cissel et al., 2006). Subsequent efforts in the early- to mid-2000 s, either new treatments or re-framing/analysis of existing experiments, expanded to direct manipulation of spatial patterns and complexity (Keeton, 2006) and focused more on biological complexity including functional traits and diversity in shrub and ground-layer plant communities (Fahey and Puettmann, 2007; Burton et al., 2011; Kern et al., 2012). Active creation of biological legacies and enhancement of diversity became more common in the late-2000 s, as did explicit actions designed to affect ecosystem functioning (Churchill et al., 2013). Finally, in the 2010 s design and implementation of silvicultural experiments and new analyses on existing experiments have focused on resilience and adaptive capacity (Nagel et al., 2017).

4.3. Connecting complexity conceptions in practice

Reconciling and bridging structural, functional, and adaptive complexity concepts (Fig. 1) is an important goal that will help the field of silviculture capitalize on existing work and more efficiently and effectively incorporate new concepts associated with resilience theory and complex adaptive systems (Drever et al., 2006; Messier et al., 2013). There is certainly value in designing and implementing new silvicultural experiments with an explicit focus on these concepts (such as ASCC; Nagel et al., 2017). However, given limited resources and the long history of manipulative experiments in silviculture, there is also likely to be great value in utilizing existing projects and adapting analysis frameworks to address these new objectives (D'Amato et al., 2011; Puettmann, 2011), as detailed in our case studies. Here we focus on three avenues that should be useful in integrating these new concepts with existing studies and previously implemented treatments and systems.

One important tactic will be to utilize existing silvicultural experiments – both "legacy" experiments like the USFS Experimental Forest network (Lugo et al., 2006) and more recent complexity-focused experiments (Table 2) – to understand mechanistic connections between structural, functional, and adaptive complexity (i.e., arrows in Fig. 1). Legacy silvicultural experiments pre-date the ecological forestry movement, and thus generally did not explicitly focus on complexity in their initial design. However, these studies can potentially be useful in several ways – for example, assessment of current complexity in treatment units that have undergone long-term application of different silvicultural systems, which can then be related to potential future treatments with complexity-focused goals (D'Amato et al., 2011; Schaedel et al., 2017). Additionally, long-term data from these experiments may have enough information to evaluate starting conditions and make periodic assessments of complexity over time in relation to treatments (Fahey et al., 2015). Analysis of treatments with long-term data available can also help validate modeling focused on resilience and adaptive capacity (see below), and provide a foundation on which to base the design of treatments that could explicitly affect these factors (D'Amato et al., 2011). More recent experiments that have focused on affecting structural or biological complexity will also be essential to efforts to understand functional and adaptive complexity. As detailed in our case studies, a shift in analysis strategies can be used to develop a better mechanistic understanding of the relationship between structural complexity and ecosystem functioning or adaptive capacity. An example of such an analysis is the work of Kern et al. (2013) on the Divide Canopy Gap study that assessed the functional role of gaps in driving biodiversity and related adaptive capacity. Other existing experiments had a more explicit focus on manipulation of specific ecosystem functions (e.g., Flambeau, DMS, ICO; Cissel et al., 2006; Churchill et al., 2013; Forrester et al., 2013) and a shift to assessing adaptive capacity related to these functions requires only continued monitoring or modeling (Burton et al., 2014; Burton et al., 2017).

Adaptive management experiments with long-term monitoring designed to inform future changes to silvicultural systems should lend themselves well to combining conceptions and building adaptive complexity from existing conceptions (Larson et al., 2013). The focus on adaptive management in restoration ecology provides a useful model that silviculture has certainly incorporated, but should continue to emulate (Sarr et al., 2004; Stanturf et al., 2014). An example of this type of integration of silviculture with restoration ecology and adaptive management principles is the Hardwood Ecosystem Experiment (Swihart et al., 2013), which has both a very large-landscape (Table 2) and very long-term focus (100+ years). In this study, the treatments and systems are applied in an adaptive manner, such that new information and changing conditions (both ecologically and socially) could drive future adaptation of the treatments applied. This process is also reflected in the progressive development of new experiments and silvicultural treatments in specific forest types or regions, as illustrated in the case studies (Sections 3.1 and 3.2). Regional or landscape-level adaptive management and "bet-hedging" to promote resilience (ICO, DMS, YSTDS; Table 2) was a common theme among many studies.

Restoration-based management of fire-prone forests in the western US provides a good example of resilience-focused silviculture that has been applied on an extensive scale (Churchill et al., 2013). Application of adaptive management at finer scales may be more difficult, but has been applied to stand-scale treatments, for example by applying expanding-gap approaches (Poznanovic et al., 2014; Carter et al., 2017).

Another important avenue to bridging existing structural and functional complexity frameworks with adaptive complexity is likely to be scenario modeling of the response of functions and structures to future conditions and the use of these responses as indicators/metrics of adaptive complexity (Fig. 1; Parrott and Lange, 2013; Reyer et al., 2015). Such analyses will require improved understanding of the mechanistic relationships between structural components, ecosystem functions, and the combined response of these factors to perturbations (Filotas et al., 2014). This improved understanding and modeling framework will allow researchers to focus on evaluating potential mechanisms by which forest ecosystems could be made more resilient/adaptable and indicate specific structures and patterns (and functions) that can be utilized to promote these mechanisms. These analyses can then be conducted using scenario modeling, informed and validated by data derived from existing silviculture experiments, both long-term "legacy experiments and more recent complexity-focused projects (Burton et al., 2017).

4.4. Implications for silvicultural practice

We have illustrated patterns in the incorporation of complexity concepts and terminology into the forest management and silviculture literature, including literature on silvicultural treatment design and implementation. Our results documented increasingly widespread adoption of these ideas over time in the literature and in design of silvicultural experiments. However, although we believe that the temporal patterns illustrated here are indicative of the dissemination of ideas through the academic silviculture community, we recognize that there is often a significant gap between academic and experimental silviculture research and operational silviculture and forest management. An important next step could be to assess the incorporation of complexity-focused concepts and treatments in forest management plans and other documents detailing current silvicultural practices in different forest types and regions. In addition, a better understanding of relationships between structural and attribute forms of complexity and measures of functional and adaptive complexity will allow managers to more directly manipulate and predict the latter long-term, indirect responses. However, a significant component of adaptive complexity in any managed forest system stems from the human element of the system (Filotas et al., 2014). Therefore, increasing awareness of functional and adaptive complexity concepts among the forest management community (as documented here) could, in and of itself, potentially promote resilience and adaptive capacity in forest ecosystems more broadly.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2018.01.011.

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