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FORESTS AS COMPLEX ADAPTIVE SYSTEMS: IMPLICATIONS FOR FOREST MANAGEMENT AND MODELLING

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Addressing natural resource issues in the face of profound global changes presents new challenges for forest managers. These challenges have initiated a new cycle of development in approaches to management of forests for a wide variety of ecosystem goods and services. One of these approaches is based on the science of complex systems. Viewing forests as Complex Adaptive System (or CAS) is an emerging paradigm based on development of systems theory in other fields, such as physic, medicine, and socio-economics. This new conceptual framework recognises the complexity of systems (ecological, economic, and social), their hierarchical structures, the interactions and energy flows between these hierarchies, and their capacity for self-organisation and adaptations. One of the major challenges in forestry is to learn how to use these concepts to facilitate the ability of forest systems to self-organise and adapt in the face of global change in order for the forest to continue to fulfill human needs for ecosystem goods and services. Consequently, applying complexity systems thinking in this context has implications for our usage of new, but also conventional concepts and practices. In this paper we briefly review the science of complexity as applied to forest management and discuss how this science can be linked to modelling tools used in forest management. We specifically focus on predictability and modelling challenges to contrast the differences between our conventional view of forests and viewing forests as CAS. We conclude by suggesting that a new forest management paradigm based on heterogeneity, unpredictability and adaptability, rather than on uniformity, predictability, and "command and control" is better suited to deal with future challenges.

INTRODUCTION

Forest management objectives for private and public forest landowners were mostly well defined until the late 20th century. Until then, global changes were occurring slowly and had a small impact on forest management, especially in the northern hemisphere. Forest management was generally focused on a single dominant objective, most commonly timber or revenue production in a sustainable manner. Even notable exceptions to the prominence of timber production as the primary goal had a clear defined purpose, such as avalanche or landslide protection in steep, alpine regions.

Hand in hand with the focus on single objectives was a dominant emphasis on increasing efficiency by simplifying and homogenizing forest structures and operations (PUETTMANN *et al.*, 2009). Overall, foresters were quite successful at improving productivity in intensively managed operations.

In contrast, the current diversity of ownership objectives and public viewpoints about forests (e.g. the increasing concern about biodiversity) and the accelerating changes in global climate, species invasions, and market forces are forcing a complete re-evaluation of forest management. Increased concerns about the maintenance of biodiversity and other eco-

system services in the face of global changes have led to a replacement of the focus of timber production to an emphasis on a wide range of economic, social, and ecological objectives (DAILY et al., 1997; MEA, 2005). This is especially obvious on public lands in North America and central Europe. However, the trend is evident to various degrees in most parts of the world to the extent that globally, forest management is struggling with a paradigm shift. In addition to the altered expectations from forests, forest managers are under pressure to incorporate new scientific developments into management practices. Especially challenging in this context is our improved understanding of the importance of variability, diversity, and heterogeneity in the context of complexity and adaptability in forest ecosystems (PUETTMANN et al., 2009) and how this should be incorporated into modelling tools used in forest management. In this paper, we (1) review some basic concepts relating to complexity science, (2) show how they can be used to modify current forestry approaches and practices, and (3) demonstrate their relevance using predictability and modelling as examples.

THE SCIENCE OF COMPLEXITY - IMPLICATIONS FOR PREDICTABILITY

Complexity theory is based on a holistic view of systems where large-scale measures describing the most probable behaviour of the system or its recurrent spatiotemporal patterns are understood as emergent properties resulting from the local interactions among the system's components (PARROTT, 2002; PROULX, 2007; ANAND et al., 2010). To fully appreciate this definition, we provide a brief historical review of systems theory and predictability. The science of complexity has a varied history in a variety of scientific fields, such as physics, economics, and neuroscience (see WALDROP, 1992). Because of its heavy emphasis on mathematics and predictability, it is closely tied to chaos theory. In fact, Langton (in WALDROP, 1992) described complexity at the "edge of chaos" (Figure 1), i.e., a system that is sufficiently cha-

otic to have creativity, novelty, and learning, but at the same time is sufficiently ordered to maintain its identity. The formal development of chaos theory began when it became evident that the prevailing linear systems theory simply could not explain the behaviour observed in many systems. This resulted in a shift in our understanding of variation, heterogeneity and predictability. Variation and heterogeneity had been traditionally interpreted in models as imprecision and simple "noise" but it is beginning to be understood as an integral component of complex systems. An important consequence of this new viewpoint is that chaotic systems are inherently unpredictable, but not random. They can only be predicted within some error bound that increases with time. Therefore, chaos needs to be contrasted with stochasticity and the distinction between determinism, stochasticity and predictability in modelling is subtle, but very important. If a natural system is inherently chaotic, the common approach of simply adding stochasticity to a deterministic, i.e., non-chaotic model does not adequately represent the range and patterns of variation of that system. Behaviours of complex systems have been defined as "a chaos … in which the components of the system never quite lock into place, yet never quite dissolve into turbulence either" (WALDROP, 1992, p. 293). Thus, a complex system is not quite fully chaotic, but neither is it completely disordered (TURCHIN and ELLNER, 2000). Internal interactions and feedback processes tend to decrease disorder if the system becomes too chaotic and increase disorder if the system becomes too ordered (Figure 1).

Two key concepts that have implications for predictability and application of complexity theory to natural ecosystems include adaptation (leading to "complex adaptive systems") and attractors. Complex adaptive systems are defined as complex systems in which the individual components are constantly interacting and reacting to one another, thus modifying the system and its response to outside disturbances, thus allowing it to adapt to altered conditions (LEVIN, 2005; PUETTMANN, 2011). Ecosystem's adaptation has an obvious link to
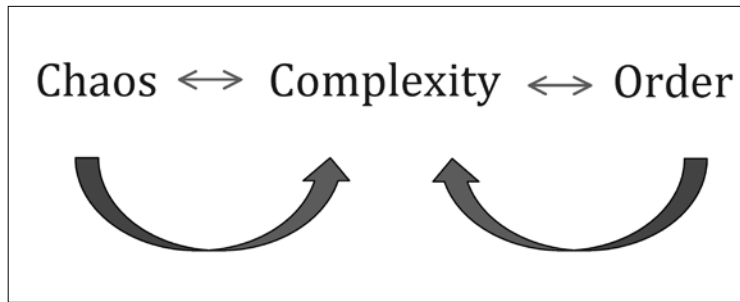
Figure 1 – Visual representation of complex systems at the edge between order and chaos. Curved arrows represent the feedback mechanisms that prevent systems from falling into chaos or order.

evolution, but differs in that adaptation is acting at the level of its individual components (the species) and not at the system level itself (LEVIN, 2005). However, changes occurring at the individual level can percolate to the whole system and affect its overall functioning. For example, a change in beak length may be viewed as evolution for the finches of Darwin, but may also result in a better dispersal of some plant species and thus modify the structure and composition of the whole system. The second concept of attractors is basically replacing the traditional notion of equilibrium and steady-state in system theory. Since complex systems are inherently dynamic and unpredictable, attractors can be viewed as a region or basin of state space to which a complex dynamical system evolves after a long enough time. This is similar to the ball-and-cup models often presented when the concept of resilience is discussed in which the attractor remain in the basin even if slightly disturbed. However, attractors are not defined as single or even stable points. Instead they are in constant motion and follow an orbit or even a path that never lead them to the same place twice. It should be evident from this brief description of complex system theory, adaptation, and attractors that viewing forests as complex adaptive systems has profound implications for traditional forest management, which is based on the assumption that ecosystem responses to silvicultural practices is highly predictable and tend to move toward a more stable late successional state.

COMPLEXITY, FORESTS AND FOREST MANAGEMENT

As our understanding of chaos theory and complexity science increases and with the advent of powerful computers, ecological systems including forests have become increasingly understood and viewed as complex adaptive systems (LEVIN, 1998, 2005; CADENASSO *et al.*, 2006; SOLÉ and BASCOMPTE, 2006). A forest can therefore be classified as complex and adaptive as it displays the following properties: (1) it is composed of many parts (e.g., trees, insects, soil) and processes (e.g., nutrient cycling, seed dispersal, tree mortality, decay), (2) these parts and processes interact with each other and with the external environment over multiple spatial and temporal scales (e.g., competition, dispersal, disturbance), (3) these interactions give rise to heterogeneous structures and nonlinear relationships (e.g., above and belowground species mixtures and relationship between growth and light), (4) these structures and relationships are neither completely random nor entirely deterministic, but instead represent a combination of randomness and order (e.g., precisely predicting the development of even single species stands is impossible), (5) they contain both negative and positive feedback mechanisms, stabilising or destabilising the system, depending on conditions (e.g., N-fixation, rainfall interception, density-dependent mortality), (6) the system is open to the outside world, exchanging energy, materials, and/or information (e.g., nutrient, water cycling, albedo), (7) it is sensi-

tive to the initial conditions following a major disturbance and subsequent perturbations (e.g., rodent population that feeds on the seedbank), and (8) it contains many adaptive components and subsystems nested within each other, giving rise to emergent properties (e.g., carbohydrates that form into trees).

Viewing ecosystems as complex adaptive systems emphasizes how ecosystems are organized, how interactions and relationships among individual parts or processes can give rise to collective behaviours that cannot be readily predicted by looking only at its individual parts (i.e., emergent properties), and how the interactions between the individual components are altered as the system adapts to changing conditions. While much work in these regards still needs to be accomplished a quick look shows that among biological systems, forests could be considered prime candidates for applications of complexity theory and yet, the implications of this have not been directly considered by forest managers or even treated seriously in the university curricula. Forests are not simply collections of trees. Forests, even mono-specific plantations, contain a plethora of interacting individuals, species, and physical and ecological processes. Their myriad soil organisms, herbs, lichens, mosses, insects, birds and mammals live and interact with each other and their outside environment across multiple overlapping spatial and temporal scales. Forested ecosystems modify themselves (i.e. adapt) in response to their environmental and biological surroundings and have done so for millennia. Small differences in starting conditions and in non-linear feedback loops can result in large and unexpected differences in development of complex systems (MAY, 1974; SOLÉ and BASCOMPTE, 2006) as has been shown in forests (PACALA *et al.*, 1996).

Complexity science suggests that no aspect of forests may ever be highly predictable. In fact, as we learn more about the processes that determine ecosystem dynamics, we learn that they are not united by their predictability, but rather by their rather innate unpredictability. While qualitative forecasts are possible, in that we can predict the general trend of forest development after a disturbance, precise quantitative predic-

tions of attributes at some particular place and time such as total biomass pose profound challenges that have heretofore not been met.

It should be evident from the brief description above that all forests, even homogenous, intensively managed mono-specific tree plantations and not only uneven-aged mixed species or old-growth forests possess the attributes of complex adaptive systems. Intensively managed plantations have a natural tendency to adapt and often require continued "top-down" management inputs to keep them from doing so, e.g., pest control practices. If left alone most will likely develop in a way that will not achieve the intended stand structures, and thus the desired ecosystem goods and services. Thus, the focus on single objectives, such as timber production, and the associated emphasis on homogeneity and reliance on outside interventions have not altered the ability of forests to adapt to changing conditions per se. Instead it has reduced the diversity of system components, altered their interactions, and thus limited the options for ecosystems to change and adapt. These limitations make it less likely that they can provide an adequate level of the wide variety of desired ecosystem goods and services throughout the adaptation process.

As we accept that the future ecological, social, and economic conditions are less and less certain and predictable, forest managers need new insights and tools that permit the integration of the spatial and temporal range of variation of forest ecosystems. Under uncertain future conditions, forest management would benefit having more flexible objectives and the ability to adapt to outside events and to the dynamical responses of ecosystems. The spatial (stand level) and temporal (100 year rotation) limits that are imposed by human management need to be reconsidered in order to improve flexibility, encourage heterogeneity and variation and allow management to operate at many levels (DREVER *et al.*, 2006). In ecology, heterogeneity and variation are both important aspects of the resilience of the system. Ecological resilience of ecosystems is defined by HOLLING (1973) as "the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively

different state that is controlled by a different set of processes" or as suggested by PUETTMANN (2011) as the capacity of an forest ecosystem to tolerate disturbances and changes while maintaining a similar set of ecosystem services and goods. Ecological resilience emphasizes persistence, variability, and adaptability. It recognizes that ecosystems are in non-equilibrium and that changes in ecological processes occurring at one scale can affect other processes at other scales in non-predictable ways.

Viewing forests as complex adaptive systems and studying ecological resilience through the lens of an attractor lends itself to practical applications. This provides insights into the sensitivity of forests to being pushed toward or beyond a threshold of an attractor (e.g., successional pattern, community type etc.) toward another attractor, or into a chaotic domain that is lacking an attractor. Quantifying a critical transition when a system shifts from one stability domain, i.e., attractor, to another, provides a measure of the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures (SCHEFFER et al., 2009). This will allow assessment of ecosystems dynamics after disturbances and of impacts of management practices on ecosystems development in terms of whether the ecosystem will respond to these changes in a way that maintains desired levels of ecosystem goods and services. This example highlights how viewing forests as complex adaptive systems focuses on persistence, adaptability, and variability – attributes that are at the heart of understanding sustainability. In contrast, searching for a single steady or cyclic state focuses on efficiency, control and predictability - all attributes at the core of desires for predictable fail-safe design and optimal performances under a narrow set of conditions.

MODELLING APPROACHES AND TOOLS

The neologism "biocomplexity" (COLWELL, 1998) characterizes, in a holistic way, the varied and complicated interactions between sciences, individuals, and methods for ecosystem studies, which are in themselves complex. Since then, interactions between sciences have effectively expanded resulting in the development of new statistical and modelling approaches and tools (JOPP et al., 2011). For instance, power law relationships, a tool that originated in physics to predict frequencies of events and indices originally for chaotic system studies have been used to characterize complex ecological systems (SYMONIDES et al., 1986; BAK et al., 1990; STONE and EZRATI, 1996). In contrast to normal distributions, which have gained most attention in traditional modelling efforts, power law distributions are scale invariant, i.e., theoretically they allow a generalisation of the conclusions made across all observation scales for which the power law holds. Indeed, a number of studies show that the density of certain species groups, fire frequency and the relation between size and growth of individuals can correspond to power laws (PERRY, 1994; JORGENSEN et al., 1998; ENQUIST and NIKLAS, 2001). Whether the full range of scales across which power law relations conforms to known ecological gradients is not yet well understood (HABEEB et al., 2005). Certain supposedly cyclical or random annual variations have been shown to be in fact 'complex' dynamics, i.e., are impossible to predict. For instance, the annual production of seeds by plants has been statistically linked to climate and to the individual fitness with a high associated stochasticity (or noise) in biological studies (CRAWLEY and LONG, 1995). However, the modelling efforts suggested that these quantities may vary in a quasi-chaotic fashion from year to year (SYMONIDES et al., 1986; STONE and EZRATI, 1996) or chaotically from deterministic processes at the individual level (SATAKE and IWASA, 2000). As pointed out above, these conclusions question the nature of noise in biological data and are examples of the limitation of deterministic models for predicting complex ecosystem dynamics, even when a stochastic element is added (WU and LOUCKS, 1995; PASCUAL and LEVIN, 1999).

Most discussions about forest modelling divide models into groups or dichotomies, such as empirical vs. process, deterministic vs. sto-

chastic, or spatial vs. non-spatial. Process-based models simulate key mechanisms or processes to specify the system's key internal structures, rules and behaviours; whereas, empirical models seek to describe statistical relationships among the data with limited regard to the system's processes. They are generally more precise than process models at predicting phenomena that fall within the range of conditions for which the empirical relationship was developed. But, because they assume that the processes that give rise to the dynamics of the system do not change, they do poorly at representing larger areas or even predicting the sites which they measured if something about that system changes. Process-based models, however, are much better at addressing complicated questions for which we have little previous experience, such as simulating multi-species stand dynamics, growth under a changing climate, forest management under the emerging forest ecosystem paradigm, and provide clearer discipline to the management and policy dialogue.

Models can also be classified as either deterministic or stochastic. Both empirical and process models can be deterministic, meaning that only one outcome is predicted for a given set of starting conditions. Given the inherent stochasticity involved in natural disturbances, modelling forest calls for stochastic models that produce a different result each time they are run and thus present a distribution of possible outcomes. It is important to note, however, that stochastic variation does not fully incorporate either the uncertainties or the complexity of a forest system. Traditionally, we have interpreted this variation as being a better estimate of the natural variability of the system, but we do not know how closely the model stochasticity matches nature's inherent unpredictability. HANSEN et al. (1995) has shown that many of the response variables can show non-linear behaviour across various levels of treatment. These together with feedback processes can produce chaos. What is needed is the development and application of modelling approaches that better capture these non-linearities to improve our ability to represent the total character of variation of natural systems. Complex systems studies provide this framework.

There is an increasing variety of new models that can be used to simulate stands and landscape in more "complex" ways and better represent ecosystem adaptability and resilience. Many are able to incorporate changing environmental conditions (i.e., new attractors) to predict the likely future conditions of the forest. For example, more recent models use trees as individual modelling agents (e.g., PTAEDA2: BURKHART et al., 2001) rather than stands. Other models incorporate nutrient dynamics (e.g., TRIPLEX: PENG et al., 2002), rather than assuming constant nutrient supply. Furthermore, some models are spatially explicit and thus allow spatial heterogeneity in tree distributions. Models that simulate forests by incorporating regeneration and growth routines at various spatial scales (e.g., SORTIE-ND: COATES et al., 2003) or even include stochastic elements (e.g., LANDIS-II: MLADENOFF, 2004) are even better suited to help silviculturists understand the envelope of desirable future stand structures. Recent developments in Bayesian Networks (e.g. see VERHOF, 1996; LEE and RIEMAN, 1997; BORSUK et al., 2004) and linkages to climate change models will further improve forest simulation models. However, rather than approaching these models with a mindset of improving predictability of forest development under specific conditions, development and use of the models will be improved if they incorporate a solid understanding of the characteristics of complex adaptive systems, especially accepting uncertainty, unpredictability and quasi-chaotic behaviours as intrinsic characteristics of the forest.

Since ecosystems are fundamentally a network of interacting elements, the next generation of models and modelling approaches need to represent the important elements of the system in space and time. Complexity models and modelling require an organizational hierarchy to represent their system of interest (PARROTT and ROK, 2000; GREEN et al., 2005; KOLASA, 2006; PROULX, 2007). To simulate the intricate functions of a forest, a model need to represent, in a spatially explicit manner, the most important objects and functions that affect its short- and long-term dynamics at various spa-

tial scale. Many hierarchical representations are possible, but in most cases they will encompass some or all of the following levels (individuals< populations< communities< ecosystems< biomes). Complexity theory also implies that it is not possible to simulate complex behaviours by using whole stands as modelling agents because no interacting elements are present that can generate emergent properties at that scale. In fact, ecosystem structures, functions, and processes are now interpreted as emerging from inter-hierarchical interactions. For example, the slow (e.g., tree succession) and fast variables (e.g., insect dynamics) of GUNDERSON and HOLLING (2002) represent interactions across two time scales. Behaviour of complex adaptive systems is driven "bottom-up", and models should reflect this. Following this approach, each hierarchical element is modelled as a discrete agent or object state, where each entity has functions that are characterized by relationships described by rules (or equations) and constant values or variables.

Ecosystem modellers have used a number of general approaches to simulate ecosystem development that are relevant to studying complexity including: individual-based, process-based (for studying biogeochemical complexity) and event-based models and cellular automata (PARROTT, 2002). In each of these approaches, there is a spatial component that allows individual objects to interact. SOLÉ and BASCOMPTE (2006) identified several methodologies that would be useful for studying complexity in ecosystems. Coupled map lattice models (CMLs, KANEKO, 1984) could show interesting complex dynamics, patterns and emergent phenomena. CMLs can be defined as a dynamical system, where local populations are connected through discrete time and space into a lattice structure. Cellular automata (CA, see FARMER et al., 1984) are a particular class of CMLs, in which populations are represented as having discrete states, that can be used to study host-parasitoid interactions (HASSELL et al., 1991) and biomass-litter interactions (BASCOMPTE and RODRIQUEZ, 2000) among other important ecosystem processes, and the influential work of HASTINGS and HIGGINS (1994)

on the dynamics of marine organisms. As an example of using a CA for studying fire dynamics in forests, BAK et al., (1990) demonstrated self-organization using tree plots as cells that interacted by means of fire spreading between forested cells. Percolation theory, which analyzes the patterns of propagation of events like fire or disease or other processes such as seed dispersal through a lattice, is another approach (SOLÉ and BASCOMPTE, 2006), and graph theory has a suite of tools useful for studying complexity in ecosystems (SOLÉ and BASCOMPTE, 2006; FALL et al., 2007).

While reviewing all these modelling approaches, it is important to remember that the definition of the modelling elements, the hierarchical levels being represented, the spatial and temporal scales, and the functions and variables represented all depend on the questions being asked, the available data and the skill and approach used by the modellers. To take advantage of insights from viewing forests as complex adaptive systems, it is important to remember the basic elements that are required in modelling complex systems: (1) representation of many hierarchical levels, (2) representation of both spatial and temporal scales, (3) representation of some stochasticity or even better (4) non-linearity, and (5) some representation of discrete interacting entities or elements. HOLLING (1992) further developed the resiliency concept to incorporate the challenge of scaling in ecology and determined that the study of ecosystems requires approaches that are specifically designed for the temporal and spatial scale of the respective question (see GUNTON and KUNIN, 2007). HOLLING recognized six spatial scales in forest systems: (1) leaf or needle, (2) crown, (3) gap or patch, (4) stand, (5) landscape and (6) biome. In addition, HOLLING suggested that ecologists can make major contributions by focusing on linkages among scales, especially since studying or modelling ecosystems may require representation of lower scale processes (e.g., number 1 or 2, as listed above) into larger scale representations of ecosystems (e.g., numbers 4 and 5, as listed above). Many studies have shown (e.g., PAPAIK and CANHAM, 2006, JAMES et al., 2007, others)

that important processes, such as legacies that control forest development, can only be understood using spatial models. Many traditional forest growth and yield models that are used to calculate annual allowable cuts are non-spatial. They are build and used under the assumption of spatially homogenous stands and are not designed to reflect important effects of spatial patterns at various scales (STURTEVANT *et al.*, 2007). As our modelling tools become more sophisticated and our empirical understanding of how ecosystems work and interact at multiple scales improves, and as our social requirements for our resources become more varied, so does our need to update and refine the tools of next generation of forest professionals.

A NEW WAY TO LOOK AT FORESTS

This brief presentation of complexity science as a new way to look at forest's inner working and the implication this has on the notion of predictability and modelling efforts suggests that new tools and approaches are required that embrace the inherent interconnectedness of systems and the resulting surprises and unexpected dynamics that can arise from this interconnectedness. These new approaches and modelling tools will help forest managers to learn how to harness the ability of natural systems to self-organise/adapt/evolve in order to guide them towards a desired state that produces the necessary ecosystem goods and services. But this requires more than new tools, it implies a totally new way of looking at the forest and forestry. The science of complexity provides us with new concepts, theories, and approaches that have been shown to be useful in other disciplines and it can help foresters develop a new way of looking and thinking about forests. Clearly this new view is very different from the traditional "command and control" and reductionist approach (HOLLING and MEFFE, 1996). Within this new view, variability and heterogeneity of processes and structures are not necessarily seen as an inherent liability of the ecosystem that needs to be fixed to improve predictability. Instead, they

are key elements of the overall forest dynamics and resilience that should not be ignored or reduced. This also implies that nature cannot be controlled, simplified, and made to efficiently produce specific goods and services without long-term consequences for the environment and the ecosystem, likely a reduction in the ecosystem's ability to adapt to changing conditions (i.e. a lost in resilience).

An increased emphasis on ecosystem adaptability also means "simple" and "over the board" solutions or "recipe" prescriptions are likely not adequate for sustaining a complex system that must fulfill diverse expectations. Instead, creativity in thoughts and diversity in practices are needed in designing new forest management policies for the future. This overview is part of an effort to prepare forest managers to view and treat forests as the complex adaptive systems they are. We see this trend as a new and exciting opportunity to meet today's policy goals and insure that the many known and unknown values of our forest resources are sustained for future generations.

RIASSUNTO

Le foreste come sistemi complessi adattativi: implicazioni per la gestione forestale e la modellistica

L'analisi delle problematiche inerenti le risorse naturali in un periodo di profondi cambiamenti globali presenta nuove sfide per il mondo forestale, sfide che hanno dato vita a nuovi tipi di approcci alla gestione delle foreste in considerazione della molteplicità di beni e servizi che queste forniscono. Uno di questi approcci è basato sulla scienza dei sistemi complessi. Considerare le foreste come Sistemi Complessi Adattativi (o CAS) rappresenta un paradigma emergente basato sullo sviluppo della teoria dei sistemi in altri settori come la fisica, la medicina, l'economia. Questo nuovo quadro concettuale riconosce la complessità dei sistemi (ecologici, economici e sociali), le loro strutture gerarchiche, le interazioni e i flussi di energia tra queste gerarchie, e la loro capacità di auto-organizzazione e di adattamento. Una delle maggiori sfide in campo forestale è come imparare a utilizzare questi concetti per favorire la capacità dei sistemi forestali di auto-organizzarsi e adattarsi di fronte al cambiamento globale, in modo da permettere alla foreste di continuare a soddisfare i bisogni umani quali beni e servizi ecosistemici. In questo lavoro si analizza brevemente la scienza della complessità applicata alla gestione forestale e si discute come questa scienza possa essere rapportata agli strumenti di modellistica utilizzati nella gestione forestale. In particolare, ci si sofferma sul concetto di prevedibilità e sulle sfide legate all'uso di modelli, per

mettere in evidenza le differenze tra la visione convenzionale della foresta e la visione della foresta come un sistema complesso adattativo. Si conclude proponendo un nuovo paradigma di gestione forestale, più adatto alle sfide del futuro, basato su eterogeneità, imprevedibilità e adattabilità, piuttosto che su uniformità e prevedibilità e sull'approccio "comando e controllo".

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