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DISCUSSION

Historical roots and the evolving science of forest management under a systemic perspective[1]

S. Nocentini, O. Ciancio, L. Portoghesi, and P. Corona

Abstract: In recent history, both a growing awareness of how scientific and societal uncertainty impacts management decisions and of the intrinsic value of nature have suggested new approaches to forest management, with a growing debate in forest science over the need for a paradigmatic shift from the classic conventional world view, based on determinism, predictability, and output-oriented management, towards a world view that has roots in complex adaptive systems theory and is consistent with a nature-based ethic. A conceptual framework under this context is provided by systemic silviculture. In this discussion, we analyze how this approach can be linked to three fundamental moments of the history of forestry and forest science: the Dauerwald theory, Gurnaud's control method, and the origins of environmental ethics. Relationships with the recent history of forest management science and current research perspectives are also highlighted.

Key words: silviculture, complex adaptive systems, Dauerwald system, Gurnaud's control method, environmental ethics.

Résumé : Dans l'histoire récente, la façon dont l'incertitude scientifique et sociétale influence les décisions de gestion ainsi que la valeur intrinsèque de la nature sont de plus en plus l'objet d'une prise de conscience qui ouvre la voie à de nouvelles approches en gestion forestière. Cette situation engendre un débat qui s'intensifie en science forestière au sujet de la nécessité d'un changement de paradigme : d'une conception classique conventionnelle du monde fondée sur le déterminisme, la prévisibilité et la gestion axée sur la production vers une vision du monde qui a ses racines dans la théorie des systèmes adaptatifs complexes et est compatible avec une éthique fondée sur la nature. Dans ce contexte, la sylviculture systémique offre un cadre de travail conceptuel. Dans ce document de réflexion, nous analysons comment cette approche peut être reliée à trois moments fondamentaux de l'histoire de la foresterie et des sciences forestières : le concept de la forêt pérenne de Dauerwald, la méthode de contrôle de Gurnaud et les origines de l'éthique environnementale. Les relations avec l'histoire récente en science de la gestion forestière et les perspectives courantes de recherche sont également mises en valeur. [Traduit par la Rédaction]

Mots-clés : sylviculture, systèmes adaptatifs complexes, système de Dauerwald, la méthode de contrôle de Gurnaud, éthique environnementale.

Introduction

Forests have a long history of management worldwide, which has shaped their structure and composition to answer a wide and changing range of social and economic needs, following the evolution of social, political, and economic dimensions of forest policy and perceptions through time. Both theoretically and operationally, forestry is based on a specific paradigm and a definite set of principles, concepts, and assumptions regarding how forest ecosystems function and react to management: all these influence both management philosophy, including normative aspects of management, and the perception of the human–nature relationship (Rist and Moen 2013). Scientific research has supported the evolution of forestry in time, providing the reference paradigm for translating scientific results into the desired outcomes of forest management.

Starting from the 18th century, forests and their utilization became the object of scientific enquiry, in accordance with "the quantifying spirit" of the century (Heilbron 1990), when mathematics and geometry became fundamental tools of forest management for organizing wood production. According to Lowood (1990), Germany was one of the most striking examples of this spirit: forest management, as part of the state administration, was scrutinized to fit "scattered pieces of knowledge . . . into systems" and to transform "all sorts of activities previously left to habit . . . into a science" (Bechstein 1797, in Lowood 1990, p. 316). Quantification and rationalization were thus applied to the description of nature and to the regulation of economic practice. The result was that, in large areas of central Europe, the aim of maximizing and regulating wood production resulted in the transformation of natural forests into conifer plantations

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(Wolf and Berg 1988; Schabel 2001). Starting from the end of the 19th century, as a reaction to the problems caused by widespread clear-cutting and conifer monocultures, forest management approaches based on natural regeneration (such as shelterwood and selection systems) were increasingly advocated and have been applied in many areas in Europe (e.g., Gayer 1886; Parade 1883; Montero et al. 2008; Nocentini 2009; Bončina 2011; O'Hara et al. 2018). But the final objective of these different silvicultural systems was still the optimization of commodity production according to a regulated management model.

This approach is coherent with what ecologists have termed the "classic paradigm", which characterized natural resource utilization during most of the last century (Meffe and Carroll 1997). According to this paradigm population, community and ecosystem dynamics are treated as if they were functioning in a static environment and following predictable trajectories. Scientific attention was concentrated on defining quantitative laws that regulate the relationship between birth rate, death rate, and somatic growth (Hilborn et al. 1995). The consequence of this view is that if the exploitation rate does not exceed regeneration and growth rates, the resource will not be consumed; thus, an accurate prediction of such rates is fundamental for guaranteeing continuity of production. "Ecology, . . . , therefore, was a science born to explore the natural order, that balance of nature, that normalcy within the landscape" (Fiedler et al. 1997, p. 84).

It is not difficult to see in this paradigm the concept of the "normal forest", or "fully regulated forest", an ideal forest that fulfills the requirements of sustained yield, i.e., growth equals annual harvest (Davis et al. 2001, p. 9). This view considers the future as being virtually unchangeable, at least regarding the main factors affecting forest production and development, and forest ecosystems as systems that can be entirely understood in their functioning, so that they can be managed to meet predetermined aims (Nocentini 2011; Wagner et al. 2014). This implies trust in the fact that ecosystems will react to cultivation in a predictable manner and that other disturbances have typically a minor role.

According to Tahvonen (2004, p. 206), the "normal forest [concept] has played an important explicit or implicit role in forest science". According to Reed (1986, in Tahvonen 2004, pp. 206–207): "The idea of the normal forest is thus linked to sustained yield, and it has, it seems, occupied a central place in forestry thinking, for as long as a scientific discipline called 'Forestry' can be said to have existed". To obtain the normal forest, a profound knowledge of the mechanisms regulating forest growth was needed, and this stimulated the advancement of forest auxology and the development of forestry as a science.

In former times, this approach produced important scientific results if considered in relation to the "world view" of the time and contributed to regulating forest exploitation and slowing down forest destruction. But it must also be acknowledged that classical silviculture and management, pursuing the aim of a predictable regeneration rate and a constant yield of merchantable wood, have in practice transformed forests from complex ecosystems to simplified systems.

From the research point of view, the aim for order, rationality, and predictability was transferred in experimental protocols and designs; with a few exceptions, experimental field plots were actually much more uniform than the stands to which the results were to be applied (i.e., resulting target forests have been much more uniform and homogenous than those found in reality; Puettmann et al. 2009), and foresters have sometimes turned "idealizations into realities through their management approaches" (Persson et al. 2018, p. 4).

Furthermore, silvicultural studies have rarely been based on theories and have relied mostly on empirical analysis (Puettmann et al. 2009). The outcome of this type of research is the limited possibility of generalization. Nevertheless, foresters have usually adopted research results (e.g., yield tables or the optimal diameter distribution for uneven-aged stands) as a dependable representation of forest reality and have managed forests to match "scientifically sound" forest models.

More than two centuries after the birth of forestry as a science, silvicultural systems, practices, and approaches currently applied are mostly still based on the same paradigm (Puettmann et al. 2009).

A critique of "classic silviculture" and the underlying scientific paradigm was developed in Italy in the last decade of the 20th century, with the proposal of systemic silviculture (Ciancio and Nocentini 1997), which envisioned a shift towards considering forests as complex biological systems and the recognition of the intrinsic value of the forest. More recently, Puettmann et al. (2009), starting from a very similar historical analysis of the development of silviculture, have given a strong impetus to the idea of managing forests as complex adaptive systems.

Systemic silviculture is a conceptual approach that goes beyond the recommendation of specific management practices (Messier et al. 2019). According to the systemic approach, silviculture and management should aim at the renaturalization of simplified forest systems, sustaining natural processes, i.e., the natural self-organizing mechanisms that increase the resilience of the system (Ciancio and Nocentini 1997, 2011; Puettmann et al. 2009; Nocentini et al. 2017). The aim is to maximize the role of natural energy in the functioning of forest ecosystems and minimize anthropogenic inputs for management (Allen and Hoekstra 1992). Interventions are cautious, continuous, and targeted to the needs of the various stands, favoring natural regeneration, diversified structures and composition, and without any reference to a predefined rotation age. A practical case study is reported in the Appendix and applicative operative examples with guidelines for tree marking in comparison with conventional approaches are reported in Bravo-Oviedo et al. (2020), with distinctive reference to table 4 therein.

The adaptive approach, fundamental in systemic silviculture, is based on the detailed and continuous monitoring of the forest reaction to treatment. A co-evolutionary continuum between human intervention and the system's reaction guides management, ruling out the typical finalism that is instead inherent in the normal forest theory (Ciancio et al. 1994, 1995).

Systemic management involves the overcoming of top–down centralized decision-making models and the diversification of silvicultural treatments (Nocentini et al. 2017). By considering human action as part of the system, it recognizes the needs of society without forcing on the forest a predefined structure and composition aimed at specific products or services. Wood production is not the aim, but the consequence of management carried out in the interest of the forest. This means helping the forest maintain its natural processes and the ability to perpetuate itself, reorganize following disturbances, and continue functioning as a forest, thus increasing its resilience and adaptive capacity. Finally, systemic silviculture considers the intrinsic value of the forest, not only its instrumental, utilitarian value (i.e., its value in relation to the services it provides to humans).

In this discussion, we analyze how the systemic approach can be linked to three fundamental moments of the history of forestry and forest science: the Dauerwald theory, Gurnaud's control method, and the origins of environmental ethics. In the subsequent section, the systemic approach to silviculture is also highlighted in relation to the recent history of forest management science and current research perspectives.

Historical foundations of systemic silviculture

Möller's Dauerwald

The prodromes of the systemic concept of the forest can be found in Alfred Möller's (1922; permanent forest) Dauerwald. Alfred Möller (1866–1922) was a professor at the Academy of

Forestry in Eberswalde in the German region of Brandeburg. In the development of his theory, he was certainly influenced by other silvicultural innovators of the time, such as Karl Gayer and his studies on natural forests. An important part was played by his training as a mycologist, which made him particularly attentive to the role of the soil as a source of vitality for the forest. This led him to support the importance of maintaining permanent soil cover and to exclude clear-cutting (Bode 1992; Schabel and Palmer 1999; Schabel 2001). But what makes his proposal not a simple silvicultural system but a real scientific innovation is the interpretation of the forest as a complex and dynamic organism (Ciancio and Nocentini 2000): to pursue wood production and other functions of the forest, it is necessary to maintain the stability and health of the forest organism. A decisive role was also played by his observations and analysis of the results achieved in the Bärenthoren pine forest where clear-cutting and artificial regeneration had stopped and the stands had been managed for several decades following criteria in which Möller recognized the Dauerwald principles (Helliwell 1997). The concepts of age class and rotation had been abandoned, and the trees to be felled were selected following silvicultural criteria, releasing the most vigorous and healthy ones, and not aiming at predetermined wood volumes or assortments. His preference for a multi-aged mixed forest with natural regeneration was clear but he strongly emphasized that the Dauerwald did not identify with the uneven-aged forest; nor even with the Plenterwald system (i.e., the single-tree selection system) although some detractors of the method have tried to reduce it to this type of treatment. In regard to the silvicultural system being preferred, he actually stated: "we must use all forms of treatment to achieve silvicultural purposes" (Schabel and Palmer 1999; Ciancio 2014).

In its day, this theory was the object of much discussion. The Dauerwald introduced the principle according to which, in the cultivation approach, it is the forest that "tells" the forester what the extent of his intervention should be, and not the other way around. According to Möller, the forester should respect soil integrity and indigenous biodiversity, because the forest can fully manifest its vigor and productivity only if all the parts are healthy (Schabel 2001). Möller's philosophy can be summarized in the phrase: "I believe I have found the right word. The forest is truly a living organism" (Ciancio and Nocentini 2000, p. 50). Thus, the permanent forest was a revolutionary and, at the same time, farsighted theory. That is why it was passionately defended, or quickly liquidated as it actually was. The organicistic view, which enjoyed so much success in America with F.E. Clements, did not receive the same attention among European foresters and researchers.

The permanent forest is neither a silvicultural system, nor a norm. It is a protocol of cultivation intentions, aimed at conserving the efficiency of the forest. Perhaps, Möller was ahead of his time. And many foresters have not understood that, with appropriate adjustments, the Dauerwald would give a decisive contribution to the progress and development of forest science and technique. It is now a fact that to respond to the needs of modern society, many forms of forestry and forest management have adopted, adapted, and developed, more or less consciously, the principles of the Dauerwald even if often without mentioning the inspiring source (for a list, see O'Hara 2014).

Gurnaud's control method

In 1927, Troup (Helliwell 1997) noted that there was little new in the Dauerwald and highlighted that such an approach had already been applied in various places in Switzerland, France, and Germany for at least 40 years. He was probably also referring to the control method proposed by a French forester, Adolphe Gurnaud (1825–1898). It has many points in common with the Dauerwald but, unlike the latter, at the basis of the method there was not the enunciation of an innovative vision of the forest, such as the organicistic concept, but a series of operating principles to make productive management more efficient. To be put into practice, the criteria enunciated by Gurnaud required a different way of conceiving forest management.

Gurnaud rebelled against the idea that the silvicultural system and even more the rotation, defined a priori, could be considered indicators of stand development and, therefore, of the treatment to be carried out. Instead, he claimed that a modern forest planning strategy had to be centered on the increment of individual trees, analyzing actual stand dynamics as a reaction to the previous intervention and as the basis for the following one (Anonymous 2009). The principles of the method are simple: forest compartments must be managed independently of each other; the cutting cycle is short (5–6 years) to maintain a high growth rate; wood yield and volume increment are assessed by comparing subsequent inventories; allowable cut is equal to the increment if the forest is in "balance". But, above all, tree selection is made by foresters based on their experience and knowledge of the forest (Pardé 1991).

In this last point lies the most original aspect of the method: it frees the forest, and the forester, from rigid management rules (Ciancio 2014). The control method can be considered, in its strict definition, as avant-garde, anticipating the most modern forms of management assistance, because it is, in spirit, a decision support system (Schütz 2006). The inventory method — a comparison between the wood volume at the beginning of the management period and the wood volume at the end of the period, taking into account felled trees — is not only a technique for measuring volume increment of forest stands: it is the basis for controlling the reaction of each stand and adapting successive interventions, which is the innovative and fundamental aspect of Gurnaud's method.

The control method owes a lot to Henry Biolley (1858–1939) who listened to Gurnaud illustrating his theories at the Paris Universal Exposition in 1878 and understood that it was what he needed to put into practice a closer to nature management, based on intensely cultivated multi-aged mixed forest ("jardinage cultural contrôlé") (Schütz 2006; Anonymous 2009). He applied and disseminated the ideas of his colleague and friend by experimenting, adapting, and practicing the method, starting with the Couvet forest (Biolley 1897) and spreading it throughout the canton of Neuchâtel and in various parts of Switzerland. Other distinguished foresters have made the method known in several European countries and the world (Pardé 1991).

Adolphe Gurnaud's (1884, 1886) presentation of "La Méthode du contrôle" provoked strong opposition because it questioned a consolidated practice. Regulation based on rules was offset by regulation based on assessment: regulation focused on predetermination of the prescribed cut was replaced by regulation based on verification of the yield. That idea has the same operative perspective of the modern so-called adaptive management, which explicitly considers the low predictability of natural systems dynamics and requires learning from system reactions to confirm its resilience. The methodological shift from a priori determination to a posteriori assessment involves a heuristic approach or trial and error. In the light of this, von Detten (2011, p. 462) stresses that "incremental and adaptive management strategies directed towards feedback mechanisms and reflexive learning processes seem the proper way to cope with an undetermined future and the problems of risk, uncertainty, ignorance and indeterminacy".

The Dauerwald and the control method, with the rejection of the normal forest concept, did not suggest only technical changes. They sparked a real mutation of silviculture and forest regulation: by adapting the cut to the reaction of the stands, both the Dauerwald and the control method apply an adaptive approach that anticipates concepts linked to managing forests as complex adaptive systems.

Table 1. Comparison of systemic silviculture against the Dauerwald system and Gurnaud's control method according to their general principles and assumptions.

Issue	Dauerwald system	Control method	Systemic silviculture
Concept of the forest	Organism	Dynamic tree system	Complex, adaptive system with intrinsic value
Main goal of forest management	Maximum wood production, ensuring the health of all components of the forest	Maximum wood production, optimizing the stock/increment ratio	Increase forest ecosystem complexity as a guarantee of resilience, adaptive capacity, and multi-functionality
Favoured silvicultural system	All but clear-cutting	In principle, all systems, but the selection system is considered the most suitable ("jardinage cultural")	Diversified interventions, driven by stand structure and response of the system to previous treatments
Human–nature relationship	Anthropocentric	Anthropocentric	Ecocentric

Systemic silviculture is in historical continuity with the Dauerwald and the control method. However, it also goes beyond them (Table 1) not only because it can use scientific knowledge that has emerged only in the last century, but also because it reflects the shift in the nature–humankind relationship, which has been determined by the numerous environmental crises and events occurred in the last decades, overall framed under the term "global change".

The intrinsic value of forests

Systemic silviculture explicitly recognizes that the forest has intrinsic value (Ciancio et al. 1994; Ciancio and Nocentini 1997; Nocentini et al. 2017). This ethical standpoint has its roots in the thought of Aldo Leopold and applies Leopold's land ethic (actually, an Earth ethic, according to Callicott 2013) to the forest as an integral part of the land and the natural community. Paraphrasing Leopold (1923), systemic silviculture brings out what probably many of us have felt intuitively, that there exists between humankind and the forest [earth in the original] a closer and deeper relation than would necessarily follow the mechanistic conception of the forest as just a provider of commodities.

Systemic silviculture is coherent with what Callicott (2013, p. 21) defines the "underlying, persistent thematic thread that Leopold weaves through the fabric of his masterpiece [. . .]: the exposition and promulgation of an evolutionary-ecological world view and its axiological (ethical and aesthetical) and normative (practical moral) implications". It refers to an ecocentric environmental ethic, one that grants moral standing to both individuals and wholes — i.e., ecocentrism as defined by Callicott (1980, in Goralnik and Nelson 2012).

Natural resource management is an application of ethics (Batavia and Nelson 2016), which reflects normative ideas about how we ought to behave or interact with the world around us (Nelson and Vucetich 2012). In recognizing the intrinsic value of forests, systemic silviculture owes much to the concepts and ideas of environmental ethics. This conceptually differs from classical sustainable forest management, which is fundamentally output oriented, aiming to maintain and enhance the economic, social, and environmental values of forests for the specific benefit of present and future human generations.

The idea of attributing intrinsic value to non-human natural entities has been long debated among researchers in philosophy dealing with the relationship between humankind and nature. The debate has focused on defining who and what can have intrinsic value and whether it exists objectively or must be granted subjectively (Callicott 1997; Batavia and Nelson 2017). In time, intrinsic value has been attributed to conscient animals (Regan 1983), sentient animals (Warnock 1971), all living beings (Taylor 1981), species (Callicott 1986; Rolston 1988; Johnson 1991), biotic communities (Callicott 1989), ecosystems (Rolston 1988; Johnson 1991), and evolutionary processes (Rolston 1988). Soulé (1985) asserted that biotic diversity had intrinsic value and, according to Ehrenfeld (1988), value is an intrinsic part of diversity. As Callicott (1997) clearly stated, the practical aspect of recognizing the intrinsic value of something is not to make it inviolable but to shift the burden of proof, the onus of justification, onto those whose actions would adversely affect it.

More recently, the question of the intrinsic value of non-human entities has involved a growing number of institutions and, most important, jurisprudence. For example, the Millennium Ecosystem Assessment (2005) has acknowledged the intrinsic value of biodiversity, while legal provisions recognizing the Rights of Nature, sometimes referred to as Earth Jurisprudence, now include constitutions, national statutes, and local laws. From the seminal article of Christopher Stone (1972; "Should trees have standing? Towards legal rights for natural objects"), following decades of debate over the possibility and consequences of natural objects becoming legal rights holders, various countries have recently implemented rights of nature laws in their national legal systems (Schimmöller 2020). Ecuador, Bolivia, and a growing number of communities in the United States are developing their environmental protection policies on the premise that nature has inalienable rights (Borràs 2016).

Although Leopold pioneered the philosophy of ecology (Callicott 2013) and is very well known to most foresters, the normative and ethical foundations of forest management have been largely neglected (Batavia and Nelson 2016). A Sand County Almanac (Leopold 1949) was the most cited book in three annual *Journal of Forestry* readership polls (Society of America Foresters 1992, in Forbes and Lindquist 2000), but his "Land Ethic" has never been really adopted as the ethical foundation of forestry.

The utilitarian ethic underlying traditional forest management (Batavia and Nelson 2016) is characteristic of an anthropocentric world view that is often used to justify human cultivation or control of nature (Callicott 1990, 1997). According to Heinrichs (1985), foresters usually identified with timber more than with forests, with no substantial change from what Cotta had written in 1816: there would not be doctors without illnesses, there would not be forest science without wood scarcity. Of course, a much wider focus on different so-called ecosystem services has been proposed since the end of the 19th century, and there has been a continuous development of management approaches along this path through the last century, but they have generally been conceived under the same output-oriented, utilitarian conceptual framework.

In the last decades of the 20th century, this position was challenged by a series of articles in the *Journal of Forestry*, published by the Society of American Foresters (SAF). In 1989, the journal republished Leopold's (1933) article and his foreword to a Sand County Almanac (Leopold 1989). This sparked an intense debate whether the moment had come to include the Land Ethic in the SAF Code of Ethics (Coufal 1989). Among the many contributions, Coufal (1989) strongly supported the need to answer Leopold's appeal for an ethic that would change the role of *Homo sapiens* from conqueror to simple member and citizen of the Earth's community. He maintained that foresters, in managing the land, should start to think not only in economic terms but also in ethical and aesthetical terms.

The outcome of these proposals was the creation of a Land Ethics Task Force to recommend a land ethic canon for inclusion in the SAF Code of Ethics (Craig 1992*a*, 1992*b*). A reference to the land ethic canon was eventually included in the Code of Ethics, but not as explicitly as the advocates of this change had proposed.

In that period, also others wrote in favor of including ethical considerations in forestry. When Franklin (1989, p. 44) proposed a "new forestry" he pleaded for the adoption of a forest ethic: "Let us approach forest ecosystems with the respect that their complexity and beauty deserve". But, according to Batavia and Nelson (2016), this overtly ethical thread never again appeared in the literature, and in the *Journal of Forestry*, from 2000 to 2018, just six articles have dealt with ethics (Radcliff 2018).

In European forestry literature, there has been little reference to the importance of considering the ethical stand point and related world view of forestry (anthropocentric vs. biocentric/ecocentric), even though the need for a change in forestry has been increasingly discussed following the growing perception that society's expectations from forests have greatly changed over the last decades. Ethical considerations have often been dismissed on the grounds that forestry is a scientific and technical endeavor, not a philosophical one.

Systemic silviculture, with its straightforward recognition of the intrinsic value of forests, strongly linked to Aldo Leopold's land ethic and to the concepts and theories of environmental ethics, stands out distinctly in this historical background.

Evolution of management perspectives: from anthropogenic determinism to social–ecological adaptive systems approaches

The idea of considering the forest as a complex, biological, adaptive system has recently gained increasing consideration and is being currently discussed in relation to alternative management approaches (e.g., Messier et al. 2013, 2016, 2019; Filotas et al. 2014).

Over the years, alternatives to conventional forest management have been developed in various parts of the world (Puettmann et al. 2015). In continental Europe, these mainly refer to so-called close-to-nature forestry (e.g., Germany, Switzerland, Slovenia, Italy, and Spain; ProSilva 2012) while continuous cover forestry (e.g., UK and Ireland; Wilson 2013) has gained importance as a means for transforming even-aged conifer monocultures into mixed and structurally diversified stands. In North America, alternative silvicultural approaches have originated as a reaction to the impact of large-scale clear-cutting in natural forest ecosystems, especially regarding wildlife habitats, visual quality, and other ecosystem functions. These approaches have been collectively defined by Batavia and Nelson (2016) as "ecological forestry", which includes both natural disturbance-based management (e.g., Oliver 1980; Attiwill 1994; Bergeron et al. 1999; Franklin et al. 2002, 2007; Burton et al. 2006; Kuuluvainen and Grenfell 2012) and variable retention harvesting (e.g., Franklin et al. 1997; Coates and Steventon 1995; Gustafsson et al. 2012; Lindenmayer et al. 2012). In Canada, for example, increasing scientific knowledge of the full ecological complexity of boreal forests (Burton 2013) has stimulated changes in forest management practices to maintain more natural forest structures, compositions, and the full array of biodiversity and other forest values (Work et al. 2003; Burton et al. 2006); these practices generally include variable rotation lengths, different criteria for the selection of tree removals during partial cutting, and different patterns of structural retention (Burton et al. 1999, 2010; Bergeron 2004; Bouchard 2009).

Both close-to-nature forestry and continuous cover forestry (in Europe) and the various North American "ecological" approaches have been recently classified by Messier et al. (2019) as "nature-based" approaches, whereas systemic silviculture has been considered as a "conceptual" approach.

Table 2 shows a comparison between systemic forestry, conventional forestry, and "nature-based" approaches; in Fig. 1, the comparison also includes the Dauerwald system and the control method in relation to the ethical and silvicultural dimensions of the different approaches. Although there may be some similarity between systemic silviculture and nature-based approaches in some general aspects (e.g., considering not only wood production but also other goods and benefits; increased attention to forest biodiversity, etc.), there are many clear differences. Compared with these alternatives, systemic silviculture considers most of the characteristics of forests as complex adaptive systems, such as diversity, heterogeneity, memory, self-organization/emergence, nonlinearity, and uncertainty (Messier et al. 2013, 2016). There are instead more points in common between systemic forestry and "resilience thinking", which has been recently proposed by Rist and Moen (2013). In both cases, complex social–ecological adaptive systems are the reference paradigm, uncertainty and unpredictability are incorporated into management and there is a strong emphasis on adaptive co-management and governance. But from the operational point of view, systemic forestry goes further, with the definition of operational silvicultural and management criteria and methods (Ciancio and Nocentini 2011; Nocentini and Coll 2013), while on the theoretical level resilience thinking does not explicitly refer to the human–nature relationship.

Systemic forestry is based on monitoring and adaptation of silvicultural interventions to the reactions of the system, which requires an adaptive forest planning paradigm. Adaptive management is a consolidated concept in natural resource management (Holling 1978) and is being increasingly discussed in forestry. According to Bormann et al. (2007, p. 187), adaptive management is a "systematic and iterative approach for improving resource management by emphasizing learning from management outcomes". This means exploring alternatives for meeting management objectives, monitoring to learn which alternative responds better to these objectives, and then use the results to revise knowledge and consequently adjust management actions (Bormann et al. 2007). This leads to flexible approaches that promote reversible and incremental steps, based on ongoing learning and the capacity to change direction as situations change, following the imperative to learn as you go that is essential to managing forests in the face of uncertainty (Millar et al. 2007).

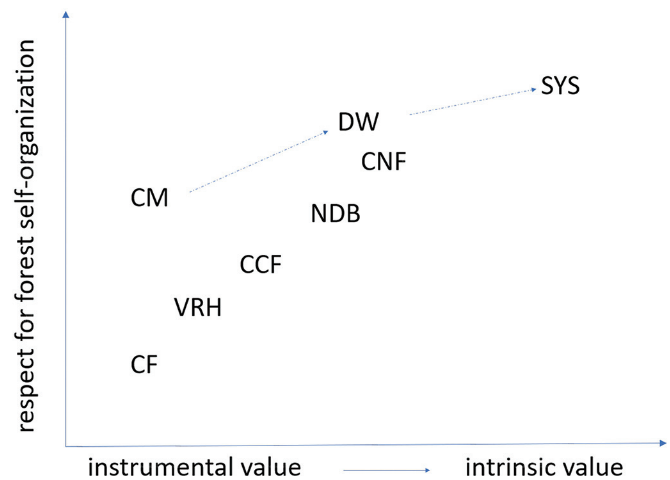
Consideration for hierarchy and cross-scale interactions, which are typical of the complex behavior of forest systems, has suggested shifting the focus from specific tree- and stand-scale objectives towards a more flexible multi-scale perspective that also considers landscape-scale processes and their interactions with the globally changing social–ecological conditions (Messier et al. 2016). In ecology, scaling in space and time is very important, because of the link between the spatial scale and the relevance of particular ecological processes (Wiens 1989; Peterson et al. 1998; Wagner et al. 2014): e.g., functional diversity within and across scales enables regeneration to occur following ecological disruption over a wide range of scales (Peterson et al. 1998).

Messier et al. (2016, 2019) have recently pointed out that focusing on building adaptive capacity shifts the decision matrix and requires foresters to emphasize the diversity of functional response traits, i.e., traits that determine a species response to disturbances. This can help the forest withstand or adapt to the largest possible spectrum of stresses. By introducing the functional complex network approach, Messier et al. (2019) exclude forest management and silvicultural approaches based on command and control, determinism and predictability, and accept instead the different

Table 2. Comparison between different selected approaches to forest management (modified from Nocentini et al. 2017).

Issue	"Conventional" forestry (sensu Duncker et al. 2012, FMA IV and V); "timber oriented" (sensu Messier et al. 2019)	Close-to-nature forestry (sensu Bauhus et al. 2013); ecological forestry (sensu Batavia and Nelson 2016); "nature-based" (sensu Messier et al. 2019)	Resilience thinking (sensu Rist and Moen 2013)	Systemic silviculture (sensu Ciancio and Nocentini 1997); "conceptual level" (sensu Messier et al. 2019)
Multi-functionality	Wake theory: if forests are efficiently managed for wood production, then all the other forest utilities will follow	The production function must comply with conservation of other values (e.g., biodiversity). Multiple-use forestry based on a sound ecological basis	Focus on maintaining options rather than a particular way of using a resource	Multi-functionality is the outcome of complex interactions between various sub-systems
The future	High predictability based on retrospective validation approaches	Predict ecological consequences of management practices	Low predictability — uncertainty is acknowledged	
Management	Approaches based on forecasting	Management based on knowledge of past disturbance regimes and (or) "desired future condition"	Maintain a desirable state (identity), or transform into a more desirable state	Approaches based on monitoring and adaptation of silvicultural interventions to reactions of the system
	Maintain an ideal, optimal condition of the resource		Maintain the system's identity — function, structure, and feedbacks	Develop optimal management
	Strictly ruled forest planning	Planning based on multifunctional optimization models	Maintain options rather than a particular way of using a resource	Adaptive forest planning
Ethical standpoint	Anthropocentric utilitarian ethic; forests as a resource for human exploitation	From anthropocentric to unexplicit attempts to dismantle the dichotomized worldview	(Not considered)	Non-anthropocentric ethic: the forest has intrinsic value; integrated and respectful perception of the humankind–forest relationship

Fig. 1. Graph showing the relative position of different forestry approaches (see Table 2 and text for references) in relation to the degree of respect for the self-organization of the forest and the instrumental (utilitarian) or intrinsic value attributed to the forest. CF, conventional forestry; CM, control method; CCF, continuous cover forestry; CNF, close-to-nature forestry; NDB, natural disturbance-based management; DW, Dauerwald system; SYS, systemic silviculture; VRH, variable retention harvesting. [Colour online.]



behavior and elements that are intrinsic to forests, as inevitable sources of uncertainty.

The "regulated forest" is the reference model of the conventional approach based on the normal forest, i.e., a set of forest compartments where the silvicultural intervention in each compartment is defined by a general "normal" model, in a top–down approach. The aim is to "homogenize" composition and structure in each compartment, conceptualizing stands of trees as uniform management units (Puettmann et al. 2009), which actually become "the building blocks of sustainable, regulated forests" (O'Hara and Nagel 2013, p. 336). Instead, with the systemic approach, each stand is treated according to its own peculiar characters, because, as suggested by O'Hara and Nagel (2013), disturbances, and natural self-organizing processes in a forest, may form discrete stand structures or uniform groups of contiguous trees, i.e., "stands". Systemic silviculture does not aim to normalize these differences within a compartment but tends to follow and adapt interventions to the response of each stand. As said before, this develops and expands Moeller's and Gurnaud's rejection of the regulated forest as an overarching model defined by predetermined production aims, which actually stifles silvicultural freedom to support the self-organization and evolution processes of each stand.

To monitor changes and feedback loops, relevant indicators at the different spatial and time scales must be identified: for example, the gene flow caused by pollen or seed dispersal of different tree species can bridge the distance between local forest stands, while water availability and quality influenced by specific forest conditions have effects at regional scales (Wagner et al. 2014). The constant integration and adaptation of interventions and responses of the system to management at all the scales is one of the challenges for future research.

Cross-scale interactions are connected to the concept of emergent properties that characterize complex adaptive systems. Emergent properties are ecosystem features that can be assigned only to certain levels of a hierarchy and there is an additional quality created by the interactions within the system that makes "the whole more than the sum of the parts" (Müller et al. 2000, p. 18). Emergent properties are always consequences of self-organizing processes; as such, they are suitable indicators of ecosystem integrity and their use should be further investigated for monitoring forest reactions to management.

Conclusions

In recent history, both an increased appreciation of how scientific and societal uncertainty enters management decisions and of the intrinsic value of nature have suggested new approaches to forest management, with a growing debate in forestry and forest science over the need for a paradigmatic shift. A paradigm can be defined as "a dominant belief structure that organises the way people perceive and interpret the functioning of the world around them" (Milbrath 1984, p. 7, in Raum and Potter 2015). At any point, new circumstances may challenge the belief and value structure of the dominant paradigm (Brown and Harris 2000), and cause a shift in focus, which can be seen as a "profound change in thoughts, perceptions and values that form a particular vision of reality" (Capra 1982, p. 30).

The new, developing forestry paradigm is a clear shift from the classic conventional world view, based on determinism and predictability, towards a world view that has roots in complex adaptive systems theory and in the ethics of nature.

These changes pose deep philosophical and practical challenges to current forest science. Accepting uncertainty as a constituent part of the forest planning objective can actually be liberating because it can translate into more flexible management options (Messier et al. 2016), which we believe can be seen as a heritage of Moeller's and Gurnaud's intuitions.

Systemic silviculture goes further and can be considered as a novel paradigm, a new conceptual framework and ethical perspective on forest management because it explicitly considers the intrinsic value of forests (Ciancio and Nocentini 1997), accepting the challenge coming from the development of an ethic of nature. In this new paradigm, forest management should try to maintain ecological resilience, i.e., enabling the system to react to stresses, while at the same time allowing for adaption when external conditions change. This means maintaining a flexible approach as an effective way for capturing the information and perspectives necessary to manage social–environmental systems and take into account all values of the forests, and not only the instrumental value (Nocentini et al. 2017). All this underpins a change in the logic of forestry action from norms to process and, consequently, in the way forest science is conceived and implemented.

Along with Bormann et al. (2007), we hope that forest management can be viewed, like science, as a never-ending set of questions rather than a series of disconnected truths. This is why it is relevant to understand the historical paths that have characterized and informed forest science (Corona 2019), as we have here shown for the prodromes of systemic silviculture in Gurnaud's control method, Alfred Möller's Dauerwald, and Aldo Leopold's land ethic. It is only on relevant historical background that our commitment as researchers can be constantly reformulated and relaunched with new ideas and motivations, in response to the accelerated dynamics of global issues.

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Appendix: Systemic silviculture at the Vallombrosa Forest (central Italy)

An example of forest management based on systemic silviculture is the forest management plan (2006–2025) of the Vallombrosa Forest in central Italy (Ciancio 2009; Ciancio and Nocentini 2011), a state-owned forest that is well known in Italy and abroad. In this forest, silver fir (*Abies alba* Mill.) has been cultivated since at least the 14th century by the Benedictine monks, but the first forest regulation plan was drawn out in 1876, after the forest became a property of the Italian state. For over a century, silver fir was planted and managed according to the classical even-aged model with a 100-year rotation, replacing the natural, mixed forests on over 600 ha. The new forest management plan based on the systemic approach aims at increasing the diversity and complexity of the forest stands, favouring natural evolution of the pure fir stands without predetermining their future structure and composition. There is no rotation age or diameter limit and silviculture is based on felling very small groups (2–4) of trees, creating gaps — maximum 200–300 m^2 — to produce diversified light conditions under the canopy that favour natural regeneration of beech, fir, and the other species that will naturally establish. The size of the gaps is quantified from the observation of natural gaps that have formed in the last decades (Bottalico et al. 2014). The silvicultural interventions are very gradual and repeated on the same compartment every 20 years; as general criteria, felling should not reduce average standing volume below 350 $m^3 \cdot ha^{-1}$. From the management point of view, the reactions of the forest to cultivation are assessed by monitoring permanent plots, 5 and 10 years after each intervention. Data from monitoring are the basis for adapting silvicultural interventions to stand response, e.g., modifying felling area or minimum standing volume if natural regeneration does not set in.