



A fuzzy logic-based approach for evaluating forest ecosystem service provision and biodiversity applied to a case study landscape in Southern Germany

Peter Biber¹ · Fabian Schwaiger¹ · Werner Poschenrieder¹ · Hans Pretzsch¹

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Abstract

In the field of assessing forest ecosystem service provision and biodiversity, there seems to be a gap between an existing large body of valuable expert knowledge and its application. We propose fuzzy logic evaluation systems as a contribution to closing that gap. With this method-focused pilot study, we explored the potential of fuzzy logic for assessing the provision of different ecosystem services in a simulation case study, covering a large forest landscape in Southern Germany. Based on expert knowledge and available literature, we designed a fuzzy logic evaluation system for biodiversity, and the ecosystem services balanced wood production, storm and bark beetle damage resistance, and recreation value. This evaluation system was applied to 100-year simulation outcomes for three contrasting forest management scenarios in the landscape of interest. While the results of the case study in general support the idea of a multifunctional forest management, fuzzy logic turned out pronouncedly useful as a method. This is due to its potential to make otherwise unused expert knowledge applicable and transparent in a formal evaluation process. Based on our results, we discuss the approach related to its potential for interdisciplinary integration of knowledge, for revealing tradeoffs and synergies, and participative planning processes.

Keywords Ecosystem service assessment · Fuzzy logic · Sustainable forestry · Simulation

Introduction

Forest ecosystem services and biodiversity: gap between information demand and supply

Benchmarking sustainability, management planning, and policy making on the basis of a multitude of ecosystem services to be provided and biodiversity is presumably the

precondition of the multifunctional forest management paradigm. This is documented by a broad body of approaches toward categorizing, labeling, and assessing biodiversity and ecosystem services in the political as well as in the scientific debate (Haines-Young and Potschin-Young 2018; Biber et al. 2015; Dobbs et al. 2011; Pretzsch et al. 2008; Schröter et al. 2005; Millenium Ecosystem Assessment 2005; MCPFE 1993). This obvious demand in information is still in a striking contrast with the information that is actually and workably available to forest management. On the one hand, this has to do with the traditional focus on wood production alone—and tradition always comes with inertia—but on the other hand, there is a methodical problem of its own. Given the focus of this study, both aspects are worth a closer look.

For the greatest part of the time since methodical forest management exists, i.e., about three centuries, it was concerned with supplying timber, the all-purpose raw material that had become drastically scarce due to unregulated forest utilization during the centuries before. And the mere reason for establishing forest science at all was to support forest management in this effort. This resulted in an enormous accumulated experience about wood production

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✉ Peter Biber
p.biber@tum.de
Fabian Schwaiger
FabianSchwaiger@hotmail.de
Werner Poschenrieder
Werner.Poschenrieder@lrz.tum.de
Hans Pretzsch
hans.pretzsch@tum.de

¹ Chair of Forest Growth and Yield Science, TUM School of Life Sciences, Technical University of Munich, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany

documented in an evolving wealth of data, concepts, methods, and tools up to the present day. No wonder, our long-term experiments, inventories, planning methods, and even the most recent growth models strongly mirror this tradition. We perceive other forest ecosystem services, in contrast, as genuinely independent qualities for not more than a few decades. While a longer and less simplifying treatment of historical aspects was beyond the scope of this paper, we should, however, mention that in Central Europe, especially Germany, the concept of *forest functions* was developed considerably earlier and independently from the ecosystem services approach. While both concepts share the same basic idea—dealing with forest benefits apart from wood production—there are also substantial differences. The interested reader will find detailed comparisons of both approaches in Kindler (2016) and Pistorius et al. (2012); from a management perspective, Tiemann and Ring (2018) and Meyer and Schulz (2017) provide deeper insights. Although this paper sees itself in the context of the internationally widespread ecosystem services concept, its methods are applicable in the forest functions framework as well. Most important for our narrative, while past foresters were not unaware of forest benefits beyond wood and their importance (cf. Assmann 1971), they traditionally considered them to come automatically “in the wake” of wood production (Rupf 1961).

Insofar, the comparatively short history of systematic research into ecosystem services beyond wood could be taken as an explanation for the gap between demand and supply of information. Probably more important than the historical burden, however, when trying to quantify the ecosystem services beyond wood provision, we encounter difficulties that cannot be solved by methods as established for measuring the quantity and quality of wood and timber. As it seems, many of these ecosystem services are very difficult or virtually impossible to measure directly. This is also true for biodiversity, which is not considered an ecosystem service itself, but a precondition for the provision of a broad range of ecosystem services (cf. Haines-Young and Potschin-Young 2018; Mace et al. 2012; Maes et al. 2012; De Groot et al. 2010; Millenium Ecosystem Assessment 2005; Scherer-Lorenzen et al. 2005). As this distinction is not crucial for the point of our study, we will take biodiversity as included when we use the term “ecosystem services” in the further text (unless otherwise stated) for the sake of easier reading.

Despite this special role of biodiversity as mentioned above, it is an ideal example for elaborating on this point: Measuring (i.e., not estimating or proxying) biodiversity at, say, a forest inventory plot would take a full survey of the plant and animal species present, not to mention spatial aspects of diversity. Extrapolating the costs of such an undertaking from one single inventory plot to a whole forest estate or a national forest inventory easily disqualifies that approach from application in practice. Implementing the

same idea in forest simulation models would take to combine them with population models of all possibly present species. This has been successfully done for single species (Köhler et al. 2002), but is virtually impossible for the whole set that ultimately constitutes biodiversity. As it turns out, forest structure in a wide sense offers itself as a proxy (see a recent meta study by Dieler et al. 2017), e.g., a forest stand comprising many tree species and a significant tree size heterogeneity is likely to harbor a large variety of habitats also for non-tree organisms and thus can be concluded to provide more biodiversity than a neighboring plantation (Gao et al. 2014).

Another kind of virtual measurement impossibility comes, e.g., with a category of ecosystem services called “Cultural Services” (Milcu et al. 2013), including historical, therapeutic, educational, recreational, and even spiritual services. Besides the primary difficulty to measure, say, the historical or therapeutic value of a forest, the perceived provision of this kind of services is frequently inseparable from value judgements that may strongly differ among social strata, interest groups, and even individuals within the same strata or group (Hobbs 2016; Hernández-Morcillo et al. 2013; Skår 2010; Hull et al. 2001).

Therefore, bypassing direct measurement attempts and searching for accessible proxies seems to be a promising undertaking. In a review of cultural ecosystem service indicators, Hernández-Morcillo et al. (2013) present five types of indicators for cultural ecosystem services ranging from *condition indicators* and *function indicators*, which describe relevant properties and functions of the ecosystem itself, to the point of *impact indicators*, which relate to peoples’ physical, economic, social, and spiritual well-being. While we are fully aware of that broad spectrum, we concentrate in this study on proxies related to the first two types, i.e., such that can be linked to forest structure for two pragmatic reasons: First, our study is embedded in the context of forest simulations and inventories, which limits us to forest structure information; second, forest structural properties are those which can be directly worked on by forest managers. Doing so, we feel in line with De Groot et al. (2010) who recommend: “Any ecosystem assessment should first aim to determine the service delivery in biophysical terms, to provide solid ecological underpinning ...”. While the weight to be given to structure-based indicators in a holistic evaluation of cultural services is under debate (cf. Meyer et al. 2019), there is no doubt, that they play a role (Hegetschweiler et al. 2017; Holg n et al. 2000; Li et al. 2014), e.g., De Valck et al. (2014) report a general public preference of more near-to nature, i.e., rich-structured mixed forests, but opposition even against measures toward that goal if these temporarily create less desired structures. Or, a significant number of accessible very large sized, thus impressing, tree individuals will, in the view of a considerable share of the population, transport spiritual

value; as Trigger and Mulcock (2005) put it, trees are—in a spiritual sense—seen as *sources of inspiration and intellectual reflection, symbols of place and metaphors for life*.

While, in the assessment of cultural services, the problem of value judgments continues to persist, structural variables like tree species composition, size heterogeneity, or number of large trees are often covered by current forest inventories, and they are traceable with modern forest growth models. In addition, many numeric indicators have been designed in order to crystallize certain aspects of forest structure like tree species richness, vertical structure, horizontal distribution patterns of trees, species, stand types, stand density (Ehbrecht et al. 2017; Gadow et al. 2012; Lamonaca et al. 2008; Maltamo et al. 2005; Latham et al. 1998) to mention only a few. From this perspective, there seems to be a wealth of information available, and the question arises how to translate the proxies into useful assessments of ecosystem service provision.

Fuzzy logic as an evaluation approach for ecosystem service provision

In a strict quantitative sense, a considerable body of literature reports approaches to statistically or even mechanistically link forest structure information with the provision of ecosystem services (Nowak et al. 2016; Schuler et al. 2017; Vilà et al. 2007; Graham et al. 2004). However, this has been done so far mostly in a punctual, case study bound way. Generalizable results that could be accepted as they are for ecosystem service assessment are broadly missing. The situation is different when we look at qualitative approaches. There is a broad body of accepted expert knowledge, often available in the form of guidelines for forest practice or textbooks (Mason et al. 2018; Beatty et al. 2018; Food and Agriculture Organization of the United Nations 2013; Kaulfuß 2012; Hein et al. 2008; NZ Forest Owners Association 2008). As a typical example, there is an online guideline for mitigating fire risk in North-East German forests, which makes (among others) the point that risk increases with the share of Scots pine and the share of trees with small diameters in a stand (Kaulfuß 2011). Every forest practitioner working in that region will agree to this idea from their own experience, and, importantly, it links forest structure with the regulating ecosystem service “forest fire preclusion.” While these large pools of expert knowledge are permanently utilized for making decisions in forest management practice, their potential for ecosystem service evaluation has virtually not been exploited so far. What is lacking is a formal way to tap such qualitative expert knowledge in a way that it becomes applicable for assessment of forest inventories as well as simulated forest scenarios regarding ecosystem services.

In a recent paper, Blattert et al. (2017) propose a promising approach based on utility theory; they map values of

forest (structure) indicator variables by way of *utility functions* to a dimensionless score between 0 and 1, 0 indicating the worst, and 1 indicating the best available performance in terms of ecosystem service provision. With this pilot study, we want to suggest an additional useful way for the same mapping task, based on fuzzy logic. We will do that by example of a case study landscape, but the focus of the paper is on the method.

The concept of fuzzy logic, introduced by Zadeh (1965), has a few key properties that seem to make it ideal for the task at hand. As fuzzy logic systems incorporate the “vague,” i.e., fuzzy reasoning of the human mind, they are useful for robustly mimicking the way experts develop qualitative assessments of a given situation (the central idea is to express variables as fuzzy sets; see methods section). The reasoning implemented in fuzzy logic systems is always based on rules which should be defined by experts. In other words, the rule set of a useful fuzzy logic system is consolidated expert knowledge. As will be discussed later, such rule-based setups are highly transparent and allow intuitive access, which is an important advantage compared to more abstract approaches in the context of decision making in forestry.

Goals of this study

With this pilot study, we want to demonstrate with a focus on the method (i) how fuzzy logic can be used to link the provision of ecosystem services and biodiversity to available information about a forest area, (ii) how this concept applies to forest management scenarios, first with a focus on single ecosystem services, second with a synoptic view. To this end, we used forest landscape simulations in a case study area in Southern Germany as our forest data. When assessing ecosystem service provision, we deliberately restricted ourselves in this pilot study to using mean stand level variables for the whole landscape only. We are doing so in order to keep the presentation at a reasonable size, and we consider this admissible, as our goal is to present the method. However, there is no fundamental reason that would forbid upscaling fuzzy logic evaluations from the level of single stands to the landscape or combining stand and landscape level evaluations.

In this paper, we follow the classification proposed by the Millenium Ecosystem Assessment (Millenium Ecosystem Assessment 2005), which distinguishes four categories of ecosystem services, namely supporting, provisioning, regulating, and cultural services. The specific services, we focus on are (i) biodiversity (precondition for many services), (ii) balanced wood production (provisioning service, precisely defined in Sect. “Fuzzy logic evaluation of balanced wood production”), (iii) the resistance against storm and bark beetle damages (risk resistance as a regulating service), and (iv)

recreational value (cultural service). We use the case study itself just as a vehicle to present and evaluate our methods; they can be applied analogously to other regions and sets of ecosystem services.

The fuzzy logic system constructed in this study was developed in its entirety with the free programming language R (R Core Team 2019), namely the package ‘sets’ (Meyer and Hornik 2009).

Material and methods

Forest management scenarios in the case study area Augsburg Western Forests

We demonstrate our approach with the case study area “Augsburg Western Forests,” where we used the same data sources and forest management scenarios as presented by Schwaiger et al. (2019). The 120,000 ha sized area with 53,000 ha forest cover is located near the major city of

Augsburg (48° 22′ N, 10° 54′ E, 300,000 inhabitants) in Southern Germany (Fig. 1). This area is of special interest in the context of our study, as highly productive and therefore economically valuable forests encounter the manifold expectations of an urban population, e.g., in terms of recreation and nature protection. The region is dominated by Norway spruce forests; young stands tend to be underrepresented in the area’s stand age distribution (see Supplementary Information S2 for more details).

For describing the forest status quo, i.e., the initial situation of all subsequent simulations we used two data sources, (i) the third German national forest inventory (NFI), and (ii) the Bavarian state forest inventory (BSFI). This allowed us to distinguish 277 stand types that could be individually treated in the subsequent simulations (see Supplementary Information S2).

Starting with the initial situation described in these data, we performed scenario simulations using the forest growth simulator SILVA (Pretzsch et al. 2002) which is valid for the most important tree species in Central Europe under

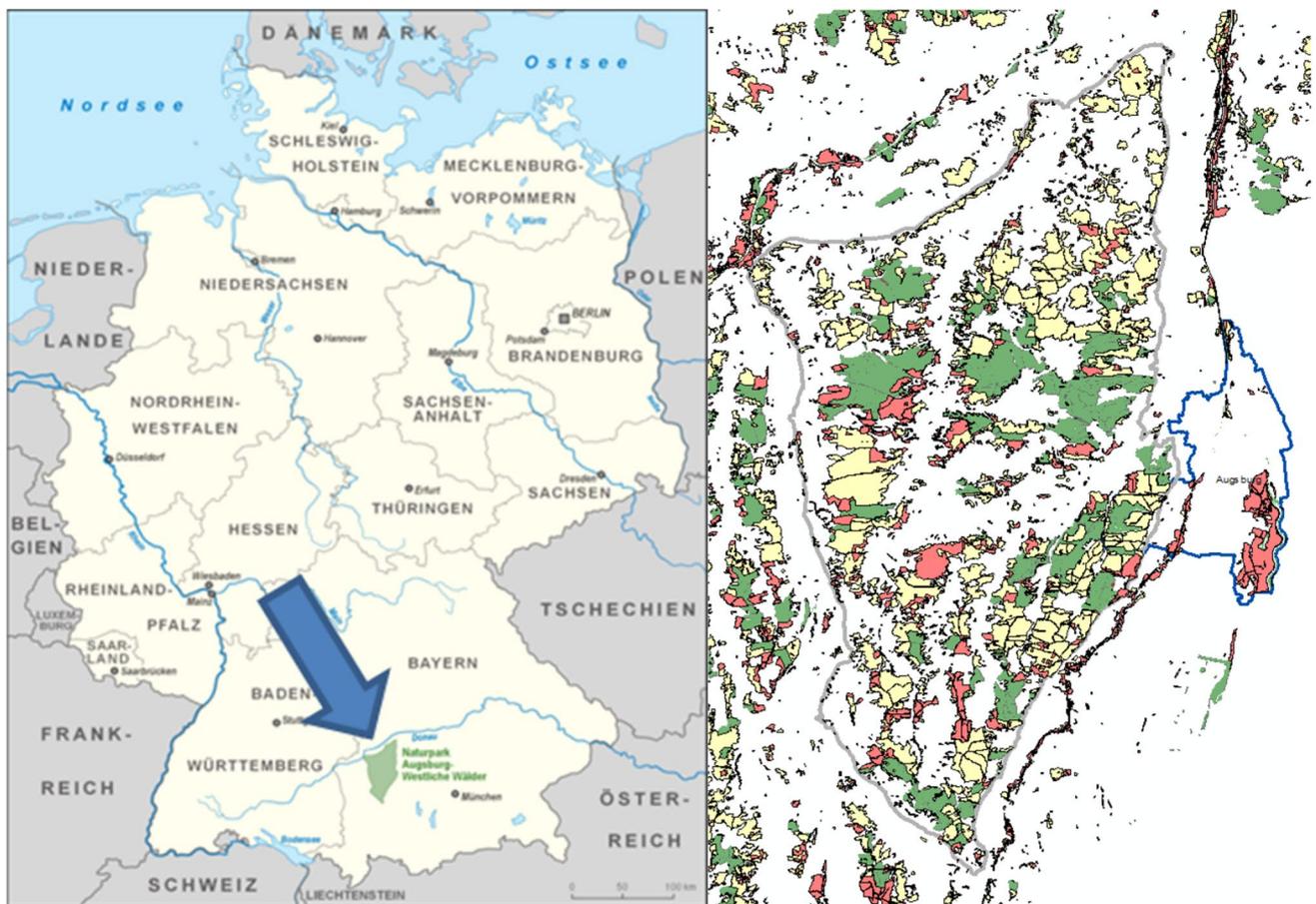


Fig. 1 The case study area Augsburg Western Forests. Location in Germany (left) and detailed view (right). The gray outline in the detailed map marks the case study area, colored shapes indicate forest

areas, with different colors for different owner categories: Green—Federal State of Bavaria; yellow—private forest; red—municipal forest. The blue outline shows the city area of Augsburg

monospecific even-aged as well as in uneven-aged mixed stand conditions. Three different overarching silvicultural concepts on landscape level were defined for simulations with SILVA. We called them (i) “multifunctional forest”, (ii) “production forest”, and (iii) “setaside”. In the multifunctional forest scenario, the goal was to actively increase the share of deciduous tree species and to develop the forest into uneven-aged mixed stands. Quite the contrary was the idea behind the production forest scenario. Here, conifer species were promoted and managed in even-aged stands for maximum wood production. The setaside scenario assumed the complete cessation of any active forest management for the sake of ecological process protection. Both active management scenarios clearly required considerable differentiation on stand type level. See Schwaiger et al. (2019) for an in-depth description. All three landscape level scenarios were simulated for a time span of 100 years; climate conditions were kept constant on the current values. This wide time horizon meets the requirements of long-term strategical considerations in forest management and policy while including the shorter view required for quantitative adaptive management planning.

Standard output variables

The growth simulator SILVA provides a set of more than thirty output variables, ranging from classic forest information like standing volume and volume increment to timber assortment volumes and indexes for stand structure and diversity (Pretzsch 2010). In this paragraph, we shortly explain just those nine output variables that were used as input for the fuzzy logic evaluation in this study. All of these variables and their simulated development over time were available for each stand type, but for the purpose of this pilot study—the demonstration of a method—we restricted ourselves to using landscape level stand average values (see above).

The input variables of interest in this study were: (1) The *Standing Volume* (m^3/ha), i.e., the above ground merchantable wood over bark including the stumps, calculated using the form factors by Franz et al. (1973). (2) The *Standing Volume of Trees with dbh > 40 cm*, and (3) *dbh > 60 cm*, was used for quantifying the occurrence of large and very large trees, which is of avail for several of the ecosystem services of interest in this study. (4) The *Volume Share of Norway spruce*, expresses the volume share of the region’s key economic tree species as a dimensionless number between zero and one. (5) The *Volume Increment* ($m^3/ha/year$) is the mean annual wood volume increment between two subsequent points in time in the simulation. (6) The *Harvest Amount* ($m^3/ha/year$) is a mean annual value in the same sense as volume increment. (7) The *Harvest Increment Ratio* is the quotient of the harvested wood volume and the volume increment of the same period. (8) The *Species Profile Index* (Pretzsch 2010, p. 281) is an extension of the

Shannon diversity index (Shannon 1948) that evaluates the overall diversity resulting from the species richness and the vertical stand structure (the range of values being between 0 for monospecific mono-layered stands, and 2 or even more for uneven-aged mixed forests). (9) *Coarse Deadwood* (m^3/ha) is the amount of above ground deadwood with a diameter of at least 7 cm over bark.

Fuzzy logic evaluation of balanced wood production

In this section, we will describe the evaluation of the ecosystem service “balanced wood production” and shortly glance into the most important principles of fuzzy logic as we move along. A full explanation of fuzzy logic basics, however, would be beyond the scope of this paper. However, in order to provide a deeper background in an application-oriented context, we included a more detailed and more complete overview of fuzzy logic using the example of balanced wood production in the supplement to this paper (Supplementary Information S1). Note that, in this article and in the supplement, we deliberately did not choose the rigorous introduction approach as one would find it in textbooks about fuzzy logic. We rather tried to explain it from a very strict and practical application perspective, leaving out all theory that is not absolutely required. For readers who are interested in a more formal and deeper introduction, we recommend modern textbooks, e.g., Buckley and Eslami (2002).

Before we delve into methodological issues, we should mention what exactly we mean with the term “balanced wood production”: In this study, we would like to understand “wood production” as the amount of wood which is actually harvested during a given period of time (10 years in our application) and (at least theoretically) available on the market as a commodity. This wood production is the more “balanced” the more it coincides with the wood increment during the same period of time. One could rightly argue that an equality of harvest and increment is the definition of “sustainable wood production.” However, since the very beginning of forest science, a multitude of sophisticated concepts for assessing sustainable wood production under a broad variety of conditions have been developed which is the reason for our choice of a more cautious terminology. In addition, while an equality of increment and harvest seems preferable in most situations, a less balanced wood production might be sometimes desired under certain circumstances (e.g., in a transition from one silvicultural concept to the other). Using the more neutral wording “balanced” instead of the highly connoted term “sustainable,” seems to be advisable from this angle of view as well.

When we propose to evaluate the ecosystem service “balanced wood production,” critical readers might argue that applying a fuzzy evaluation system for this ecosystem service makes not too much sense, because the key ingredient

variables we used, annual wood volume increment, and annual harvest are perfectly measurable. We do not at all advocate for withholding these numbers from stakeholders and decision-makers; we see, however, an advantage in additionally providing an assessment that results from a combination of both, increment and harvest, because it reduces complexity while providing the essential information.

The idea of the assessment is that on the one hand, the absolute level of increment determines the potential of balanced wood production, but that this is penalized on the other hand if the increment and the harvest do not match. In this concept, obviously, the more the harvest differs from the increment in both directions the less balanced it is. In other words, continuous underharvesting and overharvesting are

both deviations from “balancedness.” Besides the obvious overharvesting, we also considered underharvesting as unbalanced in a negative sense as it does not scoop out the potential and rules out future silvicultural options due to accumulating risk (Cameron 2002). Our fuzzy logic evaluation system was thus designed in a way that the increment, being the biological basis, defines the possible maximum performance, and that an unfavorable ratio of harvest and increment will reduce (i.e., penalize) that performance in turn. The whole rule set reflecting this concept is visualized in Table 1 which will be explained below. But before rules can be applied, the input variable values have to be assigned to fuzzy sets.

In Fig. 2, we show the attribution of the continuous input variables “volume increment” and “harvest increment ratio”

Table 1 Rule set for the assessment of balanced wood production

| Volume Increment | Harvest Increment Ratio | | | | |
|------------------|-------------------------|--------|------------|--------|-----------|
| | very low | low | normal | high | very high |
| very low | red | red | red | red | red |
| low | red | red | orange | red | red |
| medium | red | orange | yellow | orange | red |
| high | orange | yellow | green | yellow | orange |
| very high | yellow | green | dark green | green | yellow |

| Legend | very low | low | medium | high | very high |
|--------------------------|----------|--------|--------|-------|------------|
| Balanced Wood Production | red | orange | yellow | green | dark green |

The rule set consists of a matrix which combines the annual wood volume increment per unit area with the ratio of harvest and increment. In this rule system, all combinations use the AND operator. The color codes “red,” “orange,” “yellow,” “green,” “dark green” represent the balanced wood production assessments “very low,” “low,” “medium,” “high,” and “very high,” respectively”

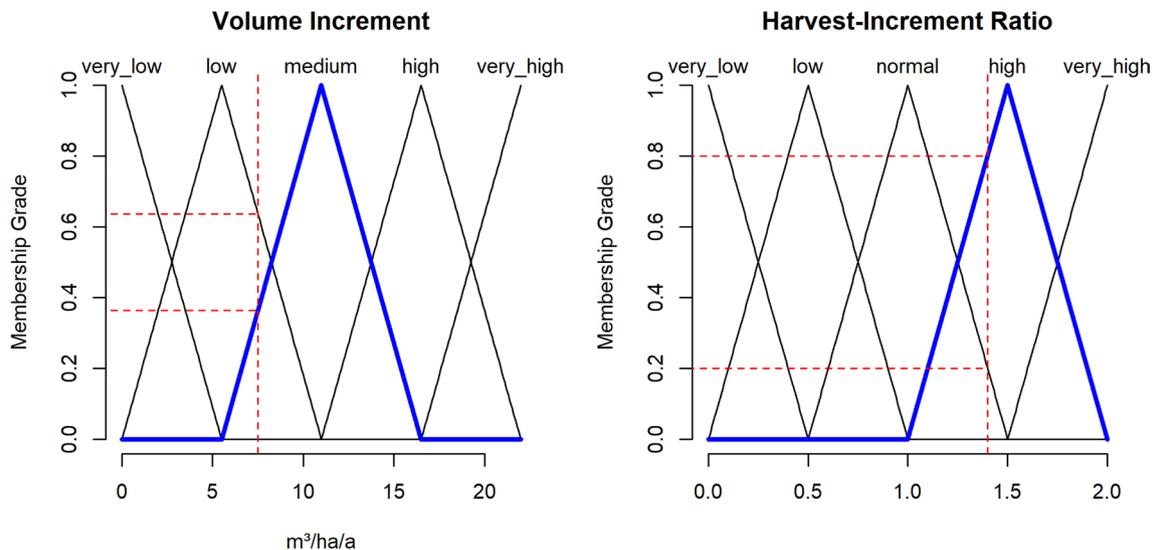


Fig. 2 Fuzzy sets and fuzzyfication of input variables. Left: Volume increment, right: Harvest-increment ratio. In the left diagram the membership function for the fuzzy set “medium volume increment” is highlighted in bold and blue; the same is done in the right diagram for the membership function of the fuzzy set “high harvest-increment ratio.” The dashed lines in the left diagram show how an arbitrarily

chosen increment of 7.5 m³/ha/a corresponds to a membership grade of 0.64 and 0.36 to the fuzzy sets “low” and “medium” respectively. In the right diagram we show how a harvest increment ratio of, e.g., 1.4 translate into a membership grade of 0.2 and 0.8 to the fuzzy sets “normal,” and “high,” respectively

to different fuzzy sets representing the categories “very low,” “low,” “medium/normal,” “high,” and “very high.” Note, that these categories are “fuzzy”; there are typical values for each category, and if a given input value is near such a typical value, its membership grade for the corresponding category is high (i.e., near 1). Away from typical values, membership grades are low; far away, they are zero. Note that fuzzy sets are not necessarily defined as isosceles triangles—many kinds of shapes have proven useful (see Buckley and Eslami 2002; Zadeh 1965). We are using equally sized isosceles triangles for all categories of one input variable in this study simply, because more complicated shapes were not required for our purpose. Typically, fuzzy sets overlap, so that one input value can belong to more than one fuzzy set (cf. Fig. 2, where the example value of volume increment is medium and low at the same time). We see here a very important advantage of fuzzy logic compared to other approaches, as the classic “number-on-the-edge problem” does not exist. One can always argue about what *exactly* is, e.g., a typical “high” volume increment and where *exactly* to delineate it from “medium” or “low.” While this typically makes a crucial (and actually an artefact) difference in a classic binary logic-based evaluation, fuzzy set-based evaluations will be robust and plausible as long as the “rough picture” is appropriate. As Zadeh (1965, p. 339) puts it: “Essentially, such a framework provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria of class membership [...]” Our decisions about how to arrange the fuzzy sets (what is a “high,” what is a “low” increment, etc.), were based on our overview of forest inventory and research plot data from central Europe, and our professional experience as growth and yield specialists. Throughout this study, we always used five fuzzy sets (from “very low” to “very high”) per variable, because this division seemed intuitive and sufficient to cover the required nuances.

Once the input variable values are assigned to categories (i.e., fuzzy sets), they can be evaluated with a system of rules. Rule-based evaluation is clearly not exclusively tied to fuzzy logic, but due to the blurring of fuzzy sets, the “blurred” reasoning of the human mind is nicely mimicked, which stands in contrast to classic binary logic. Two examples for rules out of the rule system for evaluating balanced wood production are:

1. IF volume increment is *low* AND harvest increment ratio is *high* THEN balanced wood production is *very low*
2. IF volume increment is *medium* AND harvest increment ratio is *normal* THEN balanced wood production is *medium*

Note that if an input value belongs to more than one category (e.g., if volume increment belongs to “low” and

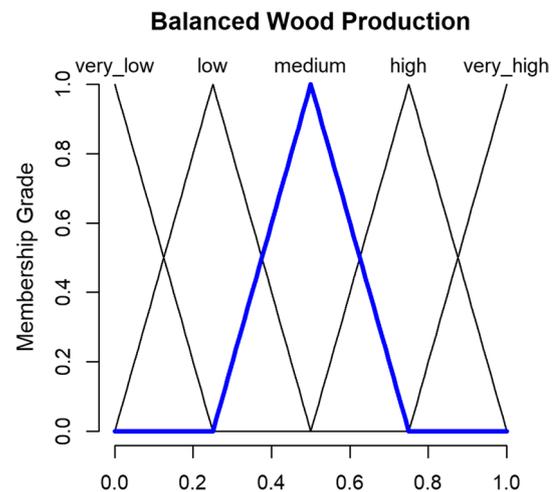


Fig. 3 Balanced wood production as a fuzzy goal variable. It consists of five fuzzy sets defining the categories “very low,” “low,” “medium,” “high,” and “very high.” The category “medium” is highlighted in blue. Balanced wood production is mapped to the number range [0, 1] as spanned by the horizontal axis

“medium” simultaneously), the rules for both categories will be applied. The higher the membership grades of the input variables to a rule, the more weight will be given its output. In Fig. 3, we show how we mapped the fuzzy output categories very low, low, medium, high, and very high to the numbers between 0 and 1. See Supplementary Information 1 for how this works in detail. Also note the operator AND used in both example rules. While we exclusively used the AND operator in all rule systems shown in this study, there exist also the operators OR, and NOT which are extensions of the classic operators to fuzzy logic (see Table S1 in the supplement for more details).

We show the whole rule set for balanced wood production in Table 1. This table can be seen as a matrix, the rows and columns representing the categories of volume increment and of the harvest increment ratio, respectively. Each matrix cell is an AND combination of a volume increment and a harvest increment ratio category. The color of a matrix cell represents the assessment of balanced wood production (“very low,” “low,” ..., “very high”; corresponding to red, yellow, ..., dark green) for the corresponding input variable combination, e.g., the bottom right cell in Table 2 expresses the rule “IF volume increment is *very high* AND harvest increment ratio is *very high* THEN balanced wood production is *medium*.”

The rule set reflects exactly the evaluation idea explained above and was designed by consensus of the authors’ group; it clearly expresses the concept that the level of volume increment determines what is possible, but that over-

underharvesting likewise mean a deviation from balancedness, thus lowering the resulting assessment of balanced wood production.

Applying each single rule that applies to a given combination of the two input variables (volume increment, harvest increment ratio) yields a membership value for the respective category of the output variable (balanced wood production); the output of all rules together forms a so-called fuzzy inference (see Meyer and Hornik 2009, and Figure S1 in the supplement), from which, finally, one single value between 0 and 1 is derived (“defuzzification”). This value is the evaluation result and, e.g., 0, 0.5, 1 would indicate very low, medium, and high balanced wood production, respectively, with all values in between possible. See Supplementary Information S1 for an in-depth description of the procedure.

Fuzzy logic evaluation of biodiversity

The fuzzy logic system developed in this study for assessing biodiversity covers four crucial forest biodiversity aspects (cf. Felton et al. 2016): (i) tree species diversity, (ii) forest structure, (iii) deadwood, and (iv) the presence of very large trees. Relevant information about all these aspects could be taken from studies and meta studies by Dieler et al. (2017), Lindenmayer et al. (2012), Lassauce et al. (2011), Müller and Büttler (2010), and Hansen et al. (1991). In our evaluation system, the aspects “tree species diversity” and “forest structure” were both covered with the Species Profile Index (Pretzsch 2010, pp. 281). The aspect “deadwood” was quantified by the average amount of coarse deadwood per unit forest area, and the presence of very large trees is expressed by the volume of trees with dbh > 60 cm per ha. Figure 4

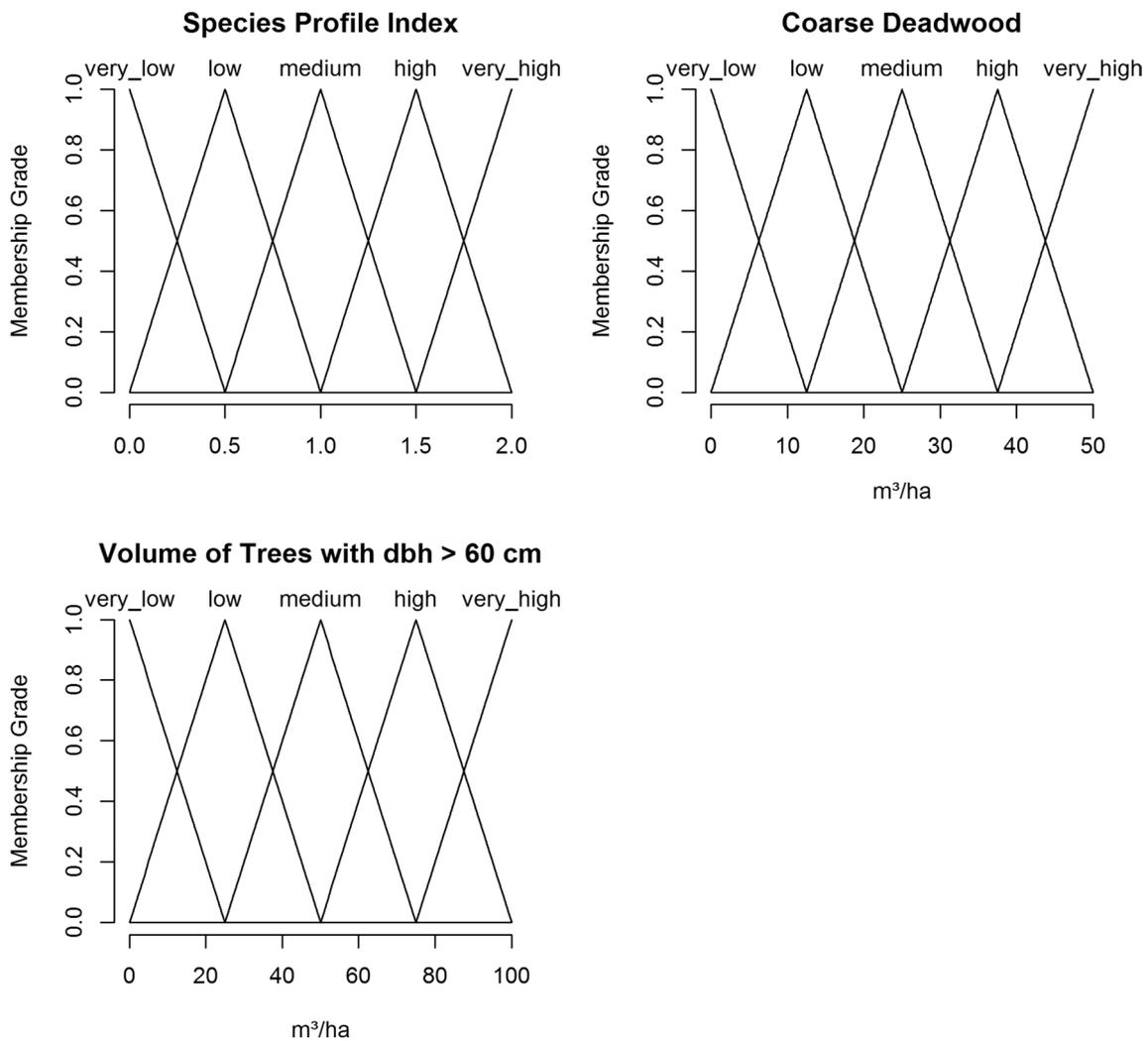


Fig. 4 Transformation of the value range of the input variables for the biodiversity evaluation into fuzzy sets. In case an input variable exceeds the range covered by the fuzzy sets it is trimmed accordingly,

e.g., a Species Profile Index of 2.31 would be cut to 2.0 and given a membership grade of 1.0 in the fuzzy set “very high”

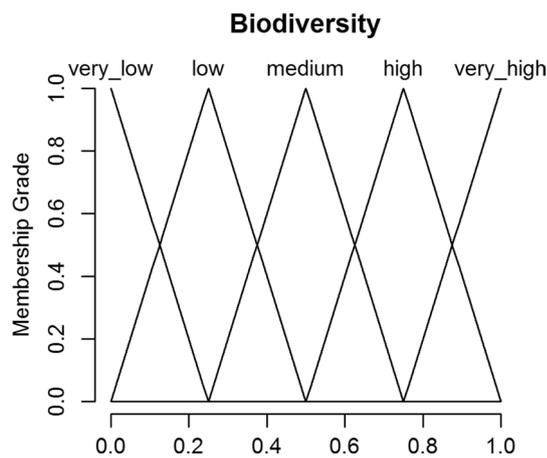


Fig. 5 The fuzzy output variable of the biodiversity assessment. The categories “very low,” “low,” “medium,” “high,” and “very” high are mapped to the number range [0, 1] as spanned by the horizontal axis

shows the range of values of these input variables and how they translate into fuzzy sets. For the species profile index, we defined “very low,” “medium,” and “very high” as typically represented by values of 0, 1, and 2, respectively. This is in accordance with what we typically found when working with extensive forest inventory and long-term research plot data from Southern Germany. In a similar way, the range of values for the volume of very large trees was adjusted. The range for deadwood volumes (0–50 m³/ha) was set to be in line with the values reported by Müller and Bütler (2010); the medium value (25 m³/ha) was defined roughly at the current average deadwood amount in the forests of Germany according to the latest National Forest Inventory. As Fig. 5 shows, the output variable which represents the assessed overall biodiversity is mapped to the number range [0, 1] with equally broad categories.

Table 2 visualizes the rule system for biodiversity assessment. It can be conveniently depicted as a set of five matrices, each one for one fuzzy value of the Species Profile Index (very low, low, medium, high, very high). Each matrix combines the volume of trees with dbh > 60 cm with

the coarse deadwood amount. The color codes in the matrix cells represent the biodiversity assessments “very low,” “low,” “medium,” “high,” and “very high,” respectively. Each cell stands for a fuzzy rule in a very simple way: Take the top left cell from the first matrix as an example. The corresponding rule is: IF the Species Profile Index is very low AND the coarse deadwood amount is very low AND the volume of large trees is very low THEN biodiversity is very low. Thus, basically, this rule system functions in the same way as was described above for balanced wood production. However, as there are three input variables for biodiversity, more than one matrix is required for visualizing it.

The idea behind the rule system is that stand structure and diversity, as given with the species profile index, defines the “base level” for overall biodiversity, because it is crucial for the overall availability and variety of habitats of plants and animals. For this reason, structure and tree species diversity play a key role in many approaches of evaluating forest naturalness and biodiversity (Winter 2012; Winter et al. 2010; Tierney et al. 2009; McElhinny et al. 2005; Hansen et al. 1991). Thus, if the species profile index is low (i.e., tree species and structural diversity is poor), we allow even high amounts of deadwood and very large trees to contribute in a confined way only to biodiversity. This is assumed to be considerably different at medium and higher levels of the species profile index. Here, there is considerable differentiation of biodiversity with the deadwood amount and the occurrence of large trees, and highest overall biodiversity values are not possible without both components (Table 2). The rule set in its present formulation was developed—based on the literature mentioned in the beginning of this section—by debate and consensus within the scientific team at the Chair for Forest Growth and Yield, which all authors belong to, and which is lead by the senior author. During the last two decades, the connection of biodiversity to variables that can be measured in the forest and provided by simulation models has been one of the focuses of our research (Dieler et al. 2017; Biber et al. 2015; Pretzsch 2005; Pretzsch and Puumalainen 2002).

Table 2 Rule set for biodiversity assessment. The rule set consists of five matrices, each one for a fuzzy value of the Species Profile Index (very low, low, medium, high, very high). Each matrix combines the volume of trees with dbh > 60 cm with the coarse deadwood amount. The color codes “red,” “orange,” “yellow,” “green,” “dark green” represent the biodiversity assessments “very low,” “low,” “medium,” “high,” and “very high,” respectively.” More explanations in the text

Species Profile Index **very low**

Coarse Deadwood Amount

| | | very low | low | medium | high | very high |
|-------------|-----------|----------|--------|--------|--------|-----------|
| Vol > 60 cm | very low | red | red | red | red | orange |
| | low | red | red | red | red | orange |
| | medium | red | red | red | red | orange |
| | high | red | red | red | orange | orange |
| | very high | orange | orange | orange | orange | orange |

Species Profile Index **low**

Coarse Deadwood Amount

| | | very low | low | medium | high | very high |
|-------------|-----------|----------|--------|--------|--------|-----------|
| Vol > 60 cm | very low | red | orange | orange | orange | orange |
| | low | red | orange | orange | orange | orange |
| | medium | orange | orange | orange | orange | yellow |
| | high | orange | orange | orange | yellow | yellow |
| | very high | orange | orange | yellow | yellow | yellow |

Species Profile Index **medium**

Coarse Deadwood Amount

| | | very low | low | medium | high | very high |
|-------------|-----------|----------|--------|--------|--------|------------|
| Vol > 60 cm | very low | red | orange | orange | yellow | yellow |
| | low | orange | orange | orange | yellow | yellow |
| | medium | orange | orange | orange | yellow | green |
| | high | yellow | yellow | yellow | green | green |
| | very high | yellow | yellow | green | green | dark green |

Species Profile Index **high**

Coarse Deadwood Amount

| | | very low | low | medium | high | very high |
|-------------|-----------|----------|--------|------------|------------|------------|
| Vol > 60 cm | very low | orange | orange | yellow | green | green |
| | low | orange | yellow | green | green | green |
| | medium | yellow | green | green | green | dark green |
| | high | green | green | green | green | dark green |
| | very high | green | green | dark green | dark green | dark green |

Species Profile Index **very high**

Coarse Deadwood Amount

| | | very low | low | medium | high | very high |
|-------------|-----------|------------|------------|------------|------------|------------|
| Vol > 60 cm | very low | yellow | yellow | green | green | dark green |
| | low | yellow | yellow | green | green | dark green |
| | medium | green | green | green | dark green | dark green |
| | high | green | dark green | dark green | dark green | dark green |
| | very high | dark green |



Fuzzy logic assessment of storm and bark beetle damage resistance

While we are seeing the *resistance* against storm and bark beetle damages as a regulating ecosystem service (in accordance with de Groot et al. 2010, and Millenium Ecosystem Service Assessment 2005), we assessed it by means of its complement, i.e., we designed a fuzzy evaluation system that actually assesses the risk. We deemed that more straightforward, because forest risk assessment, especially with regard to storm and bark beetle damages, is covered by a large body of scientific literature and practitioner guidelines as cited below. As we map the risk on a range of risk values from 0 to 1, the risk resistance value results simply from subtracting the risk value from 1.

The case study area Augsburg Western Forests, as a typical region where Norway spruce is cultivated outside its natural range, is potentially vulnerable to storm damages

and subsequent bark beetle infestations (*Ips typographus*). Although storms and bark beetles are considerably different damaging agents, we decided to deal with the combined risk of both because they are strongly intertwined in practice. On the level of detail we chose for our study, there is a broad overlap in the factors which determine the risk of both:

For assessing this combined risk on landscape level we used three input variables (see their fuzzy set representation in Fig. 6), namely (i) the volume share of the risk species Norway spruce (*Picea abies*), (ii) the volume of trees with a dbh > 40 cm per unit area, and (iii) the species profile index. While the choice of the first variable seems obvious (cf. Stadelmann et al. 2014), the second one relates to the fact that the risk of storm damages increases with tree size, whereby heights of about 30 m and more—typically reached at diameters about 40 cm in the case study region—are a critical threshold (Kaulfuß 2012). The bark beetle *Ips typographus* also typically requires

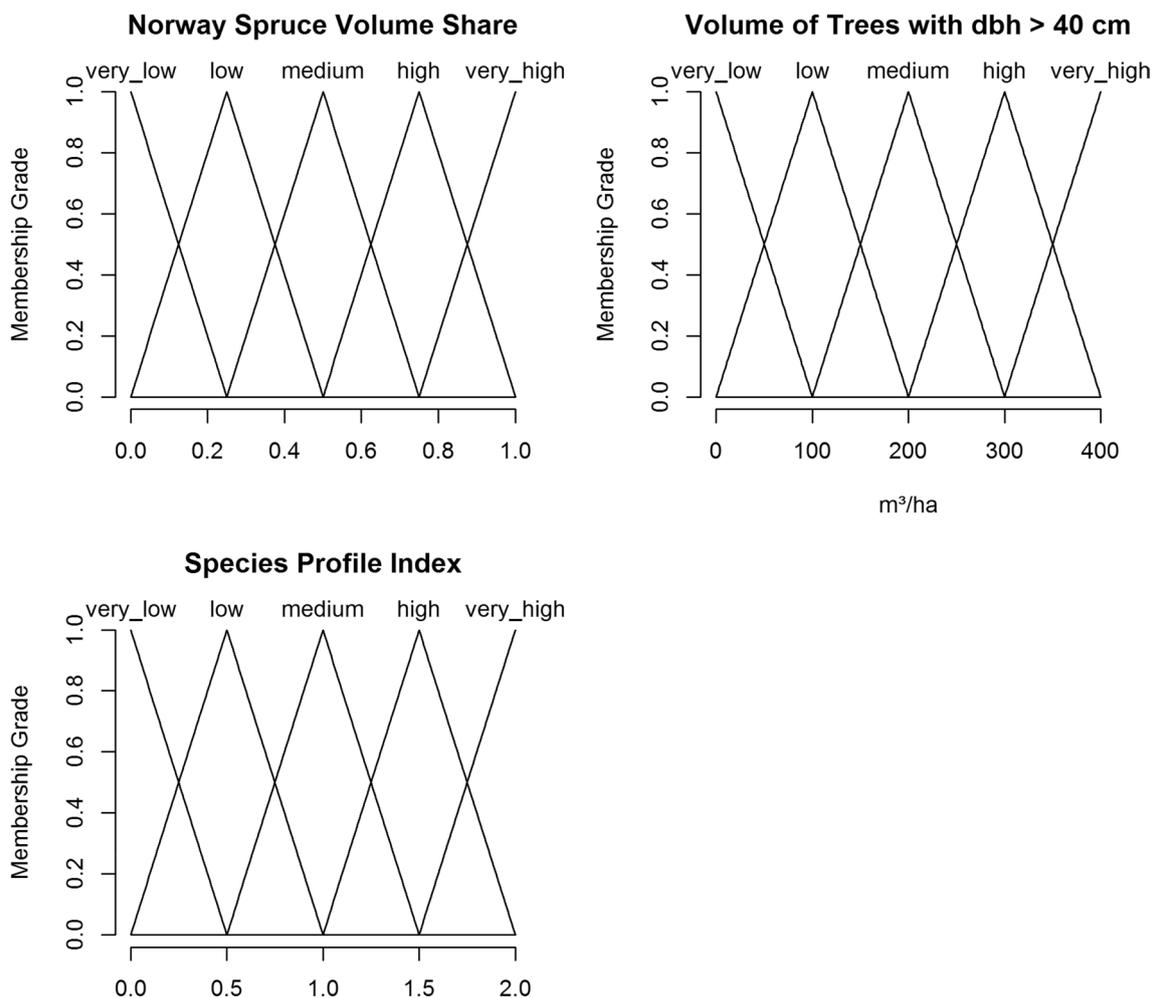


Fig. 6 Transformation of the value range of the input variables for the storm and bark beetle risk evaluation into fuzzy sets. In case an input variable exceeds the range covered by the fuzzy sets it is trimmed

accordingly, e.g., a Species Profile Index of 2.31 would be cut to 2.0 and given a membership grade of 1.0 in the fuzzy set “very high”

Table 3 Rule set for the assessment of storm and bark beetle risk. The rule set consists of five matrices, each one for a fuzzy value of the volume share of Norway spruce (very low, low, medium, high, very high). Each matrix combines the volume of trees with dbh > 40 cm with the Species Profile Index. The color codes “red”, “orange”, “yellow”, “green”, “dark green” represent the risk assessments “very high”, “high”, “moderate”, “low”, and “very low”, respectively”

Share Norway Spruce very low

| | | Species Profile | | | | |
|-------------|-----------|-----------------|------------|------------|------------|------------|
| | | very low | low | medium | high | very high |
| Vol > 40 cm | very low | dark green | dark green | dark green | dark green | dark green |
| | low | dark green | dark green | dark green | dark green | dark green |
| | medium | dark green | dark green | dark green | dark green | dark green |
| | high | dark green | dark green | dark green | dark green | dark green |
| | very high | dark green | dark green | dark green | dark green | dark green |

Share Norway Spruce low

| | | Species Profile | | | | |
|-------------|-----------|-----------------|------------|------------|------------|------------|
| | | very low | low | medium | high | very high |
| Vol > 40 cm | very low | dark green | dark green | dark green | dark green | dark green |
| | low | dark green | dark green | dark green | dark green | dark green |
| | medium | dark green | dark green | dark green | dark green | dark green |
| | high | yellow | yellow | dark green | dark green | dark green |
| | very high | yellow | yellow | dark green | dark green | dark green |

Share Norway Spruce medium

| | | Species Profile | | | | |
|-------------|-----------|-----------------|------------|------------|------------|------------|
| | | very low | low | medium | high | very high |
| Vol > 40 cm | very low | yellow | dark green | dark green | dark green | dark green |
| | low | yellow | yellow | dark green | dark green | dark green |
| | medium | yellow | yellow | dark green | dark green | dark green |
| | high | orange | orange | dark green | dark green | dark green |
| | very high | red | orange | dark green | dark green | dark green |

Share Norway spruce high

| | | Species Profile | | | | |
|-------------|-----------|-----------------|--------|--------|------------|------------|
| | | very low | low | medium | high | very high |
| Vol > 40 cm | very low | yellow | yellow | yellow | dark green | dark green |
| | low | orange | orange | yellow | dark green | dark green |
| | medium | orange | orange | yellow | dark green | dark green |
| | high | red | orange | yellow | dark green | dark green |
| | very high | red | red | orange | yellow | dark green |

Share Norway spruce very high

| | | Species Profile | | | | |
|-------------|-----------|-----------------|--------|--------|--------|------------|
| | | very low | low | medium | high | very high |
| Vol > 40 cm | very low | yellow | yellow | yellow | yellow | dark green |
| | low | orange | orange | orange | yellow | dark green |
| | medium | red | red | orange | yellow | dark green |
| | high | red | red | orange | yellow | dark green |
| | very high | red | red | orange | yellow | dark green |



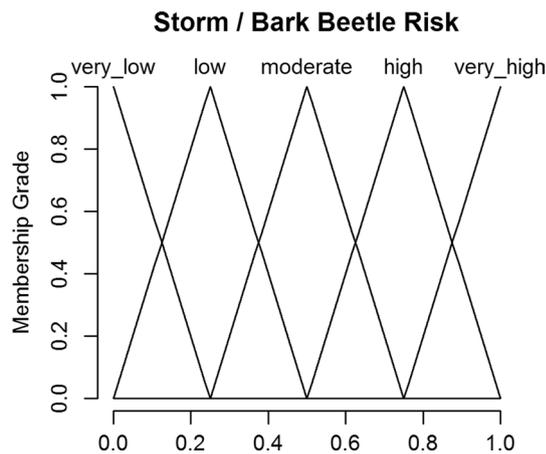


Fig. 7 The fuzzy output variable of the storm and bark beetle risk assessment. The categories “very low,” “low,” “moderate,” “high,” and “very” high are mapped to the number range [0, 1] as spanned by the horizontal axis

diameters about this size and greater for completing its life cycle (Wermelinger 2004; Becker and Schröter 2000). The third variable, the Species Profile Index, at its low value range indicates especially endangered forest areas; such are dominated by monospecific and uniform stands (Albrecht 2009; Wermelinger 2004). At its high value range, the Species Profile indicates forest conditions which are considered particularly robust against both storm damages and bark beetle attacks, i.e., multilayered mixed forests. This concept is formulated in the set of rules which is visualized in Table 3. When formulating the rule set, we attempted to incorporate and combine the crucial aspects taken from the literature cited above but especially from practitioner guidelines such as Biermayer (2017), Hein et al. (2008), and Kaulfuß (2012). A major assumption is that the risk relevance of the species profile index and the volume of larger trees increases with increasing shares of Norway spruce (see Table 3). As can be taken from Fig. 7, the goal variable, a risk indicator for storm and bark beetle damages is mapped on the number range of [0, 1] in the same way it is done for biodiversity and balanced wood production.

Fuzzy logic evaluation of the recreational value

As argued in the introduction, we focus on forest structure variables when evaluating the recreational value, well aware that this is only one aspect of this cultural service. If relevant potential input data beyond structure are available, there is no reason why these could not be included in fuzzy logic evaluation systems. With regard to forest structure and what it means for a forest’s recreational value, there is a broad variation in what forest features are liked or disliked by the

general public (Hull et al. 2001; Skår 2010). As a general trend documented in the literature (cf. Paletto et al. 2017; Edwards et al. 2011; Bernasconi and Schroff 2008; Bradley and Kearney 2007; Ammer and Pröbstl 1991), most recreationalists prefer a managed forest with a low visibility of the actual management and its effects, and a “natural” forest impression (like mixed stands and large trees). Hull et al. (2001) coin the term *cultured naturalness* for this preference. Gundersen and Frivold (2008) give, as a result of an extensive literature review, an overview of preferences that turned out very useful in designing the evaluation system at hand.

Based on literature study and discussions with local practitioners from the Augsburg government agency for food, agriculture and forestry, we structured the input information our simulator can provide into three aspects. See Hernández-Morcillo et al. (2013) for the importance of involving local knowledge when evaluating cultural services. These aspects are deemed relevant for the acceptance of a forest area by recreationalists; we called them “Species and Structural Diversity,” “Deadwood (natural and harvest residues),” and “Stand Density and Management Intensity.” For each of these aspects, the fuzzy logic system estimates an acceptance value with the base categories “very low,” “low,” “medium,” “high,” and “very high” (Figs. 8, 9, 10, right diagrams) acceptance of the forest by recreationalists. These three acceptance values are then separately defuzzified (i.e., translated into a number between 0 and 1, see Figure S1 in the supplement) and eventually aggregated into an overall acceptance value.

The two input variables for the aspect “Species and Structural Diversity” are the Species Profile Index and the volume of trees with dbh > 40 cm per unit area (Fig. 8). The former was chosen as at low values it characterizes mono-layered monospecific forest which would typically be perceived as an “industrial forest” by the public. At very high values it would characterize very rich-structured conditions, which however implies low visibility due to an abundant layer of small trees. Medium values are typically obtained for moderately structured mixed forests dominated by two main tree species. Including this variable is in line with findings by Gundersen and Frivold (2008) that tree size diversity, and species mixture are relevant (see also Paletto et al. 2017; De Valck et al. 2014; Hull et al. 2001). This variable also allowed us to include in the rule formulations that “a feeling of accessibility and provision of a view” is important (Gundersen and Frivold 2008); at high values of the Species Profile Index we consider this feeling impaired due to abundant understory.

The second variable, the volume of trees with dbh > 40 cm is intended to cover the fact that tree size is an important feature for the aesthetic perception of a forest (Edwards et al. 2011; Gundersen and Frivold 2008; Stölb 2005; Daniel and Boster 1976). A very low coverage would indicate a lack of

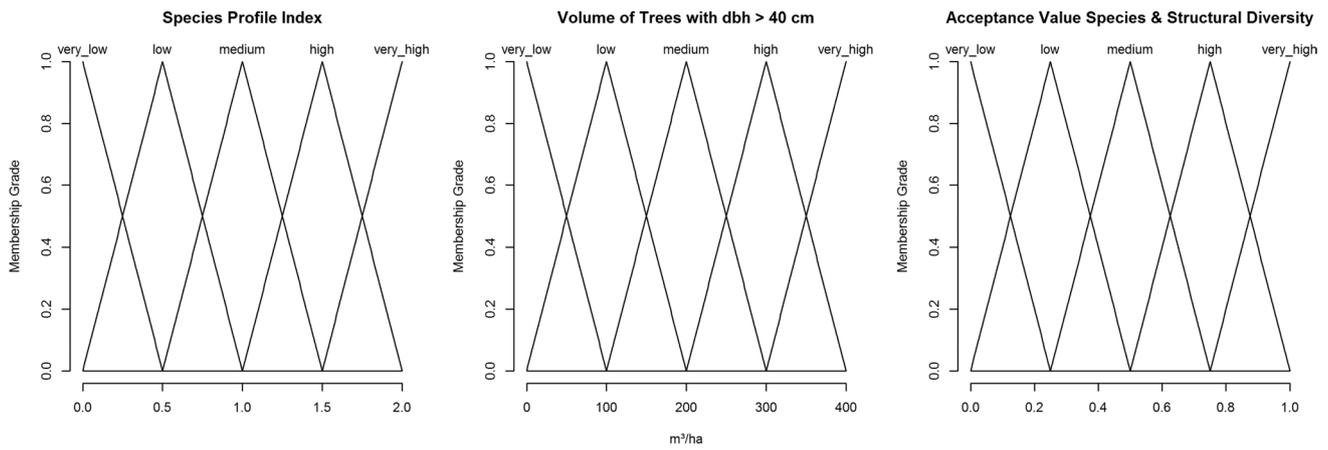


Fig. 8 Fuzzy variables for the first recreation and aesthetics aspect “Species and Structural Diversity.” Left: Input variable Species Profile Index; middle: Input variable Volume of Trees with dbh > 40 cm; right: Output variable Acceptance Value Species and Structural Diversity

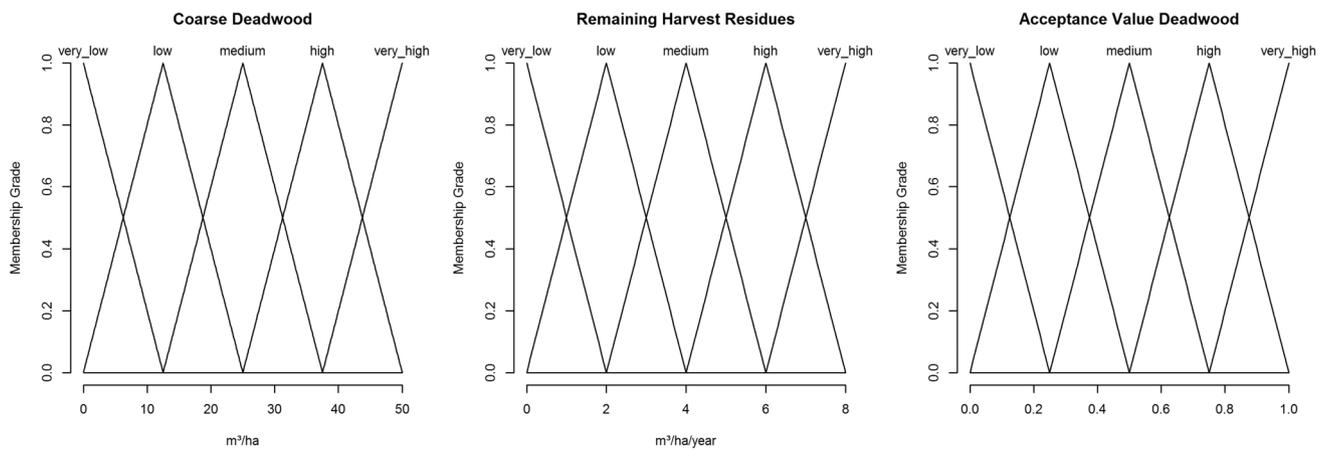


Fig. 9 Fuzzy variables for the second recreation and aesthetics aspect “Deadwood.” Left: Input variable Coarse deadwood amount; middle: Input variable Remaining Harvest Residues; Output variable Acceptance Value Deadwood

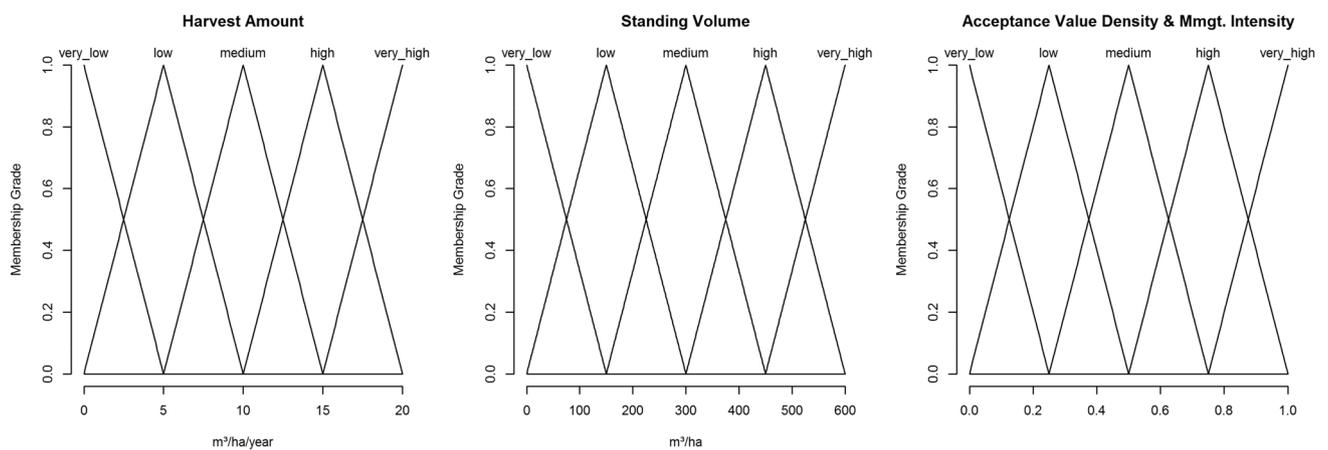


Fig. 10 Fuzzy variables for the third recreation and aesthetics aspect “Density and Management Intensity.” Left: Input variable Annual Harvest Amount; middle: Input variable Standing Volume; Output variable Acceptance Value for Density and Management Intensity

“attractive trees.” In general, more mature trees would lead to a higher acceptance; however, an extremely high coverage might even infer a dark and threatening impression (Skår 2010). The corresponding rule set is visualized in Table 4; the fuzzy representation of the related variables can be taken from Fig. 8.

The second aspect of acceptance “Deadwood (natural and harvest residues)” covers the coarse deadwood accumulated in the forest as a result of natural mortality and/or possibly low quality logs left in the forest during a past harvest operation. See Kohsaka and Flitner (2004) for the importance of this distinction. While the perception of natural deadwood by recreationalists has not frequently been the main point of studies so far, and the reported results are complex and heterogeneous (see the overview given by Rathmann et al. (2020), we interpret and apply the available results for our case study in way that expresses a generally skeptical attitude toward deadwood (Pelyukh et al. 2019; Arnberger et al. 2018; Edwards et al. 2012): While the absence or low amounts of such deadwood are frequently associated with a “clean and healthy forest,” and medium amounts are tolerated, high amounts are often perceived as somewhat “morbid.”

The other aspect of deadwood included is the average amount of fresh harvest residues remaining in the forest per year and unit area. Here, the available results are very unambiguous (Edwards et al. 2012; Gundersen and Frivold 2008): The less such harvest residues are visible in the forest, the higher the acceptance while large amounts of harvest residues are often seen as the ugly outcomes of what is perceived as “mismanagement” or “forest destruction.” Figure 9 shows both input variables and the corresponding acceptance value in their representation as fuzzy sets. Table 5 visualizes the associated rule set.

The third aspect is called “Stand Density and Management Intensity.” It is based on the average standing wood volume per unit area and the amount of harvested wood per year and unit area. The amount of standing wood volume has a lot to do with what could be called “forest impression.” While smaller low-volume areas can be very attractive for recreationalists, low volumes in a whole landscape would be less acceptable, especially when going along with high harvest amounts, because this would be perceived as a forest exploitation. Very high standing volumes can provoke a feeling of a threatening forest (as conveyed archetypally, e.g., in the Grimm brother’s tales). See Skår (2010), Hull

and Buhyoff (1986), Ribe (1989), Savolainen and Kellomäki (1981) for the esthetic perception of forest density. High harvest amounts (often connected with the presence of heavy machinery) are always perceived as unaesthetic (Ribe 1989), see also De Valck et al. (2014), and Ford et al. (2014). While harvest amounts correlate with the amounts of harvest residues produced (included in the second aspect “Deadwood”), this is not the same. Managers decide what happens to the harvest residues, i.e., to what extent they are left in the forest or removed and used for energy production; this distinction can also be made in our simulation system. For this reason, both, the harvest amount as well as the harvest residues remaining in the forest were included in the evaluation of recreational and aesthetic acceptance. Figure 10 shows the corresponding variables in fuzzy set representation. Table 6 visualizes the corresponding rule set.

As mentioned above, all three aspects are first evaluated separately, and we obtain a number between 0 and 1—the acceptance value—for each aspect; we call these three acceptance values x , y , and z . In the final step we aggregate these three into one overall acceptance value. This is achieved by calculating a weighted sum of the three value’s t-norm and s-norm (see Supplementary Information S1). In a given fuzzy logic concept, the t-norm stands for the concept of intersection, i.e., the lowest of the three acceptance values dominates the aggregation result (“minimum principle”). In the specific fuzzy logic concept we chose (“product,” see Table S1 in the supplement), the t-norm is simply the product of the three values:

$$T(x, y, z) = xyz$$

The s-norm represents the principle of union, i.e., the largest value dominates the aggregation result. The corresponding s-norm to the t-norm shown above is the algebraic sum

$$S(x, y, z) = x + y + z - xy - xz - yz + xyz$$

Our final acceptance value A is obtained as

$$A = \gamma \cdot T(x, y, z) + (1 - \gamma) \cdot S(x, y, z) \quad (1)$$

with the weight parameter γ which must be from the interval $[0, 1]$. For our evaluations, we set $\gamma = 2/3$ indicating that the worst of the three acceptance values dominates A , but that a considerable compensation is possible when the other two values are high.

Table 4 Rule set for the assessment of the acceptance aspect “Species and Structural Diversity.” The rule set consists of a matrix which combines the volume of trees with dbh > 40 cm with the Species Profile Index.

The color codes “red,” “orange,” “yellow,” “green,” “dark green,” represent the acceptance assessments “very low,” “low,” “medium,” “high,” and “very high,” respectively”

Aspect 1 Species and Structural Diversity

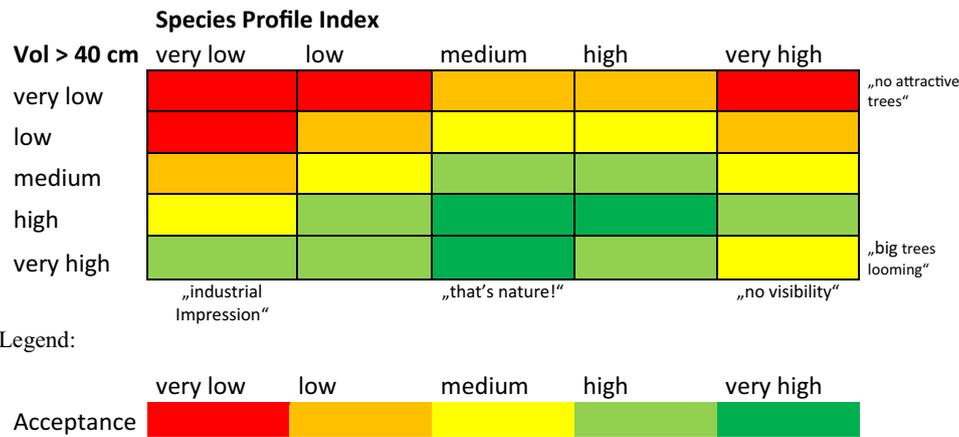


Table 5 Rule set for the assessment of the acceptance aspect “Deadwood.” The rule set consists of a matrix which combines the amount of remaining fresh harvest residues with the amount of coarse deadwood.

The color codes “red,” “orange,” “yellow,” “green,” “dark green,” represent the acceptance assessments “very low,” “low,” “medium,” “high,” and “very high,” respectively”

Aspect 2 Deadwood (natural and harvest residues)

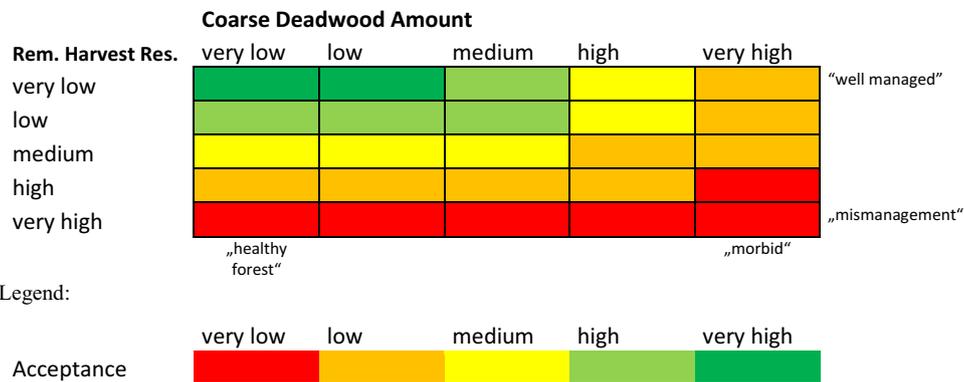
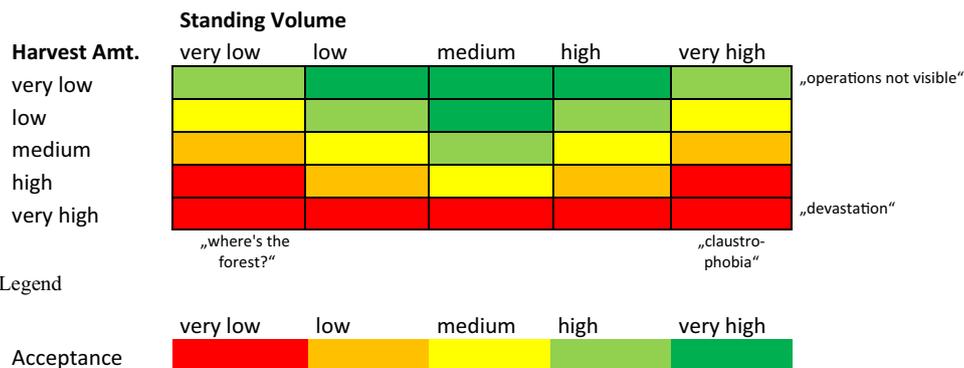


Table 6 Rule set for the assessment of the acceptance aspect “Stand Density and Management Intensity.” The rule set consists of a matrix which combines the annual harvest amount per unit area with the standing wood volume per unit area.

The color codes “red,” “orange,” “yellow,” “green,” “dark green,” represent the acceptance assessments “very low,” “low,” “medium,” “high,” and “very high,” respectively”

Aspect 3 Stand Density and Management Intensity



Evaluating the assessments of ecosystem service provision

The standard approach of evaluating estimates or predictions is to compare them with empirical data. This was not possible, however, with the assessments of ecosystem service provision obtained with our fuzzy logic systems, because their whole idea is to make variables accessible which are hard or even impossible to measure (see Introduction section). Instead, we checked all systems presented above for result plausibility above under systematic variations of the input variables, including extreme conditions and adjusted them accordingly before they were accepted. The outcomes from the final versions of the rule systems (as presented in the Results section) also underwent an important real-life test, when they were presented and discussed with stakeholders in two workshops. We elaborate about that in the Discussion section (subheading *Transparency*).

Results

Simulated input variables for the fuzzy evaluation

Before we show the outcomes of the fuzzy logic ecosystem service assessment, we outline the scenario outcomes, focused on those variables that were the input to the fuzzy evaluation (Fig. 11). As visible in the upper panel of Fig. 11, the multifunctional management scenario leads to very stable values of standing volume and volume increment. The harvest amounts are gradually receding until 2060 but stabilize after that. This goes along with strongly decreasing shares of Norway spruce throughout the simulation time (Fig. 11, bottom panel, left diagram). However, while the harvest increment ratio slightly decreases, it never substantially deviates from 1.0 (Fig. 11, middle panel, left diagram). In the production forest scenario, the initially unbalanced age-class distribution is fully kept or becomes even more pronounced. The latter is due to the very heavy initial harvests in the old stands, which are in large part considered overdue in the production forest concept. As these unbalanced age-class conditions are not mitigated, we observe strong oscillations in standing volume, volume increment and harvest amounts during the whole simulation time. As evident in Fig. 11 (upper panel) these oscillations are phase-delayed in a plausible manner. The Norway spruce shares in this scenario increase and stabilize at about 90% (Fig. 11, middle panel, left diagram); the harvest increment ratio strongly oscillates but seems—disregarding the initial extreme values—to be centered around 1.

In the setaside scenario the stands are overaging (relative to common forest practice) and approach their maximum density, therefore enormous standing volumes are accumulated (Fig. 11, top panel, left diagram). The increments in this scenario are initially high, but regressive on the long run (Fig. 11, top panel, middle diagram). The overaging of the stands in the setaside scenario is evident in the strongly accumulating volumes of trees with dbh > 40 cm and even > 60 cm (Fig. 11, middle panel, middle and right diagram). Both numbers are decreasing down to a constant low level in the production scenario, indicating the deliberate reduction of the rotation time span. In the multifunctional scenario, they are constant (dbh > 40 cm) or slightly increasing (dbh > 60 cm). The volume shares of Norway spruce in the setaside scenario are almost as high as in the production forest scenario (Fig. 11, top panel, left diagram); Norway spruce is dominating in the old stands and therefore also in the regeneration. It takes active management actions, as in the multifunctional scenario, to reduce the Norway spruce shares during the simulation period. The species profile index in the setaside scenario first increases considerably but drops gradually back toward the initial level with a further downwards tendency at the end of the simulation (Fig. 11, bottom panel, middle diagram). This pattern results from formerly managed forests first increasing structural richness but losing structure again as the stands move toward maximum density. For almost the whole simulation time, the multifunctional scenario follows the same trajectory as the setaside, only in the last 20 simulation years it stops receding and enters a slight upward tendency. Here, not only stand structure, but also increasing species richness plays an important role. As to be expected, the special profile index reaches lowest levels in the production forest scenario.

The coarse deadwood volume quickly rises and stabilizes at values between 80 and 90 m³/ha in the setaside scenario while remaining constant at about 20 m³/ha in the multifunctional forest (Fig. 11, bottom panel, right diagram). In the production forest, the deadwood volume strongly oscillates, with peaks at the times of high harvest when large amounts of harvest residues add to the stock of deadwood.

Ecosystem service provision - fuzzy logic evaluation

The fuzzy logic based evaluation of biodiversity shows distinctly different trends for all three scenarios, starting at a low level of biodiversity in the initial situation which represents the current real status of the forest (Fig. 12). The production forest scenario which creates mono-layered monospecific forests with few larger trees quickly stabilizes on a low level of biodiversity. In the setaside scenario biodiversity quickly increases up to intermediate to high levels, which is due to the steadily accumulating amounts of deadwood and initially increasing stand structural richness.

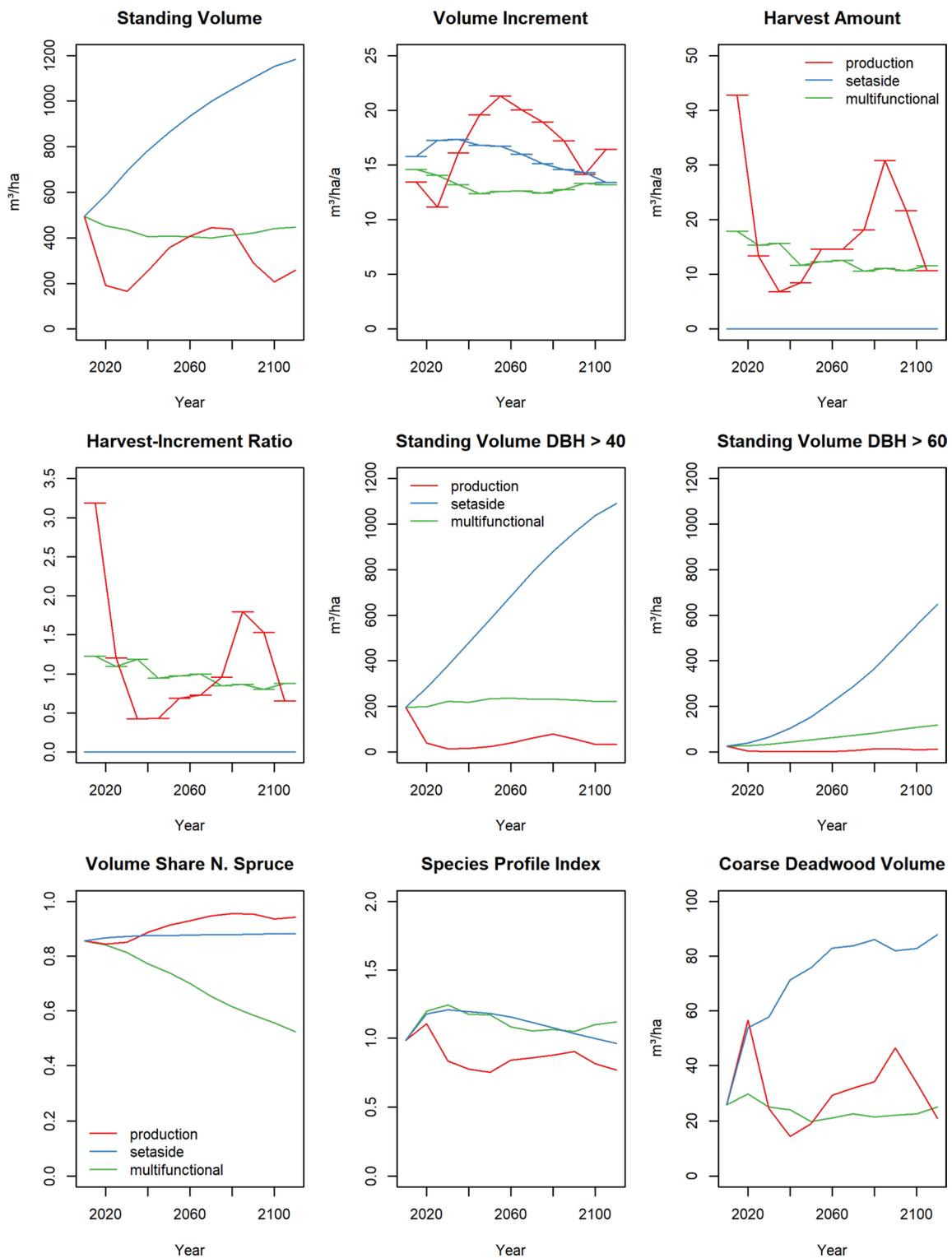


Fig. 11 Simulated development of the variables which are used as input for the fuzzy logic evaluation (see Sect. "Standard output variables"). All values are averages across the landscape. Volume Increment, Harvest Amount, and Harvest Increment Ratio are mean annual

values of 10-year periods (indicated by horizontal dashes). The colors red, blue, and green are used for the scenarios "production forest," "multifunctional forest," and "setaside," respectively

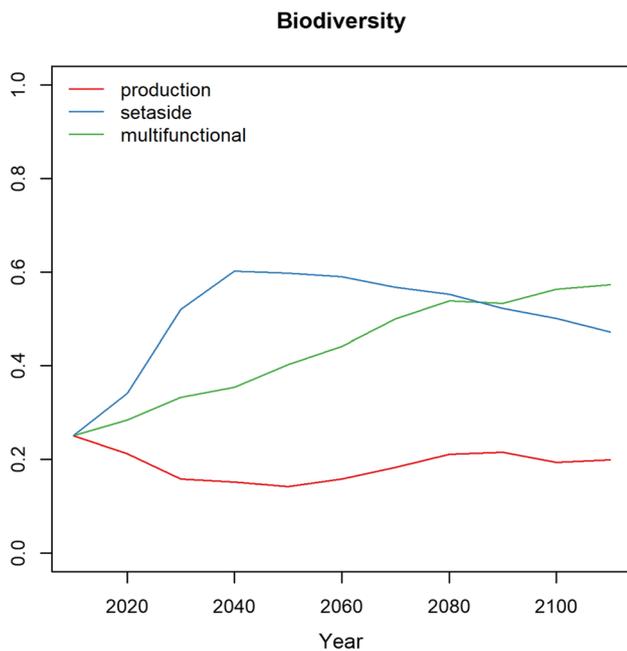


Fig. 12 Fuzzy logic assessment of biodiversity. Ordinate values of 0, 0.5, and 1 represent very low, intermediate and very high biodiversity, respectively

As the stands, with increasing density, become more and more mono-layered again, the biodiversity slowly reduces. However, at the end of the simulation period it still shows a substantially higher level compared to the initial situation. While the setaside scenario is leading in biodiversity on the short and medium term, the multifunctional scenario shows a linear increase throughout the whole simulation time, overtaking the setaside scenario between the years 2080 and 2090 with a further increasing tendency at the end of the simulation. Thus, the active multifunctional management is not able to create such a quick increase of biodiversity as the setaside scenario does. However, it avoids the fallback coming with the setasides and creates a steady increase of biodiversity leading to the highest values of all scenarios on the long term.

For the combined storm and bark beetle risk, our fuzzy evaluation assesses the risk of the initial situation (the real current forest status) as moderate (Fig. 13). Expectedly, the multifunctional scenario leads to a constantly decreasing risk ending up on a low risk level at the end of the simulation. The highest, while still moderate, risk level is attained with the setaside scenario. It is slightly increasing, but remains in the moderate scope. High shares of Norway spruce and increasing shares of big trees promote the risk in this scenario, however, the comparably high structural diversity has a risk-dampening effect. We should point out here, that stakeholders in favor of large setasides would not see this risk as something negatively connoted, more as an

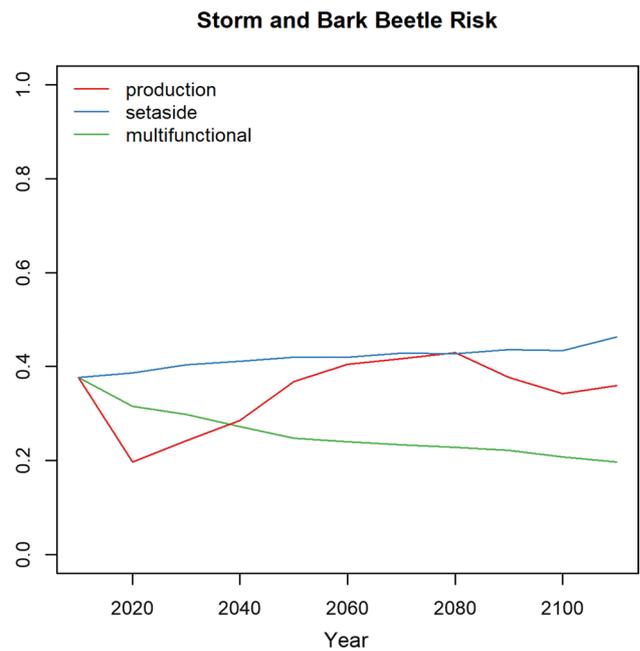


Fig. 13 Fuzzy logic assessment of the combined storm and bark beetle risk. Ordinate values of 0, 0.5, and 1 represent very low, intermediate and very high risk, respectively

increasing chance for obtaining more structure initiated by natural hazards.

Expectedly, the production forest scenario leads to wide oscillations of the assessed risk, with an increasing tendency, but never exceeding the setaside values. In this scenario, risk values are highest, when many stands near the rotation age have accumulated (2050–2080). The risk does not become extreme, however, as the old stands are harvested just about when they reach the critical tree size. At the same time structural diversity (as expressed by the species profile index, see Fig. 11, is not extremely low).

The results for the fuzzy logic assessment of balanced wood production is shown in Fig. 14. Here, the multifunctional scenario keeps constant on a level between moderate and high. Reasons are constantly high increments with no greater divergences of increment and harvest. The highest values for balanced wood production are obtained in the production forest scenario, between the years 2060 and 2080. At that time the increment is very high and the harvest amounts are not too far below. As do increment and harvest, also the assessed balanced wood production strongly oscillates, it is especially low in phases, when the accumulated old stands are harvested (periods 2020–2030, 2090–2100). So, the prevailing uneven age-class distribution that is the reason for periodically shifting discrepancies between increment and harvest leads to temporarily low levels of assessed balanced wood production. This seems plausible as such an imbalance creates a non-constant flow of harvested wood.

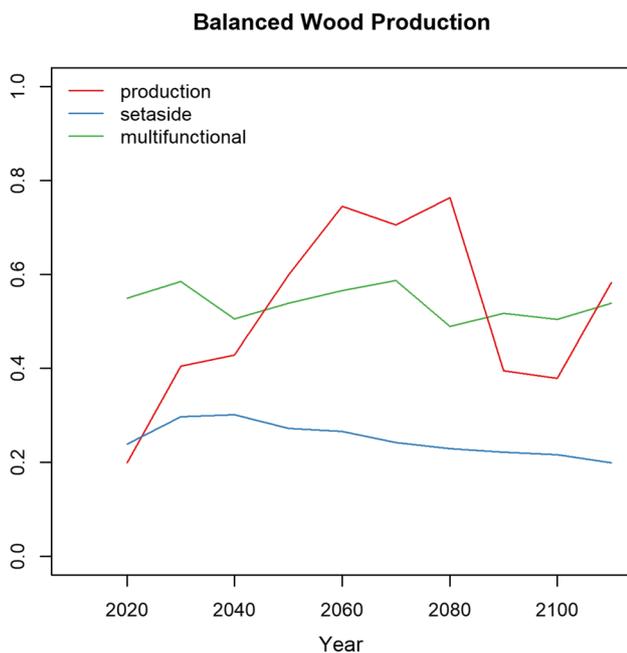


Fig. 14 Fuzzy logic assessment of balanced wood production. Ordinate values of 0, 0.5, and 1 represent very low, intermediate and very high balanced wood production, respectively

Clearly, the lowest levels of balanced wood production are obtained from the setaside scenario. Despite no harvest is taking place, the assessed balanced wood production is low, but not on the lowest level possible. The evaluation system takes into account, that still large amounts of wood are produced, even though without being harvested. Note, that already the initial values of the assessed balanced wood production are differing. This is because both input variables for this assessment, increment and harvest are initially not the same in the three scenarios (Fig. 11).

As shown in Sect. 2.6, the overall recreation value is calculated from three aspects, whose acceptance values for recreationalists are separately assessed with fuzzy logic systems. These aspects are (i) species and structural diversity, (ii) deadwood, and (iii) density and management intensity as presented in Fig. 15. Combining them into the overall recreation value (Fig. 15, top left) is done with Eq. 1 (Sect. 2.6), which makes the lowest acceptance value dominating the result while allowing for a certain degree of compensation. The first aspect of acceptance—diversity—is on high to very high levels, with an increasing tendency, for the setaside and the multifunctional scenario (Fig. 15 top right). In contrast, the production forest shows a steep drop down to low and moderate levels, which is due to the marginal volumes of big trees and comparably low species profile values coming

with this scenario. The aspect of deadwood starts high for the setaside scenario, due to the absence of harvest residues. However, as high amounts of deadwood quickly accumulate due to increasing numbers of dying trees, the acceptance value drops down to a constantly low level (Fig. 15, bottom left). In the production forest, the acceptance value due to deadwood strongly oscillates between very low and high; very low values are observed in phases of high harvest intensity, when high amounts of harvest residuals are generated and vice versa. In the multifunctional forest, this acceptance value increases from low up and stabilizes at a moderate level due to gradually decreasing harvest amounts with less harvest residuals at a more or less constant level of accumulated deadwood.

For the third aspect, density and management intensity (Fig. 15, bottom right), we observe very high initial acceptance values in the setaside scenario due to no harvest taking place, which slightly recede due to increasing stand densities. An obverse development is evident for the multifunctional forest. The acceptance values start moderate/high and steadily increase to high values due to decreasing harvest amounts. In periods with no extreme harvest amounts, the stand density and management intensity acceptance is moderate to high in the production forest. Evidently, the strong initial harvest measures and those in the period of 2090–2100 cause short-termed drop downs to very low values.

The combination of all three acceptance aspects to the overall recreation value (Fig. 15, top left), results in a constant moderate level for the setaside scenario. Essentially positive valuation of no harvest taking place and negative valuation of high deadwood amounts are counteracting here. Depending whether there is a period of intense harvest activities or not, the production forest is far below or just touching the setaside value at best. The multifunctional forest starts at about the same level as the setasides, but increases to and stabilizes at an upper moderate level, consistently showing the highest recreation values of all scenarios at any time.

Result synopsis

Our fuzzy logic evaluation maps all assessed categories of ecosystem services on the interval $[0, 1]$, designed to cover the fuzzy range from “very low” to “very high.” This concept lends itself straightforwardly to cross-goal variable comparisons, because issues resulting from how to compare differently scaled variables do not exist at this stage. Such comparisons are shown in Fig. 16 for the simulation time slices (i.e., calendar years) 2020, 2050, 2080, and 2110.

In contrast to the detailed timeline presentations of results in previous Figures, the different arrangement of the same

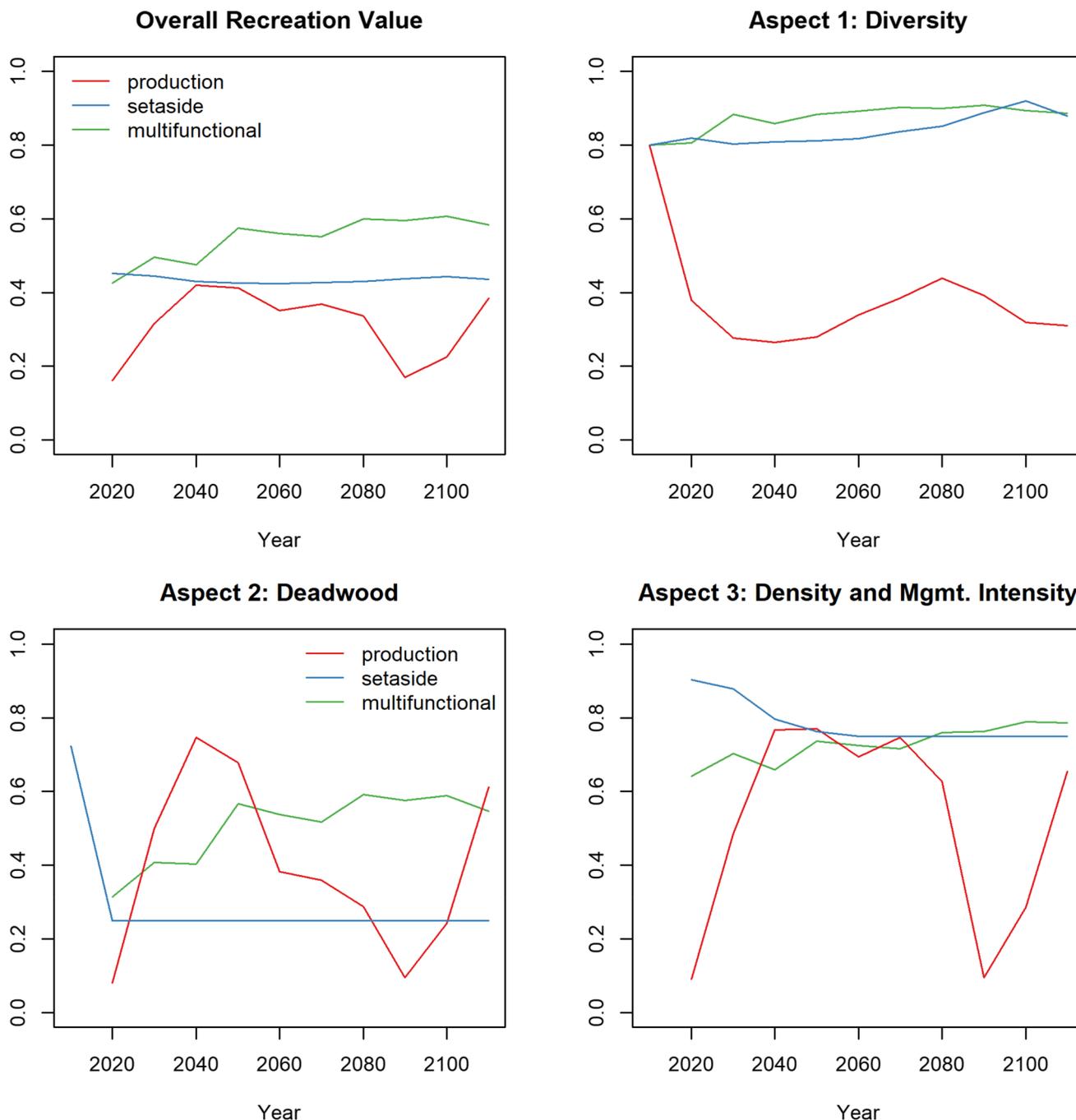


Fig. 15 Fuzzy logic assessment of the recreation value (top left) and its three contributing aspects (see Sect. 2.6). Ordinate values of 0, 0.5, and 1 represent very low, intermediate and very high acceptance values, respectively

numbers in Fig. 16 provides a comprehensive view of the different ecosystem services in relation to each other. From a decision maker’s point of view, this allows an intuitive visual distinction of management options with more or less balanced provision of different ecosystem services.

As indicated above, the radarcharts presented in Fig. 16 show the goal variables of this study for the given time

with exactly the same values as they were presented in Figs. 12, 13, 14, 15. The only exception is the variable we called “Resistance” in the radarcharts. This is just 1 minus the risk values displayed in Fig. 13 (as resistance can be seen as the opposite of risk). By doing so we make sure that all displayed variable values generally indicate more desirable conditions the further away they are displayed

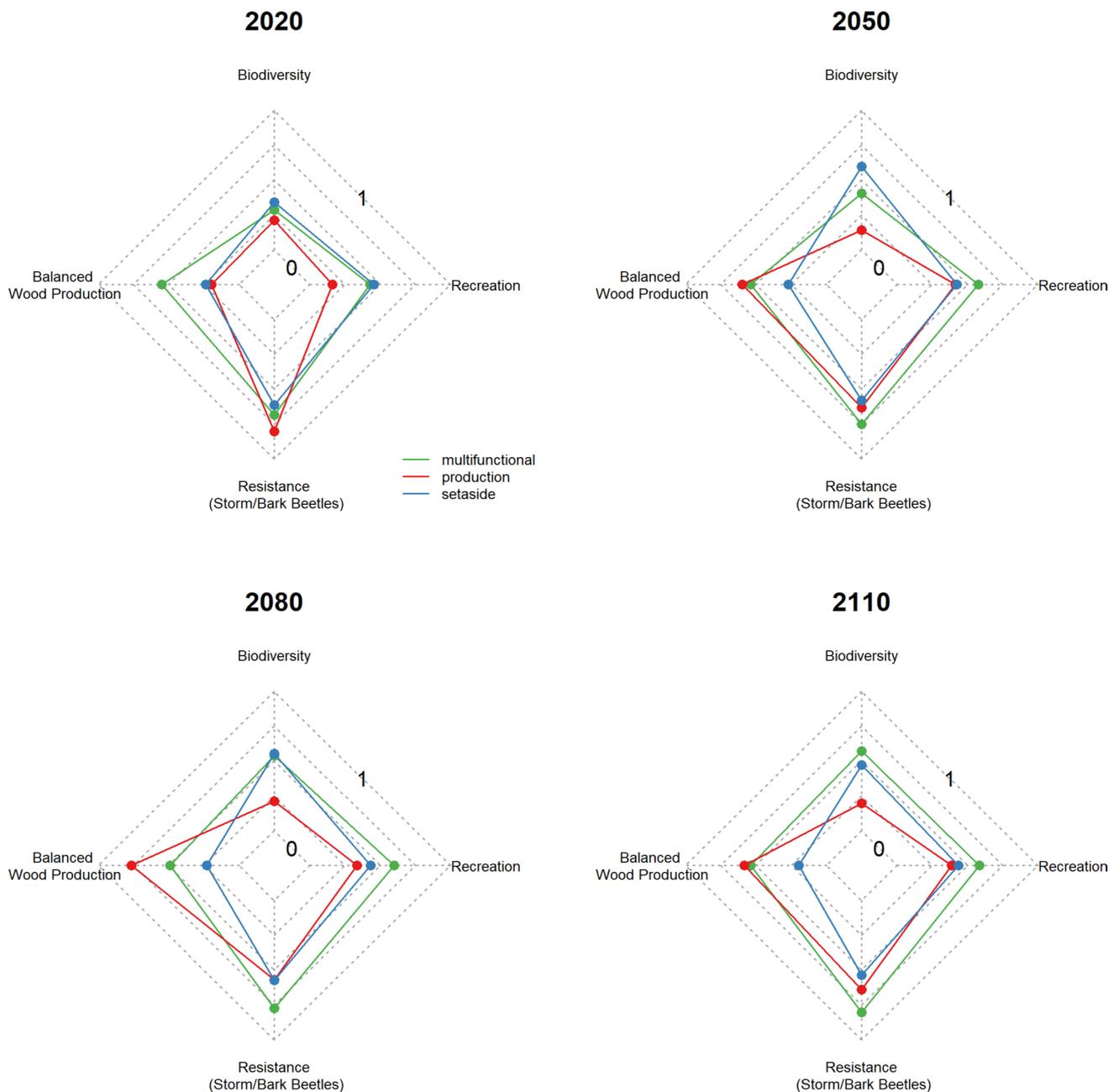


Fig. 16 Radarcharts displaying the four evaluated ecosystem services for the time slices (i.e., calendar years) 2020, 2050, 2080, and 2110. The axis extreme values are 0 (inner), and 1 (outer). Thus, the axis

range represents the fuzzy range from “very low” to “very high.” The “Resistance” values in the diagrams are 1 minus the risk values shown in Fig. 13

from the radarchart’s center. For the resistance value, this is beyond debate in the production and multifunctional forest; for the setaside scenario, resistance is clearly a desirable trait if carbon sequestration in the forest is the goal of creating a setaside. This could, however, be questioned if the purpose of the setaside is to protect natural processes.

The patterns evident in Fig. 16 show that the multifunctional forest provides the most balanced provision of the four ecosystem services from the beginning, becoming even

more balanced on the long run by increasing biodiversity and recreation values. For the setaside scenario, the main weakness is—evidently by definition—in the wood production but also in the other fields it is losing ground to the multifunctional scenario during the simulation time span. The shape describing the synopsis of the production forest scenario is the most imbalanced one. With consistently low biodiversity and low to medium recreation values, the resistance and balanced wood production do not show high

values at the same time—as a result of the strong oscillations of many key variables in this scenario.

Discussion

The novelty of this study is clearly not a scenario analysis of forest ecosystem service provision. It is rather one of the first studies doing this with a fuzzy logic approach. In the context of forest management, we are only aware of fuzzy logic being applied for ecosystem service evaluation from the works of Reynolds (Reynolds and Hessburg 2014; Reynolds 2001), while Prato (2009) uses a hypothetical case study of natural system management to explore fuzzy logic for such applications. Beyond ecosystem service evaluation, fuzzy logic has been applied punctually in other sub-disciplines of forest science (cf. R ger et al. 2004; Kivinen and Uusitalo 2002; Lexer et al. 2000; Kahn 1995).

We hypothesize that a possible reason for this method being not more widespread in the field of forest management sciences so far, could be technical hurdles at the programming stage. With software like the R package ‘sets’ (Meyer and Hornik 2009), being freely available, this should not be an obstacle anymore. Before getting into a more conceptual discussion, another technical point should be mentioned: The fuzzy logic evaluation as presented in this study was designed for post-hoc application to the output of a forest growth simulation model. While this is a practical and straightforward approach, a deeper, i.e., a dynamic connection of both is required when the goal is to automatically find optimized management strategies. Such a connection needs a feedback from the ecosystem service evaluation system to the simulator (e.g., after each time step of simulation) in terms of a comparison of the desired and actually resulting provisions of different ecosystem services. It also requires an algorithm adjusting the forest management settings at the side of the simulator in order to minimize the actual vs. target divergence. From our point of view, another fuzzy logic controller could prove useful as a main component of such an algorithm.

Generating knowledge by interdisciplinary integration

It can be argued that, in the context of solving real-world problems, interdisciplinary integration of existing knowledge is frequently more useful than deepening disciplinary research (Krohn 2017; Primmer and Furman 2012). The authors suggest to consider this study from such a point of view. Assessing the provision of a multitude of forest ecosystem services under real-life conditions is a task of making interdisciplinary knowledge utilizable for practical purposes.

As we aspired to demonstrate, fuzzy logic offers itself as a viable vehicle for such purposes.

The main reason is that fuzzy systems can be easily designed to map their output on any desired range of values and categories. In that sense, we designed the fuzzy logic systems for all ecosystem services we assessed to provide output values between 0 and 1, representing the extreme qualities “very low” and “very high,” respectively. Insofar, assessments made in the context of very different disciplines (in our example forest growth and yield, forest ecology, sociology, psychology) are transferred onto the same range. In other words, e.g., a low balanced timber provision and a low recreation value are expressed in their own disciplines in fundamentally different variables and quantities. However, the fuzzy logic evaluation tells us in the same situation, that there are two very different ecosystem services which are, however, both available to a low degree (both assessed based on knowledge from their own worlds each). For decision-makers, this is the crucial information. A fuzzy logic based evaluation of a status quo (typically based on forest inventory data) can reveal that there are ecosystem services being provided to different degrees. In a further step, scenario simulations combined with fuzzy logic evaluations, as shown in this study, can help to fathom if and which management options can have a steering influence.

Making tradeoffs and synergies accessible

An important question in forest management is the existence of tradeoffs and synergies between provided ecosystem services given certain management options, e.g., our study revealed at least temporarily strong tradeoffs between wood production, biodiversity, and recreation value for the production forest scenario, while in the multifunctional forest scenario synergies between these ecosystem services prevailed. Displaying (cf. Figure 16) and communicating such tradeoffs and synergies for practical purposes, requires an appropriate mapping of the provided ecosystem services, which—as argued before—is a strength of fuzzy logic approaches. This paves the way to working with information that would otherwise be “underused.” So far, our experiences were good in this regard, when we communicated the outcomes of this study in two stakeholder workshops (see below).

Transparency

Rule-based evaluation setups, as typical for fuzzy logic, are highly transparent, which is an important advantage compared to more abstract approaches (like utility functions and related concepts) in the context of decision making in

forestry. As is evident from the fuzzy variable construction and evaluation rule setup we presented in this study, we tried to incorporate the best available knowledge in terms of literature, available guidelines and expertise, but a certain degree of assumption was unavoidable. The transparency of the setup is crucial against that backdrop and the intuitive character of fuzzy logic is certainly helpful here (cf. Reynolds and Hessburg 2014).

For forming an opinion about a given situation and/or proposed alternatives, decision-makers and stakeholders require a small set of key information which has to be boiled down from a complex set of input information. However, on request, the way of how this “boiling down” is done must be traceable and adjustable in order to justify confidence. This is not exclusively, but especially important for such ecosystem services where provision strongly depends on perception (most prominent in our example: recreation), which means (alternative) value judgements must inevitably be possible to be included in the assessment. As fuzzy rule formulations can directly mirror human valuation processes (e.g., *IF in a forest landscape the volume share of Scots pine is high AND if there is much understorey AND young stands dominate THEN the risk of forest fires is high*), they can be easily and straightforwardly communicated to and discussed with non-scientist stakeholders and decision-makers. Even ad hoc adjustments to reflect different views of the same problem are thinkable. We deem this transparency also a valuable asset in related negotiating.

In late 2018 the authors presented the results of this study to local stakeholders with widely differing interests, i.e., state, municipal, and private estate forest managers, representatives of NGOs engaged in nature protection, recreation, farming, and hunting, as well as educationalists in two workshops in late 2018. The success of these workshops and the interest in the generated results was not to the least part due to the fact that the question “*how does this result come about?*” could always be convincingly answered. In the same context, the visualization of rules as color matrices (Tables 1, 2, 3, 4, 5, 6) turned out useful, but even more when designing the rule systems in teamwork.

Participation and citizen science

Transparency of information provided to the public by professionals is the key to participation. This is particularly important in the context of decisions that, like in forestry, shape the appearance of whole landscapes on the long term. Ill-informedness often leads to suboptimal development of democratic processes, off-point conflicts, and the frustrating suspicion to be downplayed. Fuzzy logic evaluation rules have, from our point of view, a high potential to improve such processes, because they directly translate into everyday

language. This also means, that citizens who disagree with or doubt an evaluation can clearly articulate where they surmise a flaw. Even more, their disagreeing view can be inferred into an alternative rule system, and it can be transparently demonstrated what difference the disagreeing views actually make.

Another form of participation is modern citizen science, where volunteers actively contribute data and/or knowledge to serious scientific projects. Albeit the quality of citizen science data must be carefully assessed, there is good reason for optimism (Kosmala et al. 2016), and enormous amounts of data have been collected so far, especially in the fields of ecology and environmental science (Silvertown 2009). Besides their originally intended use, such data, when combined across projects and disciplines might generate not so much new deep disciplinary knowledge, but decision-relevant integrated knowledge as addressed in the first section of this discussion. As Bonney et al. (2014) put it “*most citizen science projects work independently, and many citizen science data sets containing a wealth of information are unknown or unavailable to decision-makers.*” Involving the experts who are conducting citizen science projects, fuzzy logic approaches might be very useful in transforming this information into actual knowledge, making it usable for better-informed discussions and decisions.

Limits and perspectives

Clearly, fuzzy logic cannot generate knowledge „out of nothing,” i.e., an expert system is only as good as the integrated expert knowledge stands on solid grounds. In order to avoid subjective bias when forming a rule system, especially in strongly debated fields, formal methods of collecting expert knowledge and involving the experts beyond the mere rule setup might become necessary (Drescher et al. 2012; McBride and Burgman 2012). If there are seriously contrasting views about one ecosystem service, typically such that are essentially value judgements like the recreation value, this would require two or more alternative rule sets to be built and applied in order not to spoil a balanced discussion among stakeholders from the outset.

In such aspects, however, where the experience of experts is used to cover actual knowledge gaps, a fuzzy logic system that plausibly supports decisions in practice, must be seen as a temporary requirement and by no means an end point for science. This is especially important, when health-relevant issues are to be assessed, from forests effects on potable water quality to stress-reducing aspects of being in the forest. In certain cases, this might call for conventional empirical studies in fields that have not been sufficiently covered so far, or the comb-out of citizen science data as mentioned above.

However, expert experiences about value-loaded aspects like the esthetical perception of forests could be scrutinized by as yet less usual quantitative methods like eye-tracking (Nordh et al. 2013), EEG (Chiang et al. 2017) or specific physiological investigations like stress hormone release as recommended by Parsons as early as in 1991.

Consequently, a fuzzy logic approach as presented in this study should not be seen as an alternative to rigorous scientific evaluations. It is much more an approach to make existing knowledge ad hoc usable in actual decision making processes (in the sense of Primmer and Furman 2012), that should be as much based on quantitative science as possible. In the other direction, science might profit from spotting knowledge gaps that become evident during the build process of fuzzy evaluation rules.

Conclusions

From the process and the results of this study we conclude that fuzzy logic offers itself as a useful method for assessing forest ecosystem service provision. This is especially relevant in the frequent cases where a large body of expert knowledge exists, while directly quantifiable knowledge is lacking. This is the case for the assessment of biodiversity and the examples for a cultural, regulating and provisioning ecosystem service we presented in this study. As a considerable advantage of fuzzy logic our study confirms its intuitive rule-based setup and nearness to human assessment processes, because this facilitates both, the interdisciplinary design of evaluation systems as well as the communication of evaluation outcomes from the experts' sphere to the sphere of decision making in management, politics, and democratic negotiation processes.

Dedication

This article is dedicated to the memory of Ernst Assmann (1903–1979), one of the most influential German forest scientists in the twentieth century (cf. Pretzsch et al. 2015). While being a pioneer in the field of forest growth and yield and its biological foundations (Assmann 1970a, 1961a), Assmann never failed to see his work in the context of a broad view of sustainable forest management. Clearly, wood production was an important goal of forest management in his view, but not automatically more important than other forest functions and services (Assmann 1971, 1970b, 1961b). Arguably, to the advantage of humans and forests, this wide scope became a mainstream notion meanwhile, but it definitely was not at Assmann's time, and it is the first aspect where this article reaches back to him.

Second, Ernst Assmann valued quantitative information far above all alternatives. Galileo's famous motto "*measure*

what is measurable, and make measurable what is not so" was Assmann's likewise (Assmann 1961b). As we were hopefully able to show, this is also the central theme of this article.

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