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Scaling issues in forest ecosystem management and how to address them with models

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Abstract:	Scaling is widely recognized as a central issue in ecology. The associated cross-scale interactions and process transmutations make scaling (i.e., a change in spatial or temporal grain and extent) an important issue in understanding ecosystem structure and functioning. Moreover, current concepts of ecosystem stewardship, such as sustainability and resilience, are inherently scale-dependent. The importance of scale and scaling in the context of forest management is likely to further increase in the future because of the growing relevance of ecosystem services beyond timber production. As a result, a consideration of processes both below (e.g., leaf-level carbon uptake in the context of climate change mitigation) and above (e.g., managing for biodiversity conservation at the landscape scale) the traditional focus on the stand level is required in forest ecosystem management. Furthermore, climate change will affect a variety of ecosystem processes across scales, ranging from photosynthesis (tree organs) to disturbance regimes (landscape scale). Assessing potential climate change impacts on ecosystem services thus requires a multi-scale perspective. However, scaling issues have received comparatively little attention in the forest management community to date. Our objectives here are thus first, to synthesize scaling issues relevant to forest management, and second, to elucidate ways of dealing with such complex scaling problems by highlighting examples of how they can be addressed with ecosystem models. We have focused on three current management issues of particular importance in European forestry: (i) climate change mitigation through carbon sequestration, (ii) multi-functional stand management for biodiversity

	and non-timber goods and services, and (iii) improving the resilience to natural disturbances. We conclude that taking into account the full spatio-temporal heterogeneity and dynamics of forest ecosystems in management decision making is likely to make management more robust to increasing environmental and societal pressures. Models can aid this process through explicitly accounting for system dynamics and changing conditions, operationally addressing the complexity of cross-scale interactions and emerging properties. Our synthesis indicates that increased attention to scaling issues can help forest managers to integrate traditional management objectives with emerging concerns for ecosystem services, and therefore deserves more attention in forestry.

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Vienna, 2013-05-29

Revised manuscript EJFOR-D-12-00195

Dear Prof. Berger, dear Prof. Pretzsch,

please find attached the revised version of our manuscript " Scaling issues in forest ecosystem management and how to address them with models" (EJFOR-D-12-00195).

We have now thoroughly revised the manuscript following the suggestions of the handling Editor and the two Reviewers, and find that this revision has considerably improved the manuscript over the original submission. In particular, in line with the suggestions from the Reviewers and Editor we have

- clarified and sharpened our objectives with the paper,
- included additional literature and improved the part of the paper explaining scaling theory by means of examples,
- added to a better visibility of the overarching concept guiding us in the selection and synthesis of the examples presented in the second part of the paper, and
- revised and simplified the language throughout the text.

A complete list of changes including our responses to the issues raised by the Reviewers and Editor is attached to this letter.

We hope that the revised manuscript now meets the standards of your journal, and look forward to hearing from you soon.

Best regards,

Editor

[…] I also share the impression of the 1st reviewer who complains that the analysis remains superficial and that the quality of the manuscript still has to be improved. While reading the paper, I have the impression, that many things about emergence, scaling up and down, and the resilience of complex ecological systems have been said earlier and better. These issues are hardly debated among ecologists dealing with individual-based models, which are very similar to the single-tree models applied in forest sciences.

Response: We agree with the editor that many of the things addressed in the manuscript have been said before, and are widely accepted in the ecology community. However, we also observe that the mainstreaming of these ecological advances in the forestry community is still lacking behind considerably (see the analysis of Puettmann et al. 2009, Island Press). Furthermore, while issues of scaling are well recognized in the ecological modeling community we find that many traditional forest modeling approaches - still widely in use today - fall short on such considerations. Our aim here is not to advance ecological scaling theory, but rather to present an entry-point into scaling issues for forest managers and modelers. We have revised and sharpened the introduction and objectives in this regard, and have added sentences (at lines 70-73 and 107-110 - all line numbers pertaining to the new, revised version of the manuscript) in order to make the aim and direction of the paper more clear. Scale and scaling are increasingly important for forest managers in order to sustainably provide a growing number of ecosystem services. As such, we believe this manuscript will be a timely contribution to the literature. Furthermore, as the European Journal of Forest Research is a leading journal in the field of forestry and forest management it would be good fit for efficiently reaching the target audience of such a paper.

In order to improve the manuscript to hand, I thus recommend a comprehensive survey of this literature. Some examples:

1) Reuter et al. (2005) The concepts of emergent and collective properties in individual-based models—Summary and outlook of the Bornhöved case studies. Ecological Modelling 186: 489-501.

http://dx.doi.org/10.1016/j.ecolmodel.2005.02.014

2) Breckling et al. (2006) Individual-based models as tools for ecological theory and application: Understanding the emergence of organisational properties in ecological systems. Ecological Modelling 194: 102-113. http://dx.doi.org/10.1016/j.ecolmodel.2005.10.005

3) Grimm and Wissel (1997) Babel, or the ecological stability discussions: an inventory and analysis of terminology and a guide for avoiding confusion
http ://dx.doi.org/10.1007/s004420050090

Response: We thank the editor for pointing us towards additional important literature, which we have now included in the manuscript. In addition to bolstering the general scaling literature covered in the manuscript (e.g., via the inclusion of the recent synthesis by Chave (2013) in Ecology Letters) we have also included further literature on concepts addressed in the manuscript (e.g., Rauscher et al. (2000), Computers and Electronics in Agriculture; Tierney et al. (2009), Ecology Letters). Furthermore, we have also included (more topical) examples on scaling issues in line with the suggestions of the reviewers (e.g., Anderegg et al. (2013), Global Change Biology, McDowell et al. (2008) New Phytologist, Medlyn et al. (2003), Functional Plant Biology, Landsberg and Waring (1997), Forest Ecology and Management). In total we have included additional 16 references in the revised manuscript. In reference to the (now sharpened) objectives of the paper we would point out that a comprehensive review on the ecological scaling literature was not the scope of this manuscript. We in section 2 rather highlight and discuss selected theoretical scaling issues by means of examples, which are of importance in the management examples discussed in section 3 of the paper. This is now also more clearly stated in the objectives (lines 112-114) in order to avoid any confusion for the reader.

Reviewer #1

The conclusions are weak, and the reasoning to some extent appears circular.

Response: We have now revised and combined the discussion and conclusion section to shorten the manuscript (see comments of Reviewer #2 below). This allowed us to provide more context to the conclusions we reached in our analysis, increased the clarity of our argumentation (as the new combined section features 4+3 bullet points), and reduced redundancy with what has been said previously in the manuscript.

The language is somewhat verbose

Response: The manuscript language has been revised with a view to an easier style of writing.

The link to modelling appears logical, but is not sufficiently explained: models are tools to analyse certain issues, based on some conceptual approach. The latter is not made sufficiently clear.

Response: We have revised the manuscript in this regard and have clarified the link to modeling. We stress that models translate conceptual approaches about ecosystem functioning and structure into formal computer code that can then be used to explicitly study the effect of drivers and behavior (see lines 93-100).

In general, there appears to be an overemphasis on modelling, which is understandable given the background of the authors, but the emphasis should be on the concepts rather than on the techniques used to quantify these concepts. As one of the objectives is to synthesize how simulation modelling can inform management with regard to scaling issues, this really needs clarification. The use of simulation to inform management is a complex issue that is dealt with superficially in the paper.

Response: We'd like to stress that the emphasis on modeling is intentional, which is reflected in the title, abstract, and objectives of the manuscript. We find that in order to address scaling issues in forest management models are powerful tools. Rather than focusing solely on discussing scaling issues we aim at presenting tools and ways forward to potentially resolve such issues, and have thus made examples from simulation studies an integral part of our manuscript. In the revision of the manuscript we have consequently refrained from de-emphasizing modeling, not least because the comments of the Editor suggest to actually *extend* the modeling literature covered in the manuscript. We, however, tried to sharpen the different strengths of different modeling concepts in the text, following the suggestion of the reviewer. With regard to synthesizing the role of models, we'd like to stress that we here aim not at the role of models in forest management in general, as we agree with the reviewer that this is a complex issue and many good analyses exist in this regard (e.g., Pretzsch et al. 2008, Ann. Bot., Wolfslehner and Seidl 2010, Environ. Manage.). We rather aim at synthesizing this role particularly with regard to scaling issues, and section 4.2 is an attempt to providing such a synthesis.

The examples in the paper are useful, but the unifying concept is not clear.

Response: We have revised the manuscript in order to make the underlying concept and structure of our analysis more clear. In order to do so we have added a paragraph leading into the examples section (lines 226-232). Furthermore, we have included a new table (Table 1) showing how the scaling issues addressed in the examples relate to the general stages of forest management planning.

line 117, page 5: what is meant by "the naieve view of scale", does this refer to Urban et al (1987)?

Response: We've revised the sentence (omitting the term "the naive view") in order to clarify our point here.

line 124, page 5: the rope analogy does not require figure 1 which appears a bit trivial. Also, I find the rope analogy somewhat trivial: what about fractals, networks, or even strings? The example of the rope can be shortened, while the conceptual description might be expanded with other analogies

Response: As suggested by the Reviewer we have removed Figure 1 from the revised manuscript. Also, we have replaced the rope analogy with (more topical) ecological examples for theoretical scaling issues in three instances, explaining the concepts of transmutation (lines 160-166), Jensens inequality (lines 199-203), and cascading effects across hierarchies (lines 204-210). However, in order to keep the paper concise (see Reviewer #2) we have refrained from adding a discussion on fractals, networks and strings to section 2.

line 140 and onwards, page 6: non-linearity should be discussed in more detail; here I would also expect a discussion on scaling in relation to resource availability (notably diffuse vs. directional availability - say CO2 vs. light) and gradients in resource availability across a landscape

Response: We have added a remark on the directionality of the resource gradient in order to make the underlying process of the non-linear scaling function more clear (line 157). Also, we have expanded the discussion on the effects of nonlinearity in the revised manuscript, and now given a concrete example of its effects in the context of temporal scaling (lines 161-166).

line 187, page 7: feedbacks leading to cascading effects across the hierarchy, exerting constraints to lower levels. Intuitively, I have an idea about what is meant here, but can this be clarified? This is too much handwaving to me. Incidentally, rather than the example of rope breakdown, one could use the example of runaway cavitation, which I would find more convincing that the trivial rope analogy.

Response: We have revised the section, substituting the suggested example of cavitation fatigue during drought stress for the rope analogy (lines 204-210).

line 208, page 8: I have difficulty with the casual mention of sustainability and sustainable stewardship of forest ecosystems. What is meant here, and do you really need this for your line of reasoning? Is scaling only relevant for sustainable management, and not for management that does not specifically aim for sustainability? Is amount of stem wood an important ecological indicator for sustainability? Or do you mean volume growth as a proxy for productivity?

Response: We have revised the sentence, and have added more context and two reference in lines 321 and 326 in order to clarify our point.

line 226, page 9: yield tables are not designed to predict forest growth over time, they merely describe forest growth over time based on empirical data.

Response: We have reworded the sentence as suggested by the reviewer.

line 232, page 9: which are the information needs of managing for climate change mitigation?

Response: We have added a sentence further specifying what the most important shortcoming of such approaches are in the context of climate change mitigation.

line 239, page 9, line 245, page 10: explain what is meant by BGC

Response: Done. ‘BGC’ in brackets placed after the word ‘biogeochemical’ in line 268.

line 278, page 11, last para: are there other sampling schemes that might capture landscape heterogeneity? What is the role of stratification?

Response: The points we make regarding data aggregation apply regardless of sampling schemes or stratification. We've added a sentence to that effect in line 306-307.

line 312, page 12: why is multi-purpose forestry a paradigm? and why does the paradigm require the consideration of various constraints? Why not simply focus on multi-purpose forestry?

Response: We have omitted the term paradigm in the revised version of the manuscript.

line 330, page 13: what do you mean by "a top-down target corridor for stand-level management, fostering a routine evaluation of stand-level management decisions in the context of biodiversity conservation". These are truly terrible sentences, made to impress not to clarify.

Response: We have simplified this particular sentence and have tried to clarify the language throughout the manuscript.

lines 373-375, page 14: what exactly is stated here? Again, the sentence is impressive but not very clear.

Response: We have simplified the sentence and clarified our statement.

line 380, page 14: what is meant by ecological integrity?

Response: Reference to the concept of ecological integrity added (Tierney et al. 2009, line 409).

line 562-570, page 21: the conclusions are not very convincing, and essentially only state the importance of modelling to quantify scaling issues. Could the concluding section be expanded by bulleting the main issues and the scaling aspects once more? Can you distinguish between scaling issues in space vs. scaling in time? Now the conclusions appear somewhat trivial, partly repeating assumptions from the introduction. What is the outcome of model applications for forest management?

Response: As mentioned already above, we have revised and combined the discussion and conclusions section in order to improve clarity and increase content depth in the final section of the manuscript (while keeping the manuscript as concise as possible, re Reviewer #2). As suggested by the Reviewer, the section includes 4+3 bullet points in order to make the main findings of our analysis more visible.

Reviewer #2

The manuscript topic is limited to spatial and time scales (and don't include hierarchical scales). The authors should clarify this early in the manuscript.

Response: We now explicitly refer to scaling in space and time in the statement of our objectives of the paper (line 105). We also mention temporal and spatial scales explicitly in the definition of scaling adopted in the manuscript (line 83).

"Transmutation" should be defined.

Response: We have revised our definition of scaling and have added a sentence and reference explaining the term "transmutation" (lines 84-85). We have also included a practical example from forest ecosystems for a process transmutation across scales (lines 160-166).

The paper is lengthy, but I can see that any shortening of the text will be at the expense of clarity. Maybe this is an option to shorten the manuscript: I appreciate the need to clarify basic concepts and the "rope" provides a nice example. However, if the manuscript needs to be shortened, this section could be placed in a supplement/appendix and a shortened version be used in the text.

Response: We have revised section 2 also according to the suggestions of the Editor and Reviewer #1, and have removed Figure 1 (the rope figure) in order to streamline the paper. In addition, we have shortened and streamlined the Discussion and Conclusion sections in line with the suggestions of Reviewer #1. However, we refrained from a substantial shortening of section 2, not least because the Editor has actually asked for an extension of this (more theoretical) review section of the paper.

The manuscript contains many (over-)long sentences that should be split into two or more sentences. […] In many cases, these are examples of sentences that will benefit from being split (see comment above).

Response: The manuscript language has been revised with a view to an easier style of writing.

In the literature list: The name "Loeffler" is spelled in two different ways (in the two Lischke et al. references).

Response: This is now corrected, consistently using the German Umlaut ö.

Keane et al. 2009 (line 324) is not in the reference list. There may be others, but after one omission, I stop checking, but encourage the authors to do so.

Response: We have added the particular reference, and have once more cross-checked and homogenized the entire reference list with the citations in the text.

"for instance" should have a comma before and after it if used in the middle of a sentence.

Response: OK.

Some colloquial phrases (e.g., we can say that"; line 172) and value statement (e.g., "naïve") should be avoided (e.g., not all assumptions of linearity are naïve).

Response: We have omitted these statements in the revised manuscript.

Scaling issues in forest ecosystem management and how to address them with models

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Abstract

Scaling is widely recognized as a central issue in ecology. The associated cross-scale interactions and process transmutations make scaling (i.e., a change in spatial or temporal grain and extent) an important issue in understanding ecosystem structure and functioning. Moreover, current concepts of ecosystem stewardship, such as sustainability and resilience, are inherently scale-dependent. The importance of scale and scaling in the context of forest management is likely to further increase in the future because of the growing relevance of ecosystem services beyond timber production. As a result, a consideration of processes both below (e.g., leaf-level carbon uptake in the context of climate change mitigation) and above (e.g., managing for biodiversity conservation at the landscape scale) the traditional focus on the stand level is required in forest ecosystem management. Furthermore, climate change will affect a variety of ecosystem processes across scales, ranging from photosynthesis (tree organs) to disturbance regimes (landscape scale). Assessing potential climate change impacts on ecosystem services thus requires a multi-scale perspective. However, scaling issues have received comparatively little attention in the forest management community to date. Our objectives here are thus first, to synthesize scaling issues relevant to forest management, and second, to elucidate ways of dealing with such complex scaling problems by highlighting examples of how they can be addressed with ecosystem models. We have focused on three current management issues of particular importance in European forestry: (i) climate change mitigation through carbon sequestration, (ii) multi-functional stand management for biodiversity and non-timber goods and services, and (iii) improving the resilience to natural disturbances. We conclude that taking into account the full spatio-temporal heterogeneity and dynamics of forest ecosystems in management decision making is likely to make management more robust to increasing environmental and societal pressures. Models can aid this process through explicitly accounting for system dynamics and changing conditions, operationally addressing the complexity of cross-scale interactions and emerging properties. Our synthesis indicates that increased attention to scaling issues can help forest managers to integrate traditional management objectives with emerging concerns for ecosystem services, and therefore deserves more attention in forestry.

Key words: scale, scaling, ecosystem modelling, sustainable forest management, multi-scale approach, emergence

1 Introduction

Sustainably providing ecosystem services to society and fostering resilience to changing environmental conditions are central aspects of current forest ecosystem management. Both sustainability and resilience are by their very nature multi-scale concepts (see Forest Europe, UNECE, and FAO 2011). Ecosystem services linked to the utilization of forest biomass, for instance, depend on the tree- to stand-level extraction of resources. This extraction, however, is only sustainable at the landscape scale, where patches in different stages of stand development ensure the continuous supply of such services to society and maintain the integrity of ecosystem functions. Likewise, climatic changes affect ecosystem processes from the level of tree organs (photosynthesis) to the landscape level (disturbances), which makes considering their impacts on ecosystems and managing for increased resilience a multi-scale endeavour (Lindner et al. 2010). Issues of scale are thus central to sustainable forest ecosystem management (Hobbs 2003; Walker et al. 2004). Widely used concepts in forest management such as the "Normalwald" model of equally distributed age-classes over a management unit, or the mean tree model where a tree of average proportions represents a forest stand, implicitly apply (at times simplistic) scaling assumptions. However, recent developments in ecological scaling theory have not yet been made operational by the forestry community (Puettmann et al. 2009). This paper is an effort to redress that lack, and bring an appreciation of scaling issues to the researchers, model developers and forest practitioners responsible for sustainable forest management.

Theoretical and applied ecologists have long recognized scaling as a crucial issue in ecology. In fact, scaling has been proposed as *the* central problem in ecology, unifying population ecology and ecosystem ecology (Levin 1992). The observed variability in a system is conditional on the scale of observation (Wiens 1989), and predictability often increases when moving from individual cases to collectives. Scale is thus fundamental to all ecological inquiry (e.g., Osmond et al. 2004). Scaling of key ecosystem processes such as the metabolic rate (Enquist et al. 2003) or the frequency – size distribution of disturbance (Moritz et al. 2005) have received much attention in ecological research recently, and are even proposed to be the underlying “laws” of ecosystem structure and functioning (West et al. 2009). For the purpose of this paper we define scaling as a change in grain and/or extent with regard to the temporal and/or spatial representation of the system (see O'Neill 1989). Associated with such changes are issues of cross-scale interactions and transmutations (i.e., changes in processes or functions as one moves from one level of scale to another (Bissonette 1997)). In simpler terms, scaling is concerned with changing the viewpoint of observation (close range or long) and the effects thereof (e.g., on understanding and predicting ecosystems and their services to society).

As a result of the variability in space and time and the non-linear interactions between processes across scales such a scaling of ecosystem properties is not trivial (Green and Sadedin 2005). An approach frequently applied to deal with these complexities is simulation modelling. Simulation models are vehicles for scaling and extrapolation, and a wide variety of approaches have been developed to address scaling in forest ecosystems (Bugmann et al. 2000; Urban 2005, Lischke et al. 2007). They translate our conceptual understanding about ecosystem functioning and structure into formal computer code, allowing for a quantitative analysis of its drivers and behaviour. For example, simulation models can be used as diagnostic tools to attribute the influence of processes acting at different scales on ecosystem development (e.g., Seidl et al. 2012a). They can give insight into how short-term variation in environmental drivers scale to long-term ecosystem behaviour (e.g., Sierra et al. 2009). They are furthermore powerful tools for making predictions about how trajectories of complex systems emerge from the multi-scale interactions of adaptive agents and their environment (e.g., Smithwick et al. 2003, Breckling et al. 2006). Although such simulation models have been predominately developed for research purposes, they are increasingly applied in the context of forest management planning and decision support (Wolfslehner and Seidl 2010). Models thus offer considerable potential with regard to a more explicit consideration of scaling issues in forest management; potential that has, however, as yet only been exploited to a limited extent.

Focusing on scaling in space and time our specific objectives in this contribution are (i) to highlight scaling issues of importance for managing forest ecosystems, and (ii) to synthesize how simulation modelling can inform management with regard to such issues. Rather than advancing ecological scaling theory our goal here is to present a synthesis and entry point for forest managers and modellers into concepts of scaling. We aim at raising awareness of the importance of scaling issues for current problems of forest ecosystem management. To that end we first describe selected theoretical aspects of scaling in forest ecosystems (e.g., emergence) by means of examples (section 2). Our aim in this section is not to provide a comprehensive synthesis of the broad literature on scaling theory in ecology (for a recent synthesis on theoretical aspects of scaling we refer to Chave 2013), but rather to set the stage for discussing particular scaling issues in forest management in section 3. The latter section also includes results from simulation exercises, giving examples of how models have been successfully used to address scaling. We conclude with a discussion and synthesis across individual issues (section 4), highlighting why scaling should play a (more) prominent role in forest ecosystem management, and what can be learned from models in this regard.

2 Scaling in forest ecosystems- a short primer by means of examples

Ecosystems are often viewed in terms of being hierarchies, in the sense that the elements of the system at a particular level contain elements below or smaller than themselves, and are contained within the elements above them (Urban et al. 1987). As a starting point for scaling one can assume that these nested hierarchies are sufficient to describe a multi-scale system, in the sense that the system at one level is simply the sum of its components at lower levels. Forest ecosystems, however, are vastly more than just the sum of their parts. In these systems, where higher levels cannot be explained in terms of characteristics of the lower-level elements (i.e., complex adaptive systems, (Levin 1999)), scaling becomes a more complex issue. Selected aspects of this complexity with particular relevance to forest management (and the examples presented in section 3) will be highlighted in the following paragraphs.

2.1 Holons and hierarchy

The hierarchical nature of ecosystems can be explained by analogy to a piece of rope, where individual fibres are twisted together to form yarns, which combine to form strands, which in turn, combine to form the rope. This nested hierarchy could be extended in either direction, with the fibres being formed of cells, and several ropes combining to form a cable. Each of these components are known as 'holons' (Koestler 1967; Bland and Bell 2007), defined as units that are simultaneously an entity in themselves, but are made up of other entities. If we look at a rope (or, through analogy, a forest ecosystem) from a top-down perspective, it is simply a rope, with various characteristics of stiffness, suppleness, strength etc. (corresponding to, for instance, the productivity, carbon storage etc. of a forest). From a bottom up perspective, we can see that the rope is comprised of individual fibres (i.e., individual trees of a forest) with characteristics of their own.

In its simplest form scaling assumes that if we know the characteristics of an individual strand, and if we know how many there are, then we know the characteristics of the rope. For some properties, this is true. The mass of the rope is the sum of the masses of the strands. If we assume that the strands are identical, then the mass of one strand and the number of strands is sufficient to tell us the mass of the rope. In other words, it scales linearly with the number of strands. A suitable way to deal with the considerable heterogeneity in ecosystems (e.g., trees in a stand are hardly identical) with regard to additive properties is sampling, i.e., if we count the strands of the rope and sample enough of them to estimate their mean mass then we can estimate the rope's mass to a certain level of confidence. In the case of forest ecosystems many properties are, however, asymmetric (Cumming et al. 2008), i.e., with characteristics and their contributions to processes distributed unevenly among the holons of the system, which inhibits linear scaling. We can, for instance, derive the stand leaf area from knowing the average area of a leaf and the number of leaves in a stand (linear scaling), but we cannot in analogy derive the light absorbed by the canopy via absorption of the average leaf, because light reaching leaves situated lower in the canopy depends on the absorption of leaves higher up, and averaging would lead to disregarding the directional nature of the resource gradient. In other words, while leaf area scales linear and behaves symmetrical, radiation interception is a non-linear process with asymmetric behaviour (i.e., leaves on top of the canopy contribute disproportionally to absorbed radiation). If we are now interested in how stand-level radiation interception relates to primary productivity we can make use of scaling to increase the predictability of a complex system: While the relationship between radiation interception and primary productivity (i.e., radiation use efficiency) is highly non-linear at hourly to daily time scales, it scales linearly at monthly time scales (Medlyn et al.

2003), a fact that is harnessed in widely applied forest production models (e.g., Landsberg and Waring 1997). This change in the relationship between radiation interception and primary productivity with a change in scale is a prime example of a process transmutation (see Bissonette 1997).

2.2 Emergent properties

A rope however is more than just the sum of its strands. The interactions between the strands and their arrangement in relation to each other are what gives the rope its cohesion and stiffness. A simple bundle of individual fibres would have very different characteristics. Cohesion (the tightness of the rope's twists) and stiffness are 'emergent properties' that only appear when fibres are combined in a particular way. Even if we precisely knew the stiffness of every fibre, we could not predict the stiffness of the rope without a great deal more information that cannot be obtained from studying only fibres.

This leads us to three fundamentally different characteristics of the rope as a metaphor for hierarchical systems: Mass is present at both fibre-level and rope-level, and scales linearly across hierarchies. The same is true for mass-based properties of forest ecosystems, such as the standing volume. Stiffness is present at both levels, but to predict the stiffness of the rope from that of the fibres requires knowledge of the interactions between holons at all levels below that of the rope itself. The resistance to disturbances is an example of a corresponding property of ecosystems. Resistance to strong winds can be quantified for individual trees, but considerable additional information on the distribution and spatial arrangement of trees is required to estimate the resistance to wind at the stand or landscape level. Finally, predicting the rope's cohesion requires the same multi-level knowledge, but it is a property that has no meaning at the fibre level. An analogue in forest ecosystems would be community assembly, which is dependent on both top-down constraints (e.g., climate) and bottom-up interactions (e.g., local competition for resources between trees), but whose description is only meaningful at an aggregated level. The system is thus comprised of additive (non emergent) characteristics and two kinds of emergent characteristics: those that exist at lower levels but cannot be simply scaled in combination (also referred to as 'connective properties' by Reuter et al. (2005)), and those that come into existence only with the act of combination (i.e., 'emergent measurements' sensu

Bissonette (1997), or ‘aggregational properties’ sensu Reuter et al. (2005)). Just as the concept of cohesion has no meaning at the strand level of a rope, biodiversity or resilience have no meaning at the level of an individual organism.

2.3 Feedbacks and path dependence

It is important to note that we have until now discussed a static system, visualizing scaling over spatial levels only. However, space and time are linked, and scaling thus frequently requires considering both dimensions simultaneously. Ecophysiological processes such as photosynthesis and respiration, for instance, react strongly non-linearly to climate. Scaling up in time via using averaged climatic variables rather than considering the effect of lower-level variability (e.g., variability at daily to hourly time scales) on such ecophysiological processes will result in erroneous results, a phenomenon known as Jensen's inequality (Ruel and Ayres 1999, Sierra et al. 2009). Moreover, feedbacks between processes at different levels can lead to cascading effects across the hierarchy. For instance, an important mechanism in tree death from drought is the embolism of individual xylem cells (i.e. when air bubbles enter the xylem due to exceedingly high xylem water tensions), ultimately blocking water conductance and transport (McDowell et al. 2008). The embolism of individual cells leads to increased pressure and higher vulnerability of the remaining vessels (a phenomenon called cavitation fatigue), and thus exerts an amplifying feedback that can eventually lead to the death of the entire tree (Anderegg et al. 2013). At the level of ecosystems, insights on the importance of such cascading effects and cross-scale interactions have increased the awareness of nonlinear system trajectories and tipping points (Pietsch and Hasenauer 2005; Andersen et al. 2009), and underline the possibility of alternative stable states as a result of amplifying feedbacks to external drivers (Hirota et al. 2011).

An additional aspect to consider in scaling over temporal scales is that forest ecosystems can have a long-term system memory (via legacies such as deadwood pools, seed banks, a skewed age distribution, or a spatially heterogeneous species distribution), causing considerable inertia and distinctly influencing ecosystem dynamics (Franklin et al. 2002). Small initial differences, e.g., in a forests’ species composition, can lead to alternative trajectories of forest development, a phenomenon known as path-dependence (e.g., Eastaugh and Hasenauer 2011; Donato et al. 2012).

In the following section we proceed to give examples of how the concepts of scaling theory described above (issues of heterogeneity, asymmetry, emergence, nonlinearity, feedbacks, and path-dependence) relate to concrete, real-life issues in forest management.

3 Scaling issues in forest ecosystem management

The general process of forest ecosystem management consists of planning, implementing, monitoring, and evaluating management measures. The scaling issues in this section mostly relate to the management planning process, which comprises problem identification, alternative development, alternative selection, and authorization of implementation (Rauscher et al. 2000). Our analysis here focuses on the first two processes of management planning, as these are the main domain of ecological indicators and models (Wolfslehner and Seidl 2010). Table 1 gives an overview of the scaling issues addressed in the following sections and their relation to the steps of the management planning process.

3.1 Scaling process information to the level of information needs

3.1.1 The scaling issue

A prerequisite for effective forest ecosystem management is a comprehensive knowledge about the system, founded in an accurate description of states and trajectories of relevant ecological indicators (e.g., Forest Europe, UNECE, and FAO, 2011). Traditional indicators such as the amount of stem wood volume are directly observable and draw upon the mensurational experience of centuries (Mohren et al. 2012). However, satisfying the information needs with regard to a growing number of ecosystem functions and services of relevance for sustainable forest management (*sensu* MCPFE 1993) is more complex, since the grain and extent of ecosystem processes (and their measurement) often differ from those relevant in management decision making. Despite our advances in understanding and measuring leaf-level C exchange from seconds to days, for instance, management requires integrated information on the C dynamics of stands or landscapes over years and decades. Scaling operations are thus frequently required to derive the information needed in operational management planning. While linear scaling assumptions are commonly used, their appropriateness and effects on management decisions are rarely explicitly scrutinized. Here we use the example of forest C sequestration – an increasingly relevant ecosystem function in the context of climate change mitigation (Canadell and Raupach 2008) – to describe how modelling can address heterogeneity and asymmetry in the context of providing information on C for management decision making.

3.1.2 Example 1: Managing for climate change mitigation

Empirical models such as yield tables are designed to describe forest growth over time. They assume constant site conditions for a given stand, and were never intended to address possible changes due to, for example, global warming or changing atmospheric concentrations of nutrients such as nitrogen or carbon dioxide. Incorporation of such factors calls for the explicit consideration of the nonlinear and interacting processes driving the fluxes of carbon, nitrogen, water, and energy in forest ecosystems. Furthermore, traditional approaches such as yield tables focus on a single ecosystem compartment, bole wood, and thus are not sufficient to represent the forest C cycle and fulfil the information needs of managing for climate change mitigation. Their most important lack in this regard is the inability to track changes in soil, litter, and deadwood carbon pools.

Ecophysiological process models can combine data and process understanding from many different scales (Fontes et al. 2010), harnessing knowledge of processes such as photosynthesis (Farquhar et al. 1980; de Pury and Farquhar 1997), stomatal conductance (Jarvis 1976) and autotrophic respiration (Ryan 1991). Changes in temperature or availability of nitrogen and carbon dioxide are thus accounted for at the cellular level, with varying temporal resolution. The biogeochemical (BGC) model BIOME-BGC (Thornton et al. 2005), for instance, models these interactions on a daily time step, while allocation proportions of carbon to ecosystem compartments (stems, coarse roots etc.) are determined on an annual basis according to various empirical and modelled relationships (Running and Coughlan 1988).

These processes have been scaled to the stand (Cienciala and Tatarinov 2006), national (Lagergren et al. 2006), continental (VEMAP Members 1995) and even up to the global scale (Running and Hunt 1993) via different BGC models. As the grain of the assessment increases, so does the within-grain variability; large ‘grid-based’ simulations implicitly assume that processes over areas of many square kilometres can be represented and modelled adequately by using average values as model inputs – a clear assumption of linearity that can lead to biased results (see for instance Turner et al. 1996). Many process models are however scale indeterminate, in that the user may either define the grain assuming that any within plot variation is irrelevant, or leave the grain undetermined. The outputs are thus akin to individual point samples from an infinite population. Even if the per-point outputs are all precise and accurate, the question of how representative they are of the wider population should be carefully considered. At times the undetermined 'point-based' approach is necessary, such as when using forest data derived from angle-count sampling (Bitterlich 1948), which itself does not apply to a particular fixed area. However, many plots must be aggregated to define the population that is being measured and modelled – the meaning in the data emerges from this statistical aggregation. The appropriate level of aggregation for the outputs to have meaning will depend on the statistical variation in the input data (cf. Kennedy et al. 2006) as well as the level of accuracy which should be achieved.

Data inputs for such models are thus crucially important to capture asymmetry and heterogeneity in ecosystems, and they may come from various scales. For modelling of particular research plots it is generally possible to collect the necessary data from the plots, but in applications over wider geographic areas this is more complex. For simulations over large areas the model can be run over a large number of points, in order to explicitly account for the heterogeneity of the landscape. Eastaugh et al. (2011) for example applied the BIOME-BGC model to Norway spruce (*Picea abies* (L.) Karst.) forests across Austria by operating the model on 1188 plots of the Austrian national forest inventory (NFI, Gabler and Schadauer 2006). Input data may be derived from downscaled gridded data (i.e., the Austrian nitrogen deposition maps of Placer and Schneider 2001) and interpolated to the particular sites of interest (Petritsch and Hasenauer 2007). To account for the asymmetry in the contribution of individual patches to the landscape-scale C exchange, it is useful to consider them explicitly rather than assuming average conditions. However, it is important to recognize that if input data is drawn from sampling schemes such as an NFI, each datum will only be accurate for the precise point where it was measured. The points cannot be said to be 'representative' of a wider area (e.g., a grid cell surrounding the point), but are each simply single random samples from the broader population. The data only acquire meaning across larger scales when sufficient points have been aggregated, and the strength of the model prediction is largely influenced by the statistical adequacy of the sample set (Liang et al. 2012). These issues apply regardless of the sampling scheme or any stratification method that may be used.

In summary, managing for climate change mitigation requires a synthesis and quantitative integration of leaf-level processes understanding to forest stands and landscapes. Ecophysiological process models allow the application of what is known about carbon fluxes from experimental or monitoring sites to develop better understanding of ecosystem flux dynamics and carbon storage in forests over larger areas (e.g., Hasenauer et al. 2012). Crucially important in this regard is to choose an appropriate grain to capture the heterogeneity in the landscape and its potentially asymmetric contribution to ecophysiological processes.

3.2 Scaling management objectives to management entities

3.2.1 The scaling issue

The increasing importance of C storage in ecosystem management is just one example of the changes in societal demands on forest ecosystems in recent decades. While the prime objective of forestry since the beginnings of the discipline was sustainable timber production (Perry 1998), today’s forests are valued by society for providing a multitude of ecosystem services (e.g., Forest Europe, UNECE, and FAO, 2011). Consequently, the complexity of forest management decision making has increased considerably over recent decades. While the traditional spatial entity of timber production was the stand, the broadening of the management paradigm from sustainable timber yield to sustainable forest management (sensu MCPFE 1993) also considerably widened the range of scales of immediate relevance to forest management. The imperative of producing timber under a regime of close-to-nature forests, for instance, has brought individual tree attributes into the focus of forest management (i.e., the level of the management objective is smaller than the level of the management entity; see Hasenauer (2006)). In contrast, as a result of the importance of conserving biodiversity in managed forests, the landscape scale has also received considerable attention (where the level of the management objective is larger than the level of the management entity; see Loehle et al. (2002)). Nonetheless, operational forest management is still almost exclusively executed at the stand scale, not least because machinery has been optimized for applications at this scale (e.g., Suchomel et al. 2011), and a large body of experience with stand-centred silvicultural systems exists. A major scaling issue is thus how these new objectives (pertaining to a variety of scales) can be folded into operational stand level management. The following examples highlight such scaling issues with regard to levels both hierarchically below and above the stand level, and demonstrate how simulation modelling can help managers to deal with issues of bottom-up emergence and top-down constraints.

3.2.2 Example 2: Achieving multifunctionality in stand level management

In order to be operationally addressed at the stand level, multi-purpose forest management requires the consideration of both higher level constraints and lower level processes (see also Walker et al. 2004). In other words, if not only timber production but also the conservation of biodiversity and the provisioning of non-timber goods and services are important objectives, stand level management decisions need to be evaluated with regard to both their tree level consequences and landscape level context. The scale above the stand scale is particularly important for conserving biodiversity in managed forests, since connectivity and spatial patterns on the landscape are important attributes for species habitat (Lindenmayer and Franklin 2002). To aid conservation of biodiversity it has been proposed, for instance, to keep key system properties (e.g., deadwood stores, species composition, share of old forests) within their natural historical range of variability (HRV). This concept assumes that the HRV describes the conditions that many species of conservation value have co-evolved with and are adapted to, while acknowledging that ecosystems are never static by specifying a range of conditions rather than a singular target (Keane et al. 2009). The assessment of the HRV frequently relies on landscape simulation models which are able to factor out historical interference by management (e.g., in historically strongly human-dominated areas such as many parts of Europe). Furthermore, such models can address the complex spatio-temporal drivers that constitute the HRV explicitly (e.g., Wimberly et al. 2000, Nonaka and Spies 2005). It is important to note that the HRV cannot be assessed at the stand scale; it is an emergent property at the landscape scale. The HRV thus provides a top-down target corridor for evaluating stand-level management decisions in the context of biodiversity conservation. However, in addition to using historical conditions as a yardstick for management, conservation in managed forests also requires a proactive consideration of potential vulnerabilities to future changes in the environment (Lexer and Seidl 2009). A particularly important aspect in this regard is landscape connectivity, not least since climate change might require species to migrate rapidly (Milad et al. 2011). Spatially explicit simulation approaches can help to determine migration rates and corridors considering scenarios of climate change (e.g., Meier et al. 2012; Hamann and Aitken 2012). Such analyses at the landscape scale provide additional, spatially explicit top-down constraints to stand level management, and grant an operational consideration of conservation objectives at the stand scale.

While the previous paragraph has illustrated the importance of top-down constraints for multi-purpose forest management at the stand level, bottom-up processes are frequently of equal importance, e.g., in the context of sustainably providing many (non-timber) goods and services. To exemplify the latter aspect we here relate a case study from the Belasitsa mountains of southern Bulgaria, contrasting traditional coppicing (which epitomizes homogenous stand level management, cf. Zlatanov and Lexer (2009)) with a spatially heterogeneous group selection system (i.e., management at the level of individual trees). The study site is located at approximately 450 m asl., and the current vegetation can be described as uneven-aged mixed broadleaved forest (mainly consisting of *Castanea sativa* Mill., and *Quercus petraea* (Mattuschka) Liebl., Figure 1a) with a distinct share of individuals originating from vegetative propagation. An important objective for management in these stands is to contribute to local fuel wood supply (via coppicing), while maintaining a sufficient number of generatively regenerated *C. sativa* individuals, which are of high value for fruit production. The latter individuals further contribute to forest health in these ecosystems, as they are known to be more robust than vegetatively regenerated individuals against the spreading disease of chestnut blight (*Cryphonectria parasitica* (Murrill) Barr.).

To address how these multiple management objectives (i.e., timber, fruits, forest health) could best be met, a simulation experiment with the individual-based model PICUS v1.5 (Lexer and Hönninger 2001; Seidl et al. 2005) was conducted. PICUS combines detailed three-dimensional light regime calculations with physiological principles of growth modelling, and was recently extended to include generative regeneration (resprouting) and coppice management. To illustrate the effects of scale in the management system (stand-level vs. plot/ tree-level management) a typical clear cut (coppice) system was simulated and contrasted it with an irregular group selection system. Simulation results document that irregular management at the sub-stand scale was considerably more efficient in maintaining a satisfactorily stocking with seed-originating *C. sativa* (Figure 1b,c). Early gap-cuts, for instance, create regeneration opportunities for seed-originating individuals and thus foster their continued occurrence in the canopy (cf. path-dependence), while selective thinning further promotes healthy and vital individuals. Scaling management down to the individual tree level thus resulted in a better fulfilment of the management objectives with regard to fruit production, and facilitated forest health in this example (see also Zlatanov 2006).

Overall, these examples from biodiversity conservation and novel coppice management demonstrate that both the consideration of top-down constraints (e.g., landscape-scale migration corridors) as well as bottom-up emergence (e.g., stand-level species composition emerging from tree-level management decisions) is crucial for multi-purpose forest management at the stand scale. They furthermore illustrate the utility of simulation models in aiding stand-level management with regard to these scaling issues.

3.3 Managing for emergent ecosystem properties

3.3.1 The scaling issue

A key aspect of sustainability is the conservation of ecological integrity (Tierney et al. 2009) in order to maintain ecological functions over time. Consequently, important considerations of sustainable forest management are related to fostering, maintaining, or improving ecological conditions and processes. In other words, ecosystem management is not only concerned with managing for the extraction of natural resources, but equally with sustaining the ecological potentials that ensure the ability to obtain these ecosystem goods and services also in the future. Ecological theory suggests that stability in ecological functions over time is an emergent property of processes across multiple levels of organization in general, and of the interplay between fast and slow processes in ecosystems in particular (Levin 1999; Holling and Gunderson 2002). Ecological resilience, defined here as the ability of a system to absorb changes (in state variables, driving variables, and/ or system parameters), and still persist in its integrity and functioning (Holling (1973), but see also Grimm and Wissel (1997), Brand and Jax (2007)). This resilience is an emergent property of an ecosystem, one that cannot be defined simply by the attributes of some ecosystem components. Since resilience is inherently scale-dependent (O'Neill 2001), its management too requires a multi-scale perspective. Not surprisingly, addressing the complex interactions across scales that constitute ecological resilience is a challenging task, and studies have shown that decision makers, when presented with complex management problems, tend to revert to short-cut solutions (Hoogstra and Schanz 2008) or simplistic ‘one size fits all’ regulatory responses (Sayer and Maginnis 2005). Yet, considering the increasing pressure on ecosystems from global change, managing for stability and resilience will likely increase in importance in the future (Millar et al. 2007). Addressing aspects of cross-scale emergence and complexity more explicitly in management is thus increasingly important (Puettmann et al. 2009).

3.3.2 Example 3: Improving resilience to natural disturbances through management

Natural disturbances (abrupt and often large-scale events of tree mortality and biomass destruction) are important constituents of natural forest ecosystem dynamics (Turner 2010). However, they are increasingly a concern for forest management, as disturbance regimes have been intensifying in many forest ecosystems (Schelhaas et al. 2003), fuelled by recent changes in climate as well as in forest structure and composition (Seidl et al. 2011a). Scenario analyses indicate that a trend towards more frequent and severe disturbances will likely continue with progressing climate change (e.g., Blennow and Olofsson 2008; Seidl et al. 2009), with the potential for detrimental effects on ecosystem services including C storage and timber production (Seidl et al. 2008; Pfeifer et al. 2011). Accounting for disturbances in forest management planning is thus imperative for sustainability under changing environmental conditions.

With regard to disturbance management, the pertinent scaling issues for foresters are twofold. Firstly, while management can positively influence traits of stability at the individual-tree level and reduce stand-level predisposition to disturbance (Jactel et al. 2009), disturbance regimes play out at the landscape level, and it is the spatial dynamics at this scale that to a large degree drive disturbance patterns and damages. Secondly, a variety of disturbance agents interact (in space and time) to form a disturbance regime, making the task of reducing disturbance impacts a multi-scale effort. Process-based multi-scale models, for which examples are given by Kramer et al. (2003) and Seidl et al. (2012b), can help managers to address these issues via their ability to consistently integrate processes across scales, predict resulting systems trajectories, and highlight spatio-temporal trade-offs of management strategies with regard to resilience to disturbances.

To illustrate this ability we here give an example of simulating the ungulate browsing – wildfire regime of a mixed Scots pine (*Pinus sylvestris* L.) – broadleaved forest landscape with heathlands in the Veluwe region, central Netherlands, using the model FORSPACE (Kramer et al. 2003; 2006). FORSPACE simulates vegetation as vertically layered cohorts (at 30 m horizontal resolution), employing a radiation use efficiency approach to derive ecosystem productivity. Herbivory is modelled by keeping track of the population dynamics of different browser species, their energy intake (consumption of vegetation) and loss (respiration, mortality), as well as their fecundity and progeny. Wildfire is driven by dynamically simulated fuel availability, and spatial fire spread is calculated depending on fuels and vegetation structure. Impacts on vegetation are estimated in relation to fire intensity.

With regard to the above outlined scaling issues simulations with FORSPACE underscored the importance of a multi-scale perspective on emergent properties of ecosystem resilience and stability. Stand level management measures aimed to reduce the negative effects of herbivory (fencing) and foster regeneration (gap cuts), for instance, actually increased the overall disturbance pressure on the landscape, as a result of a reduced viable area for browser populations (exclusion through fencing) and improved foraging conditions (abundant forage in gaps) exerting positive feedbacks on browser populations (Kramer et al. 2006). Further analyses documented strong interactions between small- and large-scale disturbance agents (i.e., browsing and wildfire), highlighting the importance of cross-scale interactions on ecosystem trajectories. Simulated large-scale disturbances by wildfire were, for instance, negatively correlated with small-scale browsing through a reduction in available fuel on the landscape in general, and of ‘ladder-fuels’ (i.e., fuels that allow the fire to vertically develop from a ground fire to a canopy fire) in particular (Kramer et al. 2003). Furthermore, under a regime of high fire frequency and high population density of browsers the simulated system was shown to switch from a forested landscape to a sparsely vegetated open woodland, a behaviour that is not displayed if disturbance by browsing or wildfire individually is considered (Figure 2). In other words, if disturbances at one level (here: wildfires) are neglected in management decision making for the Veluwe landscape, the capacity of the system to return to a pre-disturbance state (i.e., its resilience) might be overestimated, and the risk of its flipping into an alternative stable state – with possible detrimental effects on ecosystem services – might be disregarded.

4 Discussion and conclusions

4.1 Why scaling should play a prominent role in forest ecosystem management

Our review of selected management problems in section 3 highlights that scaling is central to many current issues in forest management. Scaling has a well-defined theoretical background in ecology (Urban et al. 1987; Wiens 1989). Yet the diffusion of theory into applications is often a slow and gradual process, not at least because theory has the potential to fail practitioners in manifold ways (see Driscoll and Lindenmayer 2012). In our analysis we have found that a (more) explicit consideration of scaling in forest management could help managers in at least four regards:

(i) To avoid spurious interpretation of data

Forestry, although traditionally a data-limited field, is increasingly benefiting from the dawning age of "big data" (Howe et al. 2008) in the form of an increasing availability of remote sensing products (Wulder et al. 2012) and a wider public availability of National Forest Inventory data. However, as highlighted in the context of inventory plot information in section 3.1, to make sense of data their associated scale and context need to be understood. Put more generally, awareness of how ecosystem services emerge from underlying processes (Currie 2011), and how heterogeneity and asymmetry affect the spatio-temporal provision of these services, will help managers to determine appropriate scales to monitor and manage ecosystems (Urban et al. 1987).

(ii) To omit scaling errors and reduce uncertainty

Assuming linear scaling, e.g., via averaging or adding up information across scales, can oftentimes lead to errors in assessing ecosystem properties. In the context of forest management planning, neglecting scaling issues in comparing alternative management strategies can thus introduce a significant bias into the decision process (Wolfslehner and Seidl 2010). Likewise, ignoring feedback mechanisms and path dependence in temporal scaling can create an illusion of stability and facilitate ignorance of imminent tipping points (see section 3.3.2). Considering scale and scaling more explicitly in management planning can thus help to reduce uncertainty and increase the robustness of management decisions.

(iii) To improve the integration of multiple ecosystem services

Considering scales above and below the stand scale in management decision making has significant potential to improve management performance with regard to a variety of ecosystem services. While traditional stand level management was developed with one single ecosystem service in mind, namely sustainable timber production, considering scales from tree- to landscape-level can benefit ecosystem services from fruit production to biodiversity conservation (see section 3.2.2). Such ecosystem services beyond timber are gaining importance, but their integration with more traditional management objectives remains a major challenge. The explicit consideration of multiple scales in management can help to foster a more integrated approach of ecosystem services provisioning, and allows the assessment of the inherent trade-offs more explicitly and comprehensively.

(iv) To address novel management objectives

Objectives such as managing for increased resilience and integrity of ecosystems, albeit founded in mature ecological theory (Holling and Gunderson 2002), are relatively new additions to the growing portfolio of objectives to be met by forest managers. Nonetheless, the potential vulnerability of ecosystem services to climate change (Schröter et al. 2005; Seidl et al. 2011b) makes their timely mainstreaming into management practices all the more important (Millar et al. 2007). Such properties only emerge at scales larger than the stand scale, yet are fundamentally dependent on a variety of agents and processes and their cross-scale interactions. Understanding (and subsequently managing) these properties thus requires a multi-scale perspective explicitly addressing the complexity of forest ecosystems.

It is important to note that we have focused solely on ecological issues of scale and scaling here. Yet also social, economical, and political aspects of scale are of relevance for forest management (see #1, #5 and #6 in Table 1). A concerted, multi-scale management, for instance, is often complicated by multiple ownerships particularly in the highly fragmented landscapes of Europe, requiring cooperation and organizational structures facilitating landscape-scale planning (Fischer and Charnley 2012).

4.2 What we can learn from models

Recognizing the importance of scaling for forest management inevitably leads to the question how to operationally tackle this at times daunting task. We here argue that ecosystem models are powerful tools to address scaling issues in forest management, as they are designed to consistently (mathematically) integrate processes and their dynamic interactions across scales. In particular, they can support scaling in management with regard to at least three major aspects:

(i) Assess quantities that cannot be directly measured

We are currently unable to physically measure crucial ecosystem components such as the ecosystem C cycles at the scales required for management decision making (e.g., in the context of climate change mitigation). We thus require models to integrate observed proxies (e.g., Hall et al. 2012) or scale measurements and process understanding at the level of tree organs to these respective scales of interest (e.g., Running and Coughlan 1988). Moreover, models have also considerable advantages in assessing ecosystem characteristics such as resilience and quantifying management indicators such as the historical range of variability (e.g., Nonaka and Spies 2005). They can thus serve as instruments to synthesize the information needs of the manager from a complex, multi-level reality.

(ii) Account for system dynamics and changing conditions

Climate change affects ecosystem processes at multiple levels, and its effect on ecosystem services is likely going to depend on the interactions and feedbacks between the responses of individual processes across different scales. Facing a "no analogue" future, experience-based knowledge is no longer sufficient to assess potential future trajectories of ecosystems. Furthermore, global change simultaneously affects ecosystem processes at a variety of scales, rendering the consideration of cross-scale interactions and feedbacks - and thus scaling - of paramount importance in assessing impacts on ecosystems (Chave 2013). Models have great potential in this regard, not at least because they offer efficient means to conduct scenario analyses and allow managers to ask "what if" questions, e.g. with regard to species migration or changing disturbance regimes, and incorporate the lessons learned in their management considerations.

(iii) Address the increasing complexity in ecosystem management

Ecosystems are complex (in the sense of containing diverse agents interacting among each other and with a heterogeneous environment), a fact that has recently been "rediscovered" by foresters (see Puettmann et al. 2009). However, this also leads to increasing complexity for management decision makers, who will need to consider an increasing number of processes, interactions, services and constraints in decision making. Models can help managers to navigate this complexity and to make informed and transparent decisions on how ecological complexity at different levels contributes to ecosystem services. Another aspect adding to the complexity experienced by the management decision maker is the accelerated broadening of the set of forest services demanded by society. Social uncertainties, i.e., the unknowable nature of future local, regional, and global preferences of society for ecosystem services, were recently found to be in at least the same order of magnitude as climatic uncertainties (Seidl and Lexer 2013). Models can help in this regard to quantify trade-offs between current (and potential future) ecosystem services, and in so doing increase the robustness of management strategies.

It has to be noted that while scaling is a strength of ecosystems models in the context of management, it is at the same time a major challenge for modelling. For instance, while thinning and harvesting operations have by far the most profound impacts on forest ecosystems in most parts of the world (most particularly at small scales), their incorporation into process modelling is still in its infancy, and relies largely on a priori assumptions or large scale statistical modelling (i.e., Eastaugh and Hasenauer 2012). This illustrates that there is no one single model (or family of models) that particularly commends itself to address scaling issues in forest management; the specific question, ecosystem service, and study system at hand determine which models are best suited to address a particular scaling issue. This is reflected in section 3, where we have highlighted examples using a variety of different models, all with their particular strengths and domains of application. It is thus important to choose and apply models wisely. As good decision making ultimately depends on the analyst and not the model (Nelson 2003) asking questions about the scales, processes, and interactions addressed by a model can be seen as a focused scoping process for management problems. Using models to more explicitly recognize the spatio-temporal hierarchies of ecosystems can thus be an important step towards an ecosystem-oriented stewardship of forests.

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Figure captions

Figure 1: (a) Diameter distribution (year 2000) of an overstood coppice with standards in the Belasitsa mountains, Bulgaria. Simulated composition of species and their origin (vegetative or generative propagation) simulated over 100 years under (b) traditional coppice management and (c) group selection management. Note that mortality from chestnut blight was not explicitly considered in these simulations.

Figure 2: State-space diagram of producers (horizontal) versus consumers (vertical) in the Veluwe landscape (approximately 10,000 ha). Ignoring large-scale disturbances from wildfire (panel a) the system trajectory gravitates around a single attractor (a forest landscape), while if fires are considered (panel b) a flip towards an alternative stable state (open woodland) is possible. For more details see Kramer et al. (2003; 2006).

Table 1: Selected scaling issues in the stages of the forest management planning.

#	Process[1]	Description highlighting scaling issues
1	Problem identification	Management problems are identified. Scaling issues in this planning stage are not explicitly addressed in this contribution, as the management problems addressed in section 3 were selected a priori.
2	Analysis of current condition	In order to assess the current condition with regard to the management problem at hand (e.g., climate change mitigation) information on ecological processes (often available at scales above or below the scale of management decision making) need to be scaled to the level where the information is needed by the decision maker (section 3.1).
3	Identification of desired future condition	The desired future condition needs to be deduced from the high-level management goal. In this step of translating the desired future condition to the operational unit of forest management (i.e. the stand level) both top-down constraints from higher hierarchical levels as well as bottom-up emergence from lower levels need to be accounted for (section 3.2).
4	Design and assessment of management alternatives	Alternatives are designed and assessed with regard to their potential to achieve the desired future condition. If the management goal is an emergent phenomenon (such as, e.g. improved resilience) rather than an additive system property, the assessment of alternatives needs to explicitly consider the cross-scale interactions and spatio-temporal complexity underlying such phenomena (section 3.3).
5	Selection of an alternative	Judgment of the alternatives based on values, beliefs, and preferences, and alternative selection. Scaling issues in this stage are not explicitly addressed in this contribution.
6	Authorization to implement	Approval of the decision is sought inside (and outside) the institutional hierarchy. Scaling issues in this stage are not explicitly addressed in this contribution.

[1] modified from Rauscher et al. (2000)

Figure1

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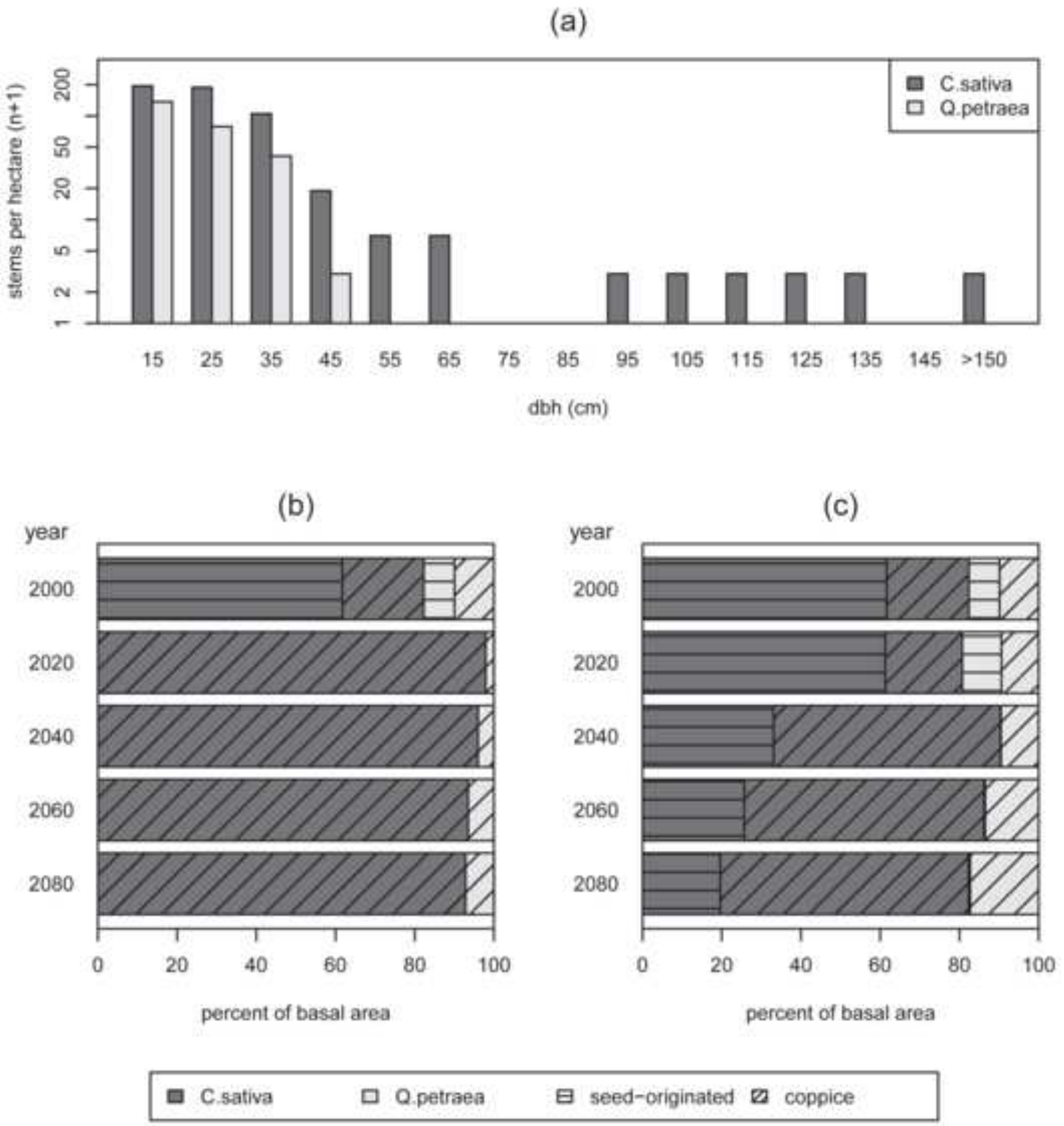

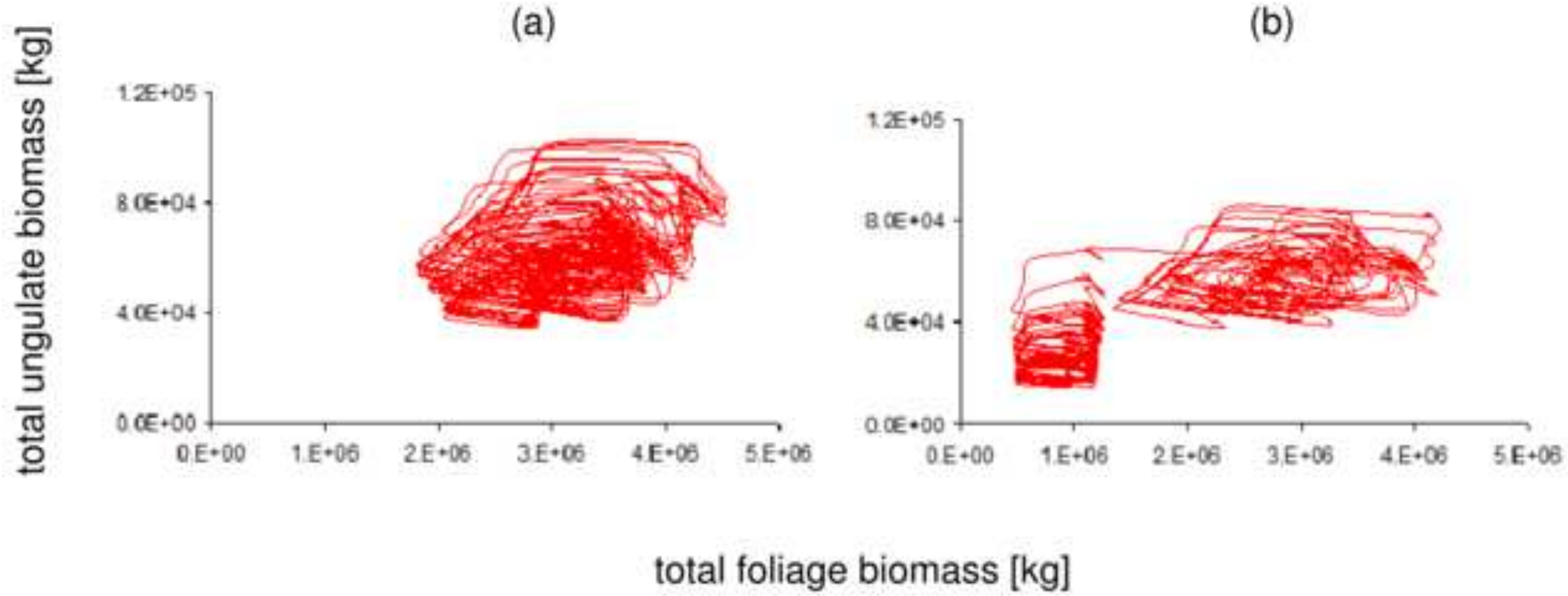
(a)
(b)
total ungulate biomass [kg]
1.2E+05
8.0E+04
4.0E+04
0.0E+00
0.E+00
1.E+06
2.E+06
3.E+06
4.E+06
5.E+06
total foliage biomass [kg]