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Conceptualizing Forest Operations Planning and Management Using Principles of Functional Complex Systems Science to Increase the Forest's Ability to Withstand Climate Change

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Abstract: The sustainable management of forest resources is greatly influenced by forest operations (FO). Interactions between humans and nature describe how people engage with and are impacted by the natural world. As we enter the Anthropocene epoch, we are being compelled to reevaluate our past and present methods of managing and planning our forest operations in order to find new ones that are more adaptable and successful at addressing the growing unpredictability resulting from accelerating global change. We briefly discuss the goals and constraints of the prior and current management and planning principles for forest operations in this study, focusing on how these principles have evolved on a worldwide scale. We then propose a promising idea, such as managing forest operations as complex adaptive systems and approaches based on resilience and sustainable use of forest resources, in order to achieve the necessary economic, social, and ecological goals. An in-depth understanding of the ecological, economic, and social factors that influence forest resilience is necessary for planning and managing forest operations efficiently. The proposed strategy combines the effectiveness of forest operations with a functional, complex network approach in order to manage forests for the Anthropocene.

Keywords: forest operations; resilience; complex systems science; climate change

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1. Introduction

Complex systems science provides a transdisciplinary framework for studying systems that are distinguished by the following characteristics: (1) interdisciplinary approach, (2) emergence, (3) nonlinearity, (4) networks and interconnectivity, (5) self-organization, (6) adaptation and resilience, (7) uncertainty and non-predictability, (8) and holistic perspective [1–3]. Theory and applied solutions for strengthening ecosystem resilience and adaptability have been influenced by complex systems thinking [4]. Complex systems science can provide important information and elements of complex human–environmental interactions and relationships that were previously overlooked during forest operations planning and management [5–7].

Complex systems science is an interdisciplinary field that studies complex systems and their behavior. Some of the main characteristics of complex systems science include [1,2]:

1. Interdisciplinary Approach: Complex systems science illustrates insights and methodologies from a variety of disciplines. It employs a multidisciplinary approach to comprehend system complexity and dynamics.
2. Emergence: Complex systems research detects emergent behavior in complex systems, which means that the behavior of the system as a whole cannot be fully understood or anticipated from the behavior of its separate components. In addition, emergence refers to the concept that new traits, patterns, or behaviors develop as a result of the system's components' interactions and dynamics.
3. Nonlinearity: Complex systems science acknowledges that complex system connections are frequently nonlinear. Nonlinearity, for instance, means that tiny changes in one area of the system can have large and unforeseen consequences on other parts of the system. Nonlinear interactions and feedback loops in complex systems can produce rich and unexpected behaviors.
4. Networks and Interconnectivity: Complex systems science frequently focuses on the structure and dynamics of networks, which are a common feature of many complex systems. Networks describe the interactions and relationships between system components, and the form of these networks can have a significant impact on the system's behavior.
5. Self-Organization: Complex systems science understands that complex systems frequently display their potential to self-organize, which implies they can spontaneously form themselves into patterns or structures without external supervision. In complex systems, self-organization can result in the emergence of order, structure, and complexity.
6. Adaptation and Resilience: Complex systems research recognizes that complex systems are frequently capable of adaptation and resilience. Resilience, according to Folke et al. (2010) [8], is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedbacks, and therefore identity, that is, the capacity to change in order to maintain the same identity Adaptation and resilience are fundamental characteristics of complex systems that allow them to survive and thrive in changing circumstances.
7. Uncertainty and Unpredictability: Complex systems science understands that complex systems frequently function in uncertain contexts marked by unpredictability and limited predictability. The behavior of complex systems can be influenced by a wide range of factors, making accurate prediction challenging due to the intricate interconnections and dynamics involved.
8. Holistic Approach: Rather then focusing exclusively on individual components or isolated behaviors, complex systems research adopts a holistic approach, analyzing the system as a whole and the interconnections between its components. This comprehensive approach aids in capturing the complexity and interconnection of complex systems, as well as understanding their emergent features and behaviors.

The aforementioned characteristics of complex systems science contribute to a rich and diverse field of study whose objective is to comprehend the fundamental concepts of complex systems, establish models and theories to explain their behavior, and use this understanding to solve practical issues in numerous disciplines, including science, engineering, the social sciences, economics, and more.

Over the years, human management activities that met human needs and expectations have resulted in the formation of forests. But forests are dynamic systems that are affected by quickly shifting socio-environmental factors. The term "human–nature interactions" describes how people interact with and are affected by their surroundings [9]. Clean water and air are provided, climate and natural disasters are controlled, food and fiber are produced, and recreational opportunities are offered, thanks to ecosystem services. As a result of the growing human population and resource consumption per capital, forests are under new pressure to provide more wood for energy and renewable materials as the cornerstone of a "green economy" [10]. The provision of advantages that are frequently taken for granted but are necessary for supporting human existence, and economic development makes ecosystem services critical for human wellbeing and a significant component of our natural capital [11,12]. Sustainable forest management techniques have been the subject of numerous research [13,14].

Climate change, socioeconomic hardships, the fragmentation of forest landscapes, pollution, invasive species, and other global changes to Earth's ecosystems are developing quickly, which is causing an escalating dynamic and, as a result, an unclear and unpredictable future in the planning of forest operations. Since human influences on Earth's systems are novel, unexpected, and occasionally extremely disruptive events, the current epoch, known as the "Anthropocene", is defined by these influences [15].

Forest operations are developing concepts, methods, and tools to support the design, control, and the continual improvement of technical and administrative processes in a forest's operation systems context. It is also a significant area of study because, according to [16–18], effective forest management is essential for resilience, reducing the effects of climate change, protecting biodiversity, and delivering essential ecosystem services.

The term "forest operations" refers to a scientific, problem-solving discipline that aids in finding forestry technology solutions. In light of shifting social needs, the climate, and working circumstances, it is crucial to comprehend the main driving forces behind the future growth of forest operations that promote economic, environmental, and social wellbeing [15]. As a result, sustainable management and forest activities interact in a complex way.

Forest operations management refers to the process of designing, organizing, and executing forestry activities in a way that ensures the sustainable use of forest resources while meeting the desired economic, social, and ecological objectives [19,20]. Overall, forest operations planning and management is a complex process that requires careful consideration of a range of factors, including environmental sustainability, economic viability, ergonomics, effectiveness, evacuation routes, and social responsibility [21,22]. By developing and implementing responsible forest management strategies, we can ensure the long-term viability of our forest resources for future generations [23,24].

Complex adaptive systems (CASs), which include variety, nonlinearity, emergence, self-organization, and cross-scale interactions, include ecosystems like forests [25–27]. Both physically and genetically, the components of forests are highly diverse. The individual components of forests interact with each other and with people. These interactions exist at the local level but span hierarchical, geographical, and temporal boundaries. These connections can also be nonlinear and contain feedback loops and response delays.

Socioeconomic demands are rising as a result of human impacts on Earth's systems, which also have an impact on the provision of ecosystem services, including those provided by forests. In order to prepare for this constantly shifting future, forest operations planning must take into account a number of new factors:

- Increasing shifts in social norms. Ref. [28] claim that society requirements and desires for the various roles that forests perform are frequently in conflict with one another, constantly changing, unexpected, and unpredictable. Refs. [29,30] both cite the importance of forests in reducing the effects of the changing climate. The diverse range of values and services provided by the forest, which include anything from timber and recreation to the management of water, should also be given more attention [31].
- Growing awareness about forest resilience. The ability to adapt to change and keep growing is resilience. It deals with the ways in which both nature and people can use shocks and disturbances, such as a financial crisis or climate change, to inspire rebirth and creative thinking [32]. Resilience thinking emphasizes that social–ecological systems, from the individual, to community, to society as a whole, are embedded in the biosphere [33]. In order to develop a new understanding of how people and nature interact, adapt, and impact each other during change, resilience was developed. We contend that in order to preserve life on Earth, it is necessary to re-establish a

connection with the biosphere, which includes all of the planet's land, water, and air [34,35].

- The disappearance of traditional reference conditions in forest management. The usefulness of using traditional reference conditions to plan and manage forest operations has diminished as a result of expanding changes in environmental, social, and biotic variables [36]. Forest operations have traditionally been divided into three major categories: (i) "Environmentally Sound Forest Harvesting" [37]; (ii) "Reduced-Impact Logging" [7,38]; and (iii) "Forest Operations Ecology" [16]. Instead, the required and ongoing evolving new challenges for forest ecosystems, ecosystem products and services, as well as conservation values owing to climatic changes must be the source of the desired future conditions in forest operations planning and management [39,40].
- Future environmental and socioeconomic conditions are becoming more unclear. In a particular location, complex and dynamic interactions between social and ecological elements are referred to as social–ecological systems (SES). The interdependence of natural systems, human communities, and the built environment is a defining characteristic of SES. They are impacted by elements including ecology, politics, economy, and culture. Additionally, because of the Anthropocene's rapid and complex social–ecological changes, it becomes even more difficult to predict how forests will behave in the future [41]. The Anthropocene idea refers to the most recent geologic epoch as being anthropogenic because of the overwhelming evidence that human activity has affected processes in the atmosphere, the Earth's crust, the oceans, the biosphere, and other parts of the Earth's system [42].
- Expanding demand for new conceptual forest operations through the study of functional complex systems. The idea of a balanced viewpoint in a new approach to forest operations should reflect the best forest practices created to satisfy local, regional, and global demands, while taking into account the forests and people. According to [21,43], the novel concept of FO offers a broad framework within which performance and assessment criteria can be constructed for various reasons.

In order to address the growing environmental, socioeconomic, and forest resilience challenges on a global scale, while achieving the multifunctionality of ecosystem services [25,44–47], this paper proposes a comprehensive and adaptable new approach to forest operation planning and management. By examining the objectives and constraints of the historical and present forest operations planning and management techniques in response to challenges of the Anthropocene, we bridge the existing paradigms of forest operations planning and management with complex systems science in the recommended methodology.

2. Materials and Methods

In this paper we examine a number of current, promising approaches in forest operations that may help us achieve the new objectives of multifunctionality and resilience while taking into consideration the highly changeable and unpredictable future socio-environmental conditions using complex system science. These reviews helped us to develop a novel idea for applying forest operations planning treatments that may be used in conjunction with functional diversity and complex systems science theory to effectively advance resistance to planetary changes. The suggested strategy is broad enough to benefit from both traditional and contemporary methods used in forest operations.

Based on their aspect and management goals, we have categorized the previous and contemporary planning and management systems for forest operations into five main categories (Table 1).

Table 1. Planning and management strategies for the world's major forest operations. Five categories have been established for them: Timber-oriented, Nature-based, Sustainable Forest Operations, Multipurpose Forest Operations, and Conceptual Global Change Driven Approaches Based on Complex Science Systems Theory. These general ideas reflect the essential characteristics of the methods, according to the pertinent literature. Using data from the literature, each technique is grouped according to their principal management aims (up to two). Any other benefits that could be attained but are not particularly targeted are marked with a cross.

Forest Operations Planning and Management Approaches	Management Goals														Key References
	Timber and Biomass	Environment					Energy Efficient	Economics			Ergonomics	Social Aspect	Cultural Aspect	Resilience	
		Biodiversity	Soil	Air	Water	Regeneration Capacity		Productivity	Added Value	Costs					
Timber-focused	1							+	+	+					[48]
	1							+	+	+					[49]
	1							+	+	+					[50]
	2							+	+	+					[51]
	2							+	+	+					[52]
Nature-based	1	+	+	+	+	+						+			[38]
	2	1	1		1	1		1	1	1		+			[53]
	2	1	1		1	1		1	1	1		1		+	[43]
Sustainable Forest Operations	2	2	2	2	2	2	+	+	+	+	+	+			[21]
	2	2	2	2	2	2	+	+	+	+	+	+			[54]
	1	+	+	+	+	+	+	+	+	+	+	+			[16]
	1	+	+	+	+	+		+	+	+	+	+			[37]
Multi-purpose forest operations	2	2	2	2	2	2		1	1	1	1	1			[55]
	1	1	1	1	1	1		1	1	1	1	1			[56]
	0	2	2	2	2	2		1	1	1	1	1	+	+	[24]
Conceptual global-change driven approaches based on complex systems science	2	2	2	2	2	2	2	+	+	+	2	2	2	2	[22]

3. Results

Timber-focused forest operations approaches make up the first group. In previous years, continual timber production was the primary focus of forest management [48–51]. Timber-focused forest operations are crucial for meeting the demand for wood products [52,57–59], and they play a significant role in forestry management and the forest industry [60–62]. Forests have been severely harmed by the mechanization of forest operations. As a result, woods were managed to maximize timber production profitability. The second half of the 20th century saw a significant change in this aspect of the forest as a source of raw materials for industrial timber products as people became more aware of the other benefits that forest ecosystems (biodiversity, carbon sequestration, water regulation, soil conservation, economic benefits, cultural benefits) provide [63–65]. This understanding of the effects of forestry practices on forest sustainability was offered by [5,9] based on scientific knowledge of the complex dynamics of forest ecosystems.

Nature-based forest operations management falls under the second category and is a crucial strategy for effective forest operations management. These methods frequently place less emphasis on economic values and more emphasis on ecological and cultural values [43,53]. Nature-based forest operations can contribute to ensuring that forests continue to offer essential ecosystem services while also supporting the livelihood of local communities, by placing a high priority on the conservation and sustainable use of forest ecosystems. Additionally, silviculture practices are guided by nature-based approaches to managing forest operations, which distinguish themselves from intense harvesting methods by imitating nature. These methods, which are based on reduced impact harvesting, can lessen the effect of disturbances on ecosystem services and biodiversity. In order to attain sustainable silviculture aims, natural processes might be taken into account [66].

The concept of sustainable forest operations as well as the challenges that forest operations encounter globally are both included in the third category, sustainable forest operations (SFO). This leads to the definition of SFO as a complex relationships system, which includes the tools, techniques, processes, and procedures used in forest operations planning, implementation, monitoring, and improvement taking into account five performance areas, including (i) environment; (ii) ergonomics; (iii) economics; (iv) quality optimization; (v) and people and the society [21,37,54]. SFO must be carried out in a sustainable and responsible manner if forest ecosystems are to be kept healthy and productive over the long run.

Our fourth category (Table 1) is multipurpose forest operations. Forest engineers must take into account a wide range of ecosystem variables at multiple geographical and temporal dimensions when planning multipurpose forest operations and managing the results of those plans. In order to achieve this, the best management techniques must be used [56,65,67,68]. These methods must reduce the negative environmental effects of forest operations and guarantee the availability of timber resources for future generations. The combination of these numerous approaches can be used to meet a range of demands and objectives [55,69,70].

In the last few decades, a number of conceptual approaches the—fifth category—that can be referred to as conceptual, global change-driven approaches based on the complex science systems theory. These have been encapsulated to explicitly incorporate the opportunities and changes in the climate into the planning and management of forest activities. These show a new framework (Figure 1) that modern forest operations should follow, one that improves and supports forest resilience to climate change while maintaining the entire forestry value chain and sustainable forest management [71,72]. We have included methods into the fifth category based on the ideas and objectives that go beyond the endorsement of certain management strategies. They describe techniques and tactics used in forest management to help forests better withstand and recover from disturbances like wildfires, insect outbreaks, disease, the effects of climate change, and human activities, while preserving their ecological integrity and productivity. Implementing sustainable and adaptive management techniques that can reduce the negative effects of disturbances and support the long-term health and vitality of forest ecosystems is a key component of resilient forest operations. These methods frequently served as a cutting-edge paradigm for developing new theoretical frameworks and moral viewpoints on the management of forest activities. As a result, the US and Canadian forest agencies have implemented a number of adaptation frameworks in the field in North America to determine how forests can be adapted to climate changes [73,74].

Forest Operations Concerning Global-Change Driven Approaches Based on Complex Science Systems Theory

Forest resilience is a key notion in sustainable goals of forest management, even though forest health and protection have always been two fundamental parts of forest management [75]. This is because of the increased danger of major disturbances and new stress causes. In this situation, increasing forest resilience becomes a clear goal of forest management and the center of attention for particular silvicultural techniques [76]. One of the key tenets of resilience management is the realization that ecosystem self-regulation and repair following unanticipated events can no longer be taken for granted in light of the rapid global changes taking place on Earth. Climate changes have an impact on all forest ecosystems. These effects adjust soil, forest ecosystems, the working conditions for forest operations, and the length of operating seasons both directly and indirectly. This may have impacts on the availability of resources, and climate change may have impacts on the distribution, composition, and productivity of forests [77].

Figure 1. A new framework for modern forest operations.

In addition, more frequent and severe disturbances to the forest, such as the spread of viruses and pests, storm damage, and wildfires, drastically change the forest's structure and function [78]. The sustainability and economic viability of the forest industries may be impacted by a change in management emphasis from wood management to forest restoration. The frequency and volume of salvage harvesting may rise in areas subjected to extensive harm from wildfires, insects, and extreme weather. Organizations in charge of managing forests have created policies and plans for doing so in various parts of the world [79] to help mitigate and adapt to climate change. Numerous strategies have been developed to solve these problems, including expanding the managed forest's capacity to respond, reducing the effects of extreme weather, insect outbreaks, and wildfires, and boosting carbon sequestration, wood output, and socioeconomic advantages.

Due to the rising greenhouse gas (GHG) emissions into the atmosphere, forest operations may contribute to climate change. The majority of the effects related to GHG emissions were discovered to occur during the harvesting stage, since fuel was used for machine operations rather than for machine construction or repair [80].

The seasonality of forest operations and site entry may be more restricted as a result of local and regional climate change. Additionally, modifications to precipitation intensity and pattern may exacerbate the risk of landslides and soil erosion [81]. In order to sustain the prior production level in a shorter period of time without jeopardizing worker safety, increased seasonal constraints on forest operations may need improved operational efficiency.

Forest roads are important for managing forests and using them for recreation, but they are also a major cause of erosion in many regions of the world [82]. To prevent increases in erosion, significant changes in road design and usage are required, especially in areas where more heavy rainstorm events are predicted.

4. Discussion

Here are the key principles and strategies associated with conceptual global-change driven approaches forest operations:

1. Human–nature harmonized interactions: At the local, regional, and global levels, the environmental effects of forest operations should be kept in harmony with the nature. Human–nature harmonized interactions in forest operations planning and management refer to the sustainable utilization of forest resources while ensuring the preservation of the natural environment. This strategy involves incorporating ecological, social, and economic factors into forest planning and management to make sure that forest operations are carried out in a way that is economically feasible, socially acceptable, and environmentally sustainable. Given the growing relevance of sustainable forest management, the idea of human–nature harmonious interactions in the planning and managing of forest operations has received a lot of attention recently. Some of the fundamental ideas that direct harmonious human–nature interactions in forest operations planning and management include the following:
    I. Environmental sustainability: Forest operations should be conducted in a way that preserves the ecological integrity of the forest ecosystem, including its biodiversity, water quality, soil health, and carbon sequestration capability.
    II. Social acceptability: Forest activities must be conducted in a way that respects the rights and interests of nearby populations, including their traditional knowledge, cultural practices, and livelihoods.
    III. Economic viability: All parties participating in forest activities, including forest owners, employees, and local communities, should profit economically from the operations.
    IV. Engagement of stakeholders: Planning and management of forest operations should actively involve all stakeholders to ensure that their opinions and requirements are taken into consideration.

In conclusion, human–nature harmonious interactions in the planning and managing of forest operations seek to encourage sustainable forest management methods that strike a balance between ecological, social, and economic factors.

2. People and society: Operations in the forest are greatly influenced by society and the human race. Interaction between a variety of stakeholders, such as foresters, local communities, Indigenous peoples, governmental bodies, non-governmental organizations, and commercial businesses, is necessary for effective forest management. The involvement of people and society in forest operations can take the following forms [83–85]:
    I. Forest employees: Planting, thinning, harvesting, and wood processing are just a few of the activities that forest workers participate in. They labor in a range of occupations, including those of loggers, foresters, and mill employees. Forest workers must receive training in safety procedures and make use of the appropriate equipment if they want to lessen the risk of accidents.
    II. Local communities: For example, grazing space, non-timber forest products, fuelwood, and lumber are all vital to the livelihoods of the local communities that live adjacent to forests. Forest management should take into account the requirements and aspirations of the local community in order to guarantee that they have access to the resources necessary for their survival.
    III. Indigenous peoples: The forests hold a special place in the hearts and minds of Indigenous peoples who rely on them for their spiritual and cultural practices. The rights of Indigenous peoples must be upheld, and they must participate in decisions about how to manage the forest.

IV. Governmental entities: Governments play a vital role in forest management by adopting laws and regulations relevant to the usage and preservation of forests. Additionally, they contribute funds to the research and development of forest management techniques that are environmentally benign.

V. Private organizations: Private organizations are involved in a variety of forest operations, including the logging, processing, and sale of timber. Regulations pertaining to social responsibility and environmentally friendly forest management must be followed.

According to [86], woodlands carry out a variety of ecological, political, economic, social, and cultural systems and processes that are crucial for individuals and society. Forest operations should be planned and executed using global-change driven methodologies based on complex scientific systems in order to sustain or improve the services and functions of the forest.

It is essential for the sustainable management of forests that society and the general public are involved.

1. Diversity and complexity: Preserving and enhancing the complexity and diversity of forest ecosystems is one of the key goals of the new techniques. This entails sustaining the habitats for various plant and animal species as well as maintaining a mix of tree species, age classes, and forest architecture.
2. These strategies entail adaptive management, which combines monitoring, evaluation, and modifying optimum management methods in response to input from the forest ecosystem. This enables flexibility in reaction to varying circumstances, such as the effects of climate change or new insect outbreaks. In order to make future management decisions that are adaptive, past management experiences must be learned from.
3. Restoration and rehabilitation activities may be a part of these strategies to restore and recover forests that have been damaged by previous management decisions or disturbances. To restore forest ecosystems and increase their resistance to future disturbances, this may entail practices like replanting, habitat restoration, and erosion control techniques via the forest operations new concept.
4. Reducing risk and vulnerability [87]: By employing techniques like fuel management, thinning, and constructing buffer zones to lessen the severity of wildfires, these measures seek to minimize the risk and vulnerability of forests to disturbances. To lessen the effects of insect outbreaks and diseases, integrated pest management strategies can also be used, such as early identification and quick action.
5. Forest operations and wildfire suppression planning. Two important facets of forest management are planning for the suppression of wildfires and conducting forest operations [88]. The term "forest operations" refers to the range of tasks required to manage a forest, such as clearing land for logging, preserving access to roads and trails, eradicating invasive plants, and keeping an eye on wildlife populations. The planning for wildfire suppression, on the other hand, entails creating plans to stop, confine, and put out potential forest fires. The prevention of wildfires and the maintenance of healthy forests depend on efficient forest operations. For instance, removing diseased or dead trees and thinning thick stands might lower the fuel loads that contribute to wildfires by selective harvesting. In the event of a wildfire, maintaining roads and trails enables firefighters to reach isolated regions faster. By lessening resource competition among plants and lowering the chance of disease outbreaks, managing invasive species can also aid in the prevention of wildfires [89,90]. Planning for wildfire suppression is coming up with ways to stop them from starting or escalating as well as how to act rapidly if they do. Public awareness campaigns on fire safety, the enforcement of fire restrictions during times of increased fire risk, and the use of controlled burns to reduce fuel loads are all examples of prevention strategies. The suppression of a wildfire may entail building fire lines to stop the spread of the fire, using fire retardants or water drops from airplanes to halt the fire's advance, and deploying ground teams to put out hotspots [91]. Collaboration between numerous

stakeholders, including governmental organizations, private landowners, and local communities, is necessary for effective forest operations and wildfire control planning. To manage forests sustainably, complete management plans must be created that take ecological, economic, and social considerations into account [92]. The goal of forest management is to preserve healthy forests while reducing the risk of wildfires, and forest operations and wildfire suppression planning are essential parts of this process. Collaboration between stakeholders and the consideration of ecological, economic, and social concerns are necessary for effective management.

6. Additionally, using the new methods, woodland paths can be used as evacuation routes. The act of finding and establishing routes for effectively and safely removing people from a particular region during an emergency or disaster situation is known as evacuation route planning [93,94]. Mapping out the primary and secondary routes for evacuating people from the impacted region to the specified safe zones. This entails weighing several options and taking into account variables including road capacity, accessibility, and probable road closures. The type of emergency or disaster, such as a storm, flood, wildfire, or earthquake, may affect the evacuation routes, necessitating the use of alternative tactics and considerations. The planning and implementation of evacuation routes is crucial for efficient emergency response and preparedness. Close collaboration with local authorities, emergency management organizations, and other pertinent stakeholders is also necessary.
7. Energy-efficient forest operations are essential for preventing climate change, protecting natural resources, and advancing sustainable forest management objectives. It calls for a comprehensive strategy that takes into account the full lifetime of forest operations, from planning and harvesting to transportation and utilization, while consuming the least amount of energy and emitting the fewest amount of greenhouse gases. Promoting and implementing energy-efficient forest operations requires the cooperation of all stakeholders, including forest owners, loggers, equipment manufacturers, and legislators. Energy-efficient forest operations are the management and harvesting of forests using sustainable and ecologically friendly methods that utilize the least amount of energy and emit the fewest amount of greenhouse gases [95,96]. The replacement of fossil fuels in forestry machinery and equipment with renewable energy sources, such as biomass and solar power, is a crucial component of energy-efficient forest operations planning [97]. By opening up new markets for renewable energy goods, this can help to drastically lower energy costs and carbon emissions while also fostering regional economic growth [98]. Adopting sustainable forestry methods that advance biodiversity, healthy soil, and water quality is another crucial tactic. This entails switching from clearcutting and other intense harvesting practices to selective harvesting and other low-impact strategies that preserve the structure and function of forests [99]. To ensure the long-term viability of our forests and the numerous advantages they offer to society, energy-efficient forest operations planning is crucial.
8. Collaboration and engagement: These strategies frequently entail cooperation between a variety of interested parties, including scientists, local populations, Indigenous peoples, and forest managers. Collaboration can aid in integrating various viewpoints, information, and beliefs, resulting in more efficient and sustainable decisions about the management of forests. By utilizing their traditional knowledge and traditions, local communities and Indigenous peoples can be included in forest operations and increase their resilience.
9. Environmental suitability of forest transportation systems planning: Considering potential environmental impacts of forest road construction and upkeep is a necessary step in planning for the environmental compatibility of forest roads. Forest roads are necessary for activities including logging, recreation, and animal management. However, these roads could harm the ecology by causing habitat fragmentation, stream sedimentation, and soil erosion. Forest roads require careful planning to minimize their

detrimental effects on the environment [100]. When establishing whether forest roads are environmentally acceptable, the road's placement is crucial. Roads constructed in sensitive locations, such as wetlands or steep slopes, are likely to have a substantially greater impact on the environment than roads constructed in less sensitive areas. Depending on how they are designed and built, forest roads may also have an impact on the ecology. Instead of filling in streams, for example, bridges or culverts can be utilized to avoid sedimentation and improve water quality [101]. The preservation of forest roads is an additional crucial factor. Increased erosion and sedimentation from poorly maintained roadways can have a negative impact on the aquatic environment and water quality. As a result, consistent upkeep and monitoring are required to make sure that forest roads do not significantly harm the ecology [102,103]. For limiting the damaging effects of forest road construction and maintenance on the ecosystem, environmental appropriateness of forest road planning is essential. To make sure that forest roads do not damage delicate ecosystems, proper site selection, planning, construction methods, and maintenance are required.

10. Designing tasks, tools, and equipment with an eye toward worker health, safety, and wellbeing, while increasing productivity and efficiency, is known as ergonomics in the field of forestry operations. Ergonomic principles must be incorporated into forest operations in order to prevent injuries, lessen fatigue, and improve overall performance given the physical demands and difficulties of working in a forest environment, where employees are frequently exposed to strenuous manual labor, uneven terrain, dangerous weather conditions, and other hazards. Employers can lower the chance of workplace accidents, improve employee wellbeing, and increase general productivity and efficiency by incorporating ergonomics into their forest operations. To ensure that work procedures, tools, and equipment are developed and used in a way that promotes the health and safety of forest workers, ergonomic principles must be implemented through cooperation between forest owners, managers, equipment makers, and employees. Forest operations must pay close attention to ergonomics to maintain worker safety, effectiveness, and productivity. Ergonomics is the science of creating tools and equipment that fit the human body. Designing tools and equipment for the collection, processing, and transportation of wood products falls under the umbrella of ergonomics in the forestry industry. The objective is to increase productivity while minimizing physical strain on employees. In addition, in the design of workstations and the arrangement of workspaces, ergonomic considerations also include the weight, size, form, and grip of tools [104,105]. The employment of mechanical equipment is a crucial part of ergonomics in forest operations. By automating processes that would otherwise require manual work, mechanization can decrease physical stress and boost productivity. Mechanized equipment must still be designed with ergonomic considerations like operator comfort and safety in mind [106,107]. Preventing musculoskeletal conditions (MSDs) such back discomfort, carpal tunnel syndrome, and tendinitis is a crucial aspect of forestry ergonomics. Because many forestry operations are repetitious and heavy machinery is used, these kinds of accidents are frequent. Preventative measures include using ergonomic tools and workstations, as well as adequate lifting technique and posture instruction [108]. Overall, ergonomics is extremely important in forest operations since it guarantees worker safety, lessens physical stress, and boosts productivity.
11. By employing sustainable and adaptive management strategies that take into account the ecological, social, and economic aspects of forest management, these approaches prioritize the long-term health and resilience of forest ecosystems. Resilient forest operations aim to ensure that forests can continue to provide the essential ecological services, such as carbon sequestration, biodiversity conservation, and water regulation, in the face of shifting environmental conditions and disturbances by promoting diversity, adaptive management, risk reduction, collaboration, and restoration.

12. Sustainable economics in forest operations refers to the practice of managing forest resources in a way that balances economic, environmental, and social considerations. This approach recognizes that forests provide a range of goods and services, including timber, clean water, wildlife habitats, recreational opportunities, and carbon sequestration. Sustainable forest management aims to ensure that these benefits are available for current and future generations by maintaining healthy ecosystems, promoting biodiversity, and supporting local communities [109]. Utilizing best management practices (BMPs) to reduce the environmental impact of logging and other forest activities is a crucial component of sustainable economics in forest operations. BMPs may include techniques for reducing soil disturbance, preserving wildlife habitats, and safeguarding water quality. BMPs can help to sustain the long-term productivity of forest ecosystems by minimizing environmental harm while also having a minimally detrimental effect on nearby communities [110]. The growth of markets for non-timber forest products (NTFPs) is another essential component of sustainable economics in forest operations. These could include things like fungi, berries, medicinal plants, and other things that can be obtained from forests in a sustainable manner. Forest managers can make money by establishing marketplaces for these goods while simultaneously promoting environmentally friendly behaviors that support ecosystem health and biodiversity [111]. Lastly, cooperation between stakeholders, including governmental organizations, business representatives, environmental advocacy groups, and local people, is necessary for sustainable economics in the management of forests. These parties may contribute to ensuring that forests continue to offer a wide range of benefits for future generations by cooperating to define shared objectives and strategies for managing forests sustainably [112].
13. Quality optimization: When it comes to forest operations, quality optimization refers to the process of maximizing the effectiveness and efficiency of forest management activities while reducing their detrimental effects on the environment. Planning, harvesting, moving, and processing forest products are just a few of the several tasks involved in this. The goal of quality optimization is to make sure that forest activities are socially conscious, economically feasible, and sustainable [113]. The utilization of cutting-edge tools and technology is one of the most important aspects of quality optimization in forest operations. In order to selectively remove trees without harming the local environment, sophisticated harvesting tools can be utilized. The best routes for carrying collected wood can also be mapped out using GPS technology. These technologies enable forest managers to limit waste and lessen their environmental impact [27]. Creating sustainable harvesting methods is a crucial component of quality optimization in forest operations. Planning is necessary to make sure that only mature trees are cut down and that new trees are planted to take their place after the ones that have been removed. The least amount of harm to the soil and other vegetation possible must be completed during harvesting operations [114]. Optimizing quality in forest operations also entails making sure that wood products are treated in an environmentally friendly way. This entails utilizing energy-efficient machinery and reducing waste generation during processing. Additionally, it is possible to certify the sustainability of forest products, which supports the advancement of ethical forestry practices [115]. Finally, quality improvement in forest operations is necessary to guarantee that forests are managed sustainably and responsibly. Forest managers may aid in environmental protection while also fostering economic growth and social wellbeing by utilizing cutting-edge technologies, creating sustainable harvesting techniques, and processing forest products in an environmentally responsible manner.

5. Conclusions

Combating the command-and-control method: managing forest operations planning as complex adaptive systems will help to improve the resistance to climate change.

Conceptualizing forest operations through the lens of functional complex systems science (Figure 2) will help to improve managing forests as complex adaptive systems and increase their resistance to climatic change.

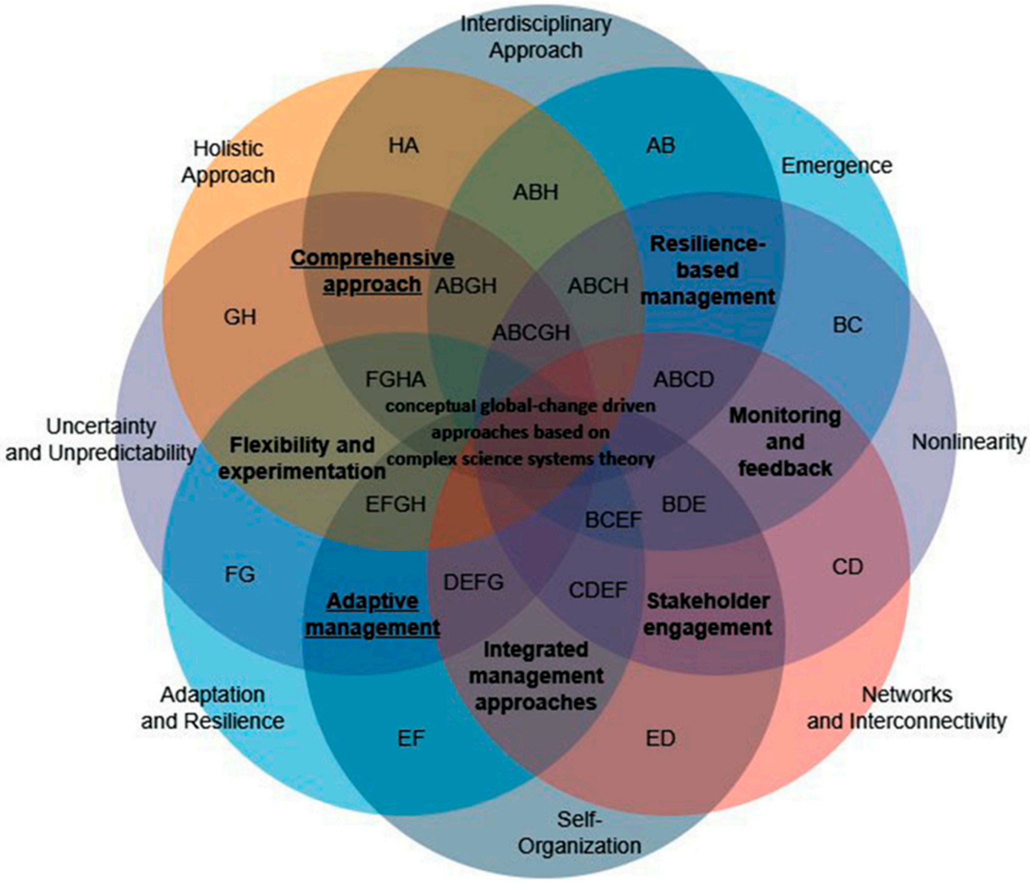

Figure 2. Conceptual global-change driven approaches based on complex science systems theory.

Firstly, seeing forest operations as a complex adaptive system rather than using other management and planning methodologies constitutes a significant distinction between the formal identification of the relationship between biological and social aspects of forest ecosystems [41].

Second, the realization that uncertainty is a natural component of the forest ecosystem forces forest engineers to emphasize the ability of the forest to adapt while managing or organizing the forest operations. This is based on the understanding that forest ecosystems need to have the ability to adapt to future unanticipated disturbances in order to continue providing the intended ecological functions and services [116].

Thirdly, the notion that complex adaptive systems are driven from the bottom up is also reflected by the ability of ecosystems to adjust to sudden and complex disruptions. The various individual qualities that interact hierarchically, incorporating feedback loops, in nonlinear and threshold interactions, produce the distinctive performance of complex adaptive systems. This emphasizes how crucial it is to preserve or improve the diversity component as well as their relationships. The idea of emergent characteristics, which pertains to the performance of unpredictability as an intrinsic aspect of complex ecosystem behavior, is further demonstrated by emphasizing multi-hierarchical interactions among elements [117].

Fourthly, there is evidence to argue for the need for more flexibility for forest engineers to enable them to prepare for future challenging conditions (wildfires, climate change, energy efficiency, etc.) by taking into account management and planning decisions and their multiple dimensions effects in human–environmental systems [118].

Last but not least, self-organization is further emphasized by assessing ecosystem responses in the context of non-linear and threshold altitude. This method emphasizes the areas that require particular forest management interventions and would maximize the accomplishment of sustainable objectives.

The importance of assessing a wide range of ecosystem functions and services at multiple dimensions is highlighted by taking all of these factors into consideration, accepting the significance of cross-scale hierarchical interactions between the forest and humans, and acknowledging that complex adaptive systems have the potential to be "open" [119]. For instance, forestry is part of a socio-ecological system.

The resilience-focused approach we previously mentioned can be influenced by the integrated approach proposed by the complex systems theory. Forest operations must be managed as complex adaptive systems, which means that management decisions must take into account factors like uncertainty, non-linearity, threshold behavior, and bottom-up control through cross-scale hierarchies [5,120] when they are being developed and evaluated [41,121].

Performing forest operations as sophisticated adaptive systems.

Recognizing and utilizing the complex, dynamic, and adaptive nature of forest ecosystems in the decision-making and management processes are essential to managing forest operations as complex adaptive systems. Some essential guidelines and tactics for managing forest operations as complex adaptive systems are provided below:

1. Adaptive management is a key idea in the management of complex adaptive systems. It involves ongoing monitoring and management strategy revisions in response to ecosystem input. Forest managers can adjust management techniques and make judgments with the aid of real-time data on forest conditions, such as tree growth rates, wildlife populations, or climatic patterns. Managers can adapt to changes and uncertainties in the forest environment thanks to adaptive management, which fosters system flexibility and learning.
2. The interconnected components of forest ecosystems include trees, wildlife, soil, climate, and human activities, to name a few. If forest operations are to be managed as complex adaptive systems, an all-encompassing strategy that takes into account the connections and feedback between various components is required. The dynamic linkages and trade-offs between ecosystem components must be understood by forest managers, and they must also take the larger ecological, social, and economic context into account when making decisions.
3. Resilience-based management: Resilience is a crucial notion in the context of complex adaptive systems because it describes a system's ability to withstand disturbances, adapt, and recover. Forestry operations can be managed in a resilient way by enhancing and preserving the forest ecosystem's tolerance to a variety of disturbances, including wildfires, insect outbreaks, and climate change. To do this, it may be necessary to implement tactics that increase species diversity, preserve habitat connectivity, or protect vital biological traits that increase the resilience of the forest ecosystem.
4. Flexibility and a keen interest in learning new managerial strategies: These two characteristics are necessary to manage forest operations as complex adaptive systems. It is crucial to understand that forests are dynamic and ever evolving, and that management techniques that worked in the past could not work in the future. Adapting their management strategies in response to environmental input requires forest managers to be willing to try new things, learn from their mistakes, and take new methods.
5. Involvement of stakeholders: Stakeholders in complex adaptive systems may include forest owners, local communities, governmental entities, and conservation groups. These stakeholders could have various interests, values, and viewpoints. In order to manage forest operations as complex adaptive systems, decision-making processes must involve stakeholders. Stakeholders can offer intelligent feedback, local expertise,

and a variety of perspectives that can guide management decisions and guarantee that the management practices are in line with the social and economic requirements of the community. Monitoring and feedback: Managing forest operations as complex adaptive systems necessitate continuous observation of the ecosystem's health and the gathering of information on a variety of ecological, social, and economic variables. Monitoring provides information on the effectiveness of management techniques and aids in the understanding of how the ecosystem is responding to various interventions by forest managers. With the aid of this feedback, future management decisions can be made in a more efficient and flexible manner.

6. Among the integrated management techniques that can be effective in managing forest operations as complex adaptive systems are silviculture, wildlife management, and ecological restoration. Integrated management approaches recognize the interdependence of the numerous components that make up the forest ecosystem and work to balance multiple objectives, including wood production, biodiversity preservation, and ecosystem services, in a coordinated and adaptive manner.

Therefore, managing forest operations as complex adaptive systems requires both an understanding of how dynamic and adaptable forest ecosystems are, as well as the application of concepts like adaptive management, resilience-based management, flexibility, stakeholder engagement, and monitoring. By understanding and using the complexity and adaptability of forest ecosystems, forest managers can make informed decisions and help manage forest resources sustainably.

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