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Teaching Complex Adaptive Systems Science in Natural Resource Management: Examples from Forestry

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ABSTRACT

Teaching theoretical concepts, such as complexity theory, provides unique challenges, especially in applied disciplines. Current trends such as global change will require natural resource disciplines, for example forestry and agriculture, to expand their scientific basis and possibly shift their dominant paradigms to adopt a broader view of the ecosystems they manage as complex social-ecological systems. This likely will result in borrowing and adapting theories and concepts from other disciplines such as complexity science. Students in natural resources will need more training in these paradigms and learn to incorporate concepts such as thresholds, uncertainty, and cross-scale interactions as they affect ecosystem dynamics and thus management or restoration prescriptions. Numerous courses and approaches exist that teach general complexity concepts, including management implications at the governance levels. However, we do not know of any courses where these concepts are specifically applied to practical management challenges. This article aims to overcome this shortcoming by sharing our experiences. Specifically, we provide examples of field exercises that can be used to link theoretical concepts from complexity science to applied forest management issues, regardless of management objectives. Instructors are encouraged to evaluate these examples and modify them as necessary for uses in graduate classes and workshops. We hope that these exercises will help expose graduate students and professionals to a wider range of theories and concepts.

Core Ideas

- Complexity science brings some very useful novel concepts to natural resource management that are important to sustainability.
- Yet, these concepts are rarely taught to graduate students in terms of how they practically can be used in natural resource management settings.
- We present a series of field exercises that have shown promise in introducing complexity science to graduate students in forest management programs and may be adapted by instructors to suit a variety of teaching contexts.

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Current and future challenges in managing ecosystems are and will be heavily influenced by global change, including changes in climate, economic, and social constraints and settings (Puettmann, 2011). These changes are acting at unprecedented rates and are resulting in challenges that do not have an historical equivalent (Hobbs and Hiccs, 2013). Examples of these novel changes include ecological effects, such as increases in temperature and drought periods (Bonan, 2008; Allen et al., 2010) and in the amount and severity of disturbances (Dale et al., 2001). Also, more frequent travel and trade are increasing the likelihood of introduction of exotic species (Meyerson and Mooney, 2007; Puettmann, 2011). As the human population and consumption of resources per capita increase, new pressures for forests to provide more wood for energy and renewable materials as the basis of a "green economy" (Clapp and Dauvergne, 2008) will likely come into conflict with increased needs to provide other ecosystem goods and services, such as habitat for a large variety of organisms (many of which have current or future medicinal and other values), opportunities for recreational use, provision of water, and spiritual values. All these trends lead to the question of whether the scientific foundations of forest management and historical management practices as applied in the past are still suitable to address these "novel" challenges (Bosch et al., 2007; Seastedt et al., 2008; Puettmann et al., 2009; Bridgewater et al., 2011; Messier et al., 2015).

Our recent review of the history and practices of silviculture (Puettmann et al., 2009) suggested that the "efficiency paradigm" that provided the basis for the "agricultural model of forestry" may have to be revisited in light of these anticipated changes. We argue that ecosystems such as forests are prime examples of complex adaptive systems (CASs) and exhibit all of their key characteristics, including diversity, nonlinearity, emergence, self-organization, and cross-scale interactions (for more detailed descriptions of forests as CASs, see Levin et al., 2013; Messier et al., 2013; Filotas et al., 2014). Forests have a high degree of diversity among components, both structurally and genetically. These components interact with each other and their

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Abbreviations: CASs, complex adaptive systems; GIS, geographic information systems; GPS, global positioning systems; LiDAR, light detection and ranging.

environment. These interactions are local but can bridge temporal, spatial, and hierarchical scales, can be nonlinear, and include response delays and feedback loops.

These ecosystem components and interactions between components in forest ecosystems respond to changing conditions. Although general ecosystem behavior may be predictable (e.g., as expressed in succession theory), any specific behavior of the system is hard to predict because of the numerous components and interactions, feedback loops, outside influences, and nonlinear relationships (Messier et al., 2013). Consequently, uncertainty is considered an inherent characteristic of CASs and "surprises" are to be expected. Complexity science provides a scientific framework, conceptual models, and quantitative tools to deal with modeling and analyzing the complexity of natural systems such as forest ecosystems. Consequently, utilizing principles and concepts developed by complexity scientists appears to provide a great opportunity to develop new management approaches better suited to a novel, uncertain world (Parrott and Meyer, 2012; Messier et al., 2013), especially as they relate to managing the adaptive capacity of ecosystems (Puettmann, 2014). For background reading, a list of references that provide more detailed information about various topics associated with CASs is provided in Supplement 1.

Main Challenges in Viewing Forests as Complex Adaptive Systems

Viewing ecosystems as CAS is a particular challenge, not only for students who are introduced to ecology and natural resource management for the first time, but also (and maybe even more so) for experienced managers and scientists. For one, CASs do not lend themselves to simple rules and single dimensional measures (for more information about measuring complexity see Parrott, 2010). Many books and papers have been published to explain the concepts [key publications include Levin, 1999 (in Supplement 1) and Gunderson and Holling, 2002; for a more complete list, see Supplement 1]. Also, around the world, classes are taught to expose students to these concepts by using a variety of pedagogical approaches and often focused on governance or other social issues (for a list of examples, see Ban et al., 2015 and Casper et al., 2016). However, our attempts to teach these concepts to natural resource students suggested that there is a gap in teaching ecological topics in this context, especially as they can be applied to practical management decisions. We saw the need to provide basic and simple exercises that are field data based (case studies) and use these to help students, managers, and scientists understand how the concepts of complexity science can be used in making decisions about management actions in the real world. For foresters, this could include how to decide the number of trees and which specific trees to harvest in a forest stand.

In various classes, workshops, and informal settings, we have gained experience in teaching CAS theory for natural resource management applications, specifically for developing novel management prescriptions for stands or forests. It became obvious at the outset that teaching characteristics of CAS in relation to forest management is an enormous challenge on its own and likely will go beyond the scope of most typical natural resource management classes (Quinn et al., 2009). We found that graduate students are often very interested in topics such as uncertainty and adaptive capacity. Once exposed, all students appear to appreciate that such topics add another dimension to their education and see that aspects of complexity science are relevant to all kinds of topics covered in other classes. However, graduate students or professionals with a solid understanding of ecological or social aspects of forest management will likely get their most benefit from a class as outlined in Supplement 2. Instructors following our example exercises need to target the specific instructions to the educational background of their students and to other curriculum components, as well as to the management settings that students are most likely to experience after their education. How specific aspects of complexity science are actually implemented in the field will vary according to context. For example conservation organizations versus investment companies aimed at maximizing profits may articulate different choices of possible futures and vary in the relative importance assigned to different ecosystem services when evaluating futures.

To get the most out of the proposed class, students and professionals will need to understand the basic elements of complexity science and benefit from thorough discussions of the theoretical concepts (e.g., see background readings sorted by concepts in Supplement 1). Numerous classes cover basic aspects of complexity science (e.g., see the examples provided by Ban et al., 2015; http://www.complexityexplorer.org/, http://www.thegreatcourses.com/courses/understanding-complexity.html; see also http://www.complexity.ecs.soton.ac.uk/index.php?page=q5 for a list of web resources and the list of general books in Supplement 1. Many of these "general" classes (see also classes taught by the authors, such as http://www.cof.orst.edu/cof/fs/kpuettmann/group.htm, click on FES543) use a variety of teaching approaches (Ban et al., 2015) including lectures, discussions, project-based learning, and games. However, besides the use of case studies, we saw the need to develop a class that focuses on actual field data and experiential learning as primary teaching objects to "operationalize" complexity concepts, especially in an ecological context. This article aims at sharing our experiences and we hope to encourage more instructors to include management aspects into their pedagogical efforts and make these challenging, theoretical concepts accessible to practitioners (in the broadest sense, i.e., including students). We provide guidance and avenues to pursue for instructors interested in exploring these issues in classes and workshops. Our examples are focused on the linkage between theory and practical aspects of forestry (as this is our expertise) and we acknowledge that the class would benefit from addition of social science instructors and materials. Nevertheless, we found that students with ecological and social science interests and backgrounds all benefitted from exposure to the concepts. Also, the pedagogical approach and tools can easily be adapted to audiences in various natural resources fields, for example, agriculture and ecosystem restoration. Our exercises assume that the participants have already had some exposure to theoretical concepts. As evident from the exercises, our (the authors) expertise is focused on ecological and silvicultural aspects of forestry and we have less knowledge about the social components of forest management (for a broader treatise of governance in complex socio-ecological systems, see, for example, Levin et al., 2013; Boyd and Folke, 2011; Cumming, 2011; Armitage et al., 2007). In this context, when assigning students to study groups we found it beneficial to ensure a wide variety of interests and backgrounds in each group.

Pedagogical Approach and Material

In contrast to many traditional management challenges and objectives, managing CASs (by definition) does not lend itself to simple rules or firm prescriptions. For example, traditional forestry classes that are based on the "command and control" approach (Holling and Meffe, 1996) teach growth/growing stock relations, i.e., certain optimal tree density regimes that efficiently achieve desired tree quality and sizes or stand volumes. However, there is no optimal tree density, that we know of, that facilitates e.g., stand resilience and adaptive capacity. Thus, we found it more useful to familiarize students with a list of basic concepts underlying complexity science as they apply to forests and especially forest management decisions. The following discussion and exercises listed in Supplement 2 are examples and materials we used successfully to encourage this awareness. Our approach aims at utilizing this awareness for putting management decisions, such as the choice of planting or thinning densities, in a broader context. Thus, the decision framework is expanded beyond conventional information bases, such as growth-growing stock relations, to include the various aspects of complexity science. Again, given that there are no simple general rules describing specifically how complexity science influences management decisions, our goal is to provide students with a minimum of background understanding that will allow them to justify their management and treatment choices in this broader context. If successful, course participants would be able to explain how the new information (e.g., about thresholds and uncertainty or other information derived from the panarchy cycle) is reflected in management decisions such as the choice of residual densities after thinning. The panarchy cycle is a model that highlights the interplay between stability and adaptability and the importance of cross-scale interactions in understanding ecosystem dynamics (for more information, see Gunderson and Holling, 2002; http://www.resalliance.org/panarchy). Our exercises are focused on ecological aspects, but students also learn to assess the challenges of forest management decisions in a larger context. For example, we had very fruitful discussions about what would have to change, e.g., in terms of legal, marketing, or social conditions to facilitate a closer linkage between concepts from complexity science to management applications (see also Puettmann et al., 2015).

In terms of understanding forest structures and dynamics, a great deal has been accomplished in the last decades in ecosystem ecology (e.g., Chapin et al., 2011) without necessarily directly referring to concepts from complexity sciences. For example, most students and professionals have no problem viewing forests as dynamic, nor with accepting that interactions such as feedback loops can be nonlinear, that developments contain elements of uncertainty, or that forest ecosystems have emergent properties. However, viewing such concepts in the context of complexity science to find ways of applying them in real-world settings is much more difficult. Supplement 2 contains detailed exercises we have used in past teaching efforts to teach complexity theory to students and professionals working in forest and natural resource management. These experiential learning exercises are case studies, i.e., field data based and use a specific study forest to facilitate the linkage between theoretical understanding and management application. Because management prescriptions are typically developed for individual stands and because of logistical limitations, we typically assign individual (but separate) stands to each student group. However, information about the larger ecological, social, and economic setting is provided by us and outside experts and necessary for the exercises. A field trip with local forest managers, and perhaps other resource managers or members of the interested public, provides a good starting point and ensures students are exposed to the real-world problems and challenges related to the management of their study forests. The exercises are specifically designed sequentially to help students progressively gain confidence in the use and application of complexity theory and to address and link such theoretical concepts to field data and observations in the real management context. Our objectives are (1) to help students think about how to "operationalize" many of these concepts, which may involve applying or modifying current forest management practices, rules, and regulations to account for systems properties; (2) to devise completely new management approaches; and/or (3) to highlight the limitations (social, legal, and marketing, as well as ecological or logistic) that prevent managers from using complex systems concepts in their decision making. To make it as lifelike as possible, student groups were assigned separate stands, typically about 10 hectares in size, from real managed forests. Groups used the real-world conditions, e.g., soil conditions, road access, distance to mills, and so forth in their exercises. On occasion, we changed the ownership setting (e.g., rather than a university research forest, we assumed the land was privately owned). The following discussion describes four key properties that we have found to be very challenging for students (and us) to apply to forest management, and which are addressed sequentially as learning outcomes by the four exercises. These exercises are all focused on the stands assigned to the student groups.

Learning Outcome 1: Students will be able to describe ecosystem structures and interactions, with a special emphasis on thresholds, nonlinearity, and feedback loops.

A great deal of effort has been spent on inventorying forests and on understanding interactions such as food-chains, trophic networks, and other cross-scale interactions, including feedback loops and emergent properties (Perry et al., 2008; Chapin et al., 2011). We also use an inventory-based approach to help students become familiar with the study forests. In addition to obtaining information currently used in forest planning and prescription development (e.g., ownership objectives, legal constraints, stand density, structure and composition, prices, and harvesting costs) we developed an expanded inventory and thus a broader definition of the system of interest (Sandri, 2013) by focusing on complexity concepts relevant in a management context. We have students put together a formal inventory of major drivers, interactions, thresholds, and variables that drive thresholds, etc., with a special emphasis on describing feedback loops. After the inventory, students are challenged to put all these aspects into a coherent, conceptual model that describes their basic understanding of ecosystem dynamics (for more detail, see Exercise 1 in Supplement 2).

In general, students with experience in ecosystem ecology had no problem developing a basic list of ecosystem components, including their interactions and feedback loops. The assessment of thresholds and variables that influence such thresholds typically led to insightful discussions that highlighted the need to include social and economic variables into an ecosystem assessment. This phase showed the benefits of having groups composed of students with different backgrounds (e.g., social, economic, and ecological sciences). Similarly, the discussion about potential external "shocks" to the ecosystem and control mechanisms were very stimulating (see Exercise 1, Table 1, in Supplement 2). Typically, groups could not come to an agreement on these topics. As instructors, we did not push the group to find an agreement. Instead, we presented our view that these discussion and associated results were an indicator of the benefits of "bottom-up" thinking and that the diversity in opinions were a valuable asset when dealing with uncertainty (e.g., Exercise 3).

Learning Outcome 2: Students will be able to assess and overcome impacts of cross-scale interactions, scale-misfits, and scale hierarchies on forest dynamics over scales of space and time.

Forest planning covers a variety of scales, from regional or ownership levels to local conditions, e.g., patches for regeneration. However, traditionally stand and rotation ages or inventory cycles receive the most emphasis in development silvicultural prescriptions (Puettmann et al., 2009). Organizing forests into stands as workable units makes a lot of sense for inventory and planning purposes (O'Hara and Nagel, 2013) if the management outcome scales up linearly from stand ownerships or landscapes (or timber supply areas or management units), such as for carbon storage, timber production, and harvest levels (Leslie, 1966). Scaling up to landscape levels is more challenging when addressing other management outcomes that do not scale linearly, e.g., visual quality, plant and animal diversity, and provision of wildlife habitat (Wilson and Puettmann, 2007). Similarly, planning for the (optimal) rotation age ignores short-term (e.g., new sawmill technology) and longer-term (e.g., climate change) trends that may influence management decisions and outcomes. Understanding the importance of scales in interpreting vegetation patterns has been a longstanding issue in ecology (Levin, 1992) and forest management (O'Hara and Nagel, 2013; Puettmann and Tappeiner, 2014). New technologies, such as geographic information systems (GIS), global positioning systems (GPS), satellite imagery, light detection and ranging (LiDAR), or even the availability of free and fairly powerful mapping and satellite imagery viewing services (e.g., Google Earth) make it easier to bridge stand boundaries in the field, but the basic challenge of dealing with planning across spatial and temporal scales remains. Our proposed exercise challenges students to inventory the multitude of social and ecological factors and associated spatial and temporal scales and decide how they influence forest management decisions and outcomes. Students are first asked to organize these factors into a scale hierarchy. Next, they pair up these factors in terms of their relevant scales and assess whether the management scales match the pertinent social or ecological scales. The ensuing discussion encourages students to think of ecosystems in terms of a multitude of scales, the likelihood that cross-scale interactions can be addressed, and—most interesting—what can be done to deal with "scale-misfits" (for more detail, see Exercise 2 in Supplement 2).

Students utilized the results from Exercise 1 as a starting point and broadened the list of factors to include social and economic aspects. Even more so than in Exercise 1, we saw that students really benefited from a diversity of group members. As instructors, we really enjoyed when students recognized how focused their individual fields were in terms of spatial and temporal scales, and how this focus limited their views and understanding of forest ecosystems. The discussion of how to overcome scale misfits led to the recognition that many critical factors are not likely to change to accommodate natural resource management, e.g., the 4-year election cycle and state boundaries that influence the temporal and spatial scales, respectively, of many political decisions. Instead, the discussion quickly focused on a "one-sided" approach, i.e., what natural resource managers can do in this context. Examples of such activities included shifting the planning cycle from the standard 5 years to align with and match the 4-year election cycles. Students also agreed that changing the spatial dimensions of management prescriptions and assessments from a focus on the stand level to lower and higher spatial levels had the most potential benefits for several reasons. First, natural resource agencies or landowners have control over the planning procedures. Second, including smaller spatial scales allows managers to take advantage of, for example, neighborhood scale differences in soil or vegetation conditions and avoid costs of homogenizing stands, such as through replanting spots where seedlings had died. Third, assessing success at larger spatial scales allows natural resource managers to accommodate variability of treatment successes, to a certain extent.

Learning Outcome 3: Students will be able to integrate inherent uncertainty of social-ecological systems into forecasting and prediction procedures.

One topic of general agreement in terms of global change is the expectation of increased variability and uncertainty in the future (Lindley, 2006; Puettmann, 2011). Uncertain future environmental conditions paired with an unknown future social, political, and economic context suggest that forest management and planning should seek to accommodate a broad range of possible future scenarios. Uncertainty arising from within the system (e.g., emergence, stochastic, and nonlinear dynamics) combined with these uncertain external drivers affects our ability to plan our future management and the degree to which we can actually do anything at the scale of a single forest management unit. For one, the global climate change predictions derived from Global Circulation Models and expectations of species introductions, market preferences, and environmental policies are subject to uncertainties. How these predictions will play out on a local scale is also subject to controversy (e.g., Daly et al., 2010). Furthermore, questions exist about the response of ecosystems to these changes and even the response of ecosystems to standard management practices under altered conditions, e.g., in a different climate or in presence of new species or diseases.

Our approach is to make students aware of the suite of assumptions, particularly those about the future, that underlie any plan. To accomplish this we have students go through a scenario planning exercise (Peterson et al., 2003; Biggs et al., 2010). Thus, rather than developing plans founded on predictions that are based on current conditions or on assumptions about the "most likely" future conditions, students are encouraged to acknowledge uncertainty and integrate it up front into the planning process. This is accomplished by having the students develop a set of scenarios of how futures may unfold (Chermack, 2011). These scenarios may vary in terms of ecological conditions (e.g., with and without invasive exotic species, with or without climate change) and in terms of social or economic conditions (e.g., with or without an increased emphasis on using wood in a green economy, with or without public concerns about ecological impacts of intensive forestry operations). It is important to stress here that the choice of future scenarios should not be biased by what is most likely or most desirable. Instead, students are encouraged to choose scenarios that provide the most opportunities to learn about uncertainties, which pushes scenarios to be more "extreme." This allows students to separate probable, possible, and plausible futures for a forest. The goal is to evaluate whether planned management activities maintain forest productivity and adaptive capacity over as wide a range of possible future scenarios as possible. Thus, any management plan students develop will be assessed in the context of all chosen future scenarios. The aim is to highlight how uncertainties could play out, which assumptions about the future are critical in this context, and thus stimulate thinking about potential problems and opportunities so as to broaden the perspective of students (for more detail, see Exercise 3 in Supplement 2).

This exercise was typically the most fun for students. Here, they really showed their creativity, e.g., in terms of what could go "wrong" in the future. Sometimes this made it tough for us instructors to decide where to set boundaries without squashing student enthusiasm, e.g., how much can be learned by assessing natural resource management decisions in a future with "total anarchy." Comparing the students' management prescriptions under multiple futures often proved one of the highlights of the class. In several cases, it turned out that a group's management prescription only performed well under one of the four possible futures, typically the business-as-usual scenario. As instructors, we found such "aha moments" very satisfying. Also, during our review at the end of class, the students acknowledged that this finding was one of the eye-opening events in their academic careers.

Learning Outcome 4: Students will be able to integrate information from the three previous learning outcomes and work with an ecosystem model that is composed of dynamic, ever-changing components and interactions and does not follow linear successional pathways.

Past and current conceptual models of forest ecosystem dynamics have relied heavily on theories of succession and stand dynamics (Oliver and Larson, 1996). These theories rely on concepts of stability and predictable vegetation development, with disturbances as external forces that set back the developmental process (Haeussler et al., 2013). In the context of complexity, we have found some aspects of the panarchy cycle more insightful when viewing vegetation development of ecosystems as CAS (Gunderson and Holling, 2002). As a fundamental difference to the traditional stand dynamics model, the panarchy model assumes that disturbances and subsequent reassembly periods are most influential in determining the suite of mechanisms and options ecosystems can use to adapt to new environmental conditions. The successional and stand dynamic phases then filter out which mechanisms and patterns actually play out in specific conditions. The panarchy model thus views ecosystem dynamics as an interplay between constructive (disturbances and reassembly that increase novelty and the diversity of potential development options) and destructive (successional and stand dynamic phases that decrease novelty and the list of potential developmental options) phases. Using information about ecosystem structure (from Exercise 1) and viewing ecosystems as a hierarchical or nested set of panarchy cycles (at least one scale above and one scale below the scale of interest; from Exercise 2) will then provide insights about whether a disturbance will only affect local, short-term conditions, or whether a disturbance has the potential to lead to a larger, long-term shift in the landscape (Drever et al., 2006). The last exercise in our class concludes with development of a nested set of panarchy cycles for the study ecosystem. It aims to utilize the different aspects of the panarchy cycle and the importance of cross-scale hierarchies and uncertainties to lead the students to a broader understanding of vegetation dynamics as an expanded basis for development of management prescriptions (for more detail, see Exercise 4 in Supplement 2).

As expected (and designed), this was the most challenging exercise in the class. We typically found that students initially struggled, making us concerned about the lack of progress after the first few hours. During this time the student groups greatly benefited from interactions with instructors and each other. Early discussions typically bounced between the forest conditions (e.g., as described in Exercises 1, 2, and 3) and a basic understanding of the panarchy concept. However, after a while we saw students reach a threshold and we saw a lot of enthusiasms and progresses. Students especially found the visual display of their nested panarchy models stimulating and insightful. The amount of details in this display and the associated understanding of the model varied as a function of student's backgrounds, e.g., groups that contained students with a quantitative modeling background really went into depth.

As highlighted above, the diversity in student's interests and backgrounds was a crucial element in the group learning environment. To make sure all students could learn from the diversity of approaches taken by their peers, each exercise ended with presentation by all groups to the class and subsequent discussions. Based on class feedback, students found this to be one of the most valuable experiences in class. First, it highlighted to them that their struggles within a group were not a sign of failure, but an indication of the challenging nature of natural resource problems. Second, they learned that there is no simple, single, or obvious solution and groups with apparently minor differences in student's backgrounds and interests could come to different conclusions. Third, viewing the combined results of the various groups gave them an appreciation of the value of managing across scales (student– group–class). Fourth, they found that repeated feedback throughout the class helped them to maintain a broader, analytical view when approaching the next exercise. Fifth, students found that the group presentations left them with a feeling of success, as the constructive discussions left them with a feeling that they had achieved a basic understanding of the topics and succeeded in completing the exercise. Last, students who have taken the course describe how challenging and difficult it was to learn to work in an interdisciplinary group and to tackle problems that required them to stretch the limits of their own understanding of forest systems. In the final debriefing, students recognized the value of being "forced" to participate in such an experience and acknowledge that the skills acquired will be invaluable to their future careers.

Evaluating student performance in a course like this can be done in many ways. In our case, for each of the exercises we typically used four criteria to assess and grade the performance of each group: (1) Quality of the analysis (40%); (2) Demonstrated understanding of CAS concepts related to the exercise's learning outcomes (40%); (3) Creativity (10%); and (4) Quality of the oral presentation (10%). Typically, student groups performed very well in the analysis (#1). The second part (#2: understanding of concepts) showed that students need prior exposure to these concepts to be able to apply them in a field setting. Our general conclusion was that some groups may struggle initially to establish a successful and productive approach to working together and to understand that there are no correct answers. However, once these hurdles have been crossed, all groups do well and succeed in completing the exercises in creative and insightful ways.

CONCLUSION

Any advancement in our understanding of scientific concepts provides unique challenges. Understanding complexity science as a basis for forest management is no exception. Here we share our experience with teaching complexity science to graduate students in forest and natural resource management. We propose a set of exercises we developed over time to assist students and professionals in viewing forests as CAS, allowing them to integrate findings from this expanded view into specific management decisions. In our classes, we have had success in exposing students to key characteristics of complexity science and their impacts on ecosystem behavior and our ability to make predictions. Making students and professionals aware of how these concepts play out in specific forests and management settings will provide an "entry" into complexity science. More importantly, we believe that increasing understanding and sensitivity to these issues is a prerequisite for developing more informed prescriptions under increasing global changes.

Specifically, the set of exercises we have developed guides students stepwise into the topic and helps them overcome key challenges of managing forests in the context of an uncertain future. They are set up as a sequence that culminates in the development of a conceptual model that addresses the dynamic, multi-scale, and nonlinear nature of ecosystem behavior while recognizing the high level of uncertainty and unpredictability of specific components. Instructors will need to assess how these exercises fit their students' backgrounds and interests and their study ecosystems. We found that groups composed of students from a wide variety of backgrounds worked best, as they were able to better address the diversity of topics that needs to be considered. A logical next step for instructors is to decide whether and how the exercises need to be modified to best fit specific educational needs and programs. Obviously, students benefit from previous exposure to the basic concepts of complexity science before undertaking these exercises. Some pre-readings (a suggested list is included in Supplement 1) with an initial discussion of the theory may be the minimum expectation. After going through the exercises and collecting the information, students learn key issues and can develop prescriptions for stands or forests that consider the main characteristics of DAS.

In conclusion, we propose that managing ecosystems based on concepts derived from complexity science provides opportunities to see forests and forest management differently than typically done (e.g., Messier et al., 2013; Filotas et al., 2014). Exposing natural resource students and managers to these concepts is an essential step in operationalizing these concepts and changing dominant paradigms of ecosystem management. The proposed exercises will sensitize students and professionals to issues and factors that are important in ecosystem behavior and contribute new and unique insights into our understanding of ecosystems. In our opinion, preparing current and future professionals to integrate these aspects into prescriptions will improve our ability to sustainably provide desired ecosystem goods and services in an uncertain and rapidly changing future. We hope that readers see opportunities to benefit from our experience in teaching these topics and—after modifications to match their specific settings—be able to utilize the exercises in their instructional activities.

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