Linking Landowner Characteristics, Stand Structure, and Topography to Conservation Potential in Small-Scale Private Forests

Dissertation

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Summary

Context Small-scale private forests (SPFs) account for a significant proportion of the total forest area. They harbor structures that are uncommon in other forests but which are important to forest nature conservation, providing habitats for numerous species. However, these ecosystems are under threat from global crises and are facing increasing economic pressure to harvest wood. SPF owners are a highly diverse group in terms of their sociodemographics, attitudes, and management approaches. Their degree of organization is low, and their land is highly compartmentalized. This poses challenges for traditional forest nature conservation outreach and policy initiatives.

Aims In the course of this thesis, I aimed to highlight the interconnections between SPF owners, their land, and its structures that many forest species depend on. Research on biodiversity in SPFs relies on difficult-to-acquire field data that requires costly monitoring campaigns. Forest structural proxies, such as tree-related microhabitats, are often used to estimate biodiversity data. My goal was to elaborate on this concept by illustrating promising new connections between topography, landowner sociodemographics, management goals and attitudes, and forest structures.

Methods This thesis was embedded in the KLEIBER research project at NW-FVA and the University of Göttingen, Germany. The project included a comprehensive SPF owner questionnaire, whose responses I used for my research. We conducted fieldwork campaigns in the study area, the Lower Saxon Hills region, and utilized existing open geodata. I developed machine learning models using various algorithms, such as random forest and gradient boosting trees, to analyze the strength of influences and make predictions.

Results Forest structures in SPFs were influenced by the landowners' goals and attitudes as well as the parcel and landscape topography. We identified two types of forest structures that are important for nature conservation. Old-growth structures, such as broadleaf wood volume and microhabitats, depended mostly on topographical parameters. Fast evolving structures, such as deadwood, were influenced by both topographical parameters and the current owner's attitudes. Owner sociodemographics and landscape topology influenced owner management goals and activities. Research data indicated that gender was not a significant factor in owner management goals and activities, and showcased major influences from parcel size and stand type that can be leveraged to promote nature conservation. Old-growth structures in SPFs were significantly influenced by landscape-related characteristics. We utilized this relationship to build a prediction model demonstrating that old-growth structure density is higher in isolated forest patches in mixed landscapes.

Conclusion Low-intensity management and non-use are effective strategies for supporting important structures on SPFs, while historical usage forms like coppice depend on active landowner engagement. Structures like large, old broadleaf trees, tree-related microhabitats, and deadwood play an important ecological role in SPFs, so their retention and continued provision should be of high priority. Rising market pressures on the other hand must be countered with targeted political action to protect nature conservation values in SPFs. Incentives, owner education, and area protection can prove successful here.

Protection efforts benefit from knowledge about the owners' situations and the spatial distribution of valuable structures in their forests. Analogous to society as a whole, SPF owners are subject to sociodemographic shifts. In the future, policymakers need to adapt their legislation and communication strategies to address the growing diversity of owners. Emerging trends in SPF ownership will involve a greater openness to the non-economic use of forests and the opportunities it provides for nature conservation. Owners of larger conifer-dominated SPF parcels should receive effective support and guidance when transitioning their forests toward greater diversity and climate resilience. Educational efforts and incentives can support the conservation-friendly attitudes of owners of broadleaf-dominated SPFs.

Free, openly available geodata can serve as predictors of old-growth structures in SPFs. Isolated forest patches in mixed landscapes can provide multiple ecosystem services to the surrounding land, but are often overlooked in nature conservation planning. Forest edge structures and habitat-rich old broadleaf trees increase the structural diversity and enhance the value of landscape mosaics. Old, large trees are especially valuable in mixed landscapes and should be prioritized for protection. SPF owners and supporting nonprofits need reinforcement in their protection efforts. Educating them about rare structures in these forest stands could foster an increased appreciation of their value for nature conservation. Precise geographic data on the distribution of valuable structures can help policymakers plan conservation efforts and communicate with owners.

Zusammenfassung

Kontext Kleinprivatwälder machen einen bedeutenden Anteil der gesamten Waldfläche aus. Sie enthalten Strukturen, die in anderen Waldbesitzarten selten sind, aus naturschutzfachlicher Sicht jedoch wichtig sind und Lebensräume für zahlreiche Arten bieten. Diese Ökosysteme sind durch globale Krisen bedroht und stehen aufgrund der steigenden Nachfrage nach Holzprodukten zunehmend unter wirtschaftlichem und gesellschaftlichem Druck. Die Waldbesitzenden sind hinsichtlich ihrer soziodemografischen Merkmale, Einstellungen und Bewirtschaftungsansätze eine äußerst heterogene Gruppe. Ihr Organisationsgrad ist gering, und ihre Flächen sind stark parzelliert. Klassische Ansätze zum Waldnaturschutz und zur Kommunikation mit Waldbesitzenden greifen daher zu kurz.

Ziele In dieser Arbeit wollte ich die Zusammenhänge zwischen den Kleinprivatwald-Besitzenden, ihrem Land und dessen Strukturen hervorheben. Die Erforschung der Biodiversität in Kleinprivatwäldern stützt sich auf Felddaten, für deren Erhebung kostspielige Monitoring-Kampagnen erforderlich sind. Oft werden Waldstruktur-Proxies wie Baummikrohabitate verwendet, um das Auftreten von Arten einzuschätzen. Mein Ziel war es, diese Herangehensweise auszubauen und vielversprechende neue Zusammenhänge zwischen Geländetopografie, soziodemografischen Merkmalen der Waldbesitzenden, ihren Bewirtschaftungszielen und Einstellungen sowie Waldstrukturen aufzuzeigen.

Methoden Diese Arbeit entstand im Rahmen des Forschungsprojekts KLEIBER an der NW-FVA und der Universität Göttingen. Im Rahmen des Projekts wurde eine großangelegte Umfrage unter Kleinprivatwald-Besitzenden durchgeführt, die ich für meine Forschung verwendet habe. Wir haben Feldforschung im Untersuchungsgebiet, dem Niedersächsischen Bergland, durchgeführt und frei verfügbare Geodaten genutzt. Mithilfe von Machine-Learning-Modellen, die verschiedene Algorithmen wie Random Forest und Gradient Boosting Trees verwenden, habe ich die Stärke von Einflüssen analysiert und Vorhersagen getroffen.

Ergebnisse Die Waldstrukturen im Kleinprivatwald wurden durch die Ziele und Einstellungen der Waldbesitzenden sowie durch die Topografie der Parzellen und der Landschaft beeinflusst. Wir haben zwei Arten von für den Naturschutz relevanten Waldstrukturen identifiziert. Altwaldstrukturen wie Laubholzvolumen und Baummikrohabitate hingen hauptsächlich von topografischen Parametern ab. Sich schnell entwickelnde Strukturen wie Totholz wurden hingegen sowohl von der Geländetopografie als auch von den Einstellungen der aktuellen Besitzenden beeinflusst. Soziodemografische Merkmale und die Landschaftstopografie beeinflussten wiederum die Bewirtschaftungsziele

und -aktivitäten der Waldbesitzenden. Die Daten zeigten, dass Gender hier kein signifikanter Faktor war, und verdeutlichten den großen Einfluss der Parzellengröße und des Bestandstyps. Diese Erkenntnisse können zur Förderung des Waldnaturschutzes genutzt werden. Altwaldstrukturen in Kleinprivatwäldern wurden maßgeblich von topografischen Merkmalen beeinflusst. Ich habe diesen Zusammenhang genutzt, um ein Vorhersagemodell zu erstellen, das zeigt, dass die Dichte solcher Strukturen auf isolierten Waldflächen in gemischten Landschaften höher ist.

Schlussfolgerung Extensives Management und Nichtnutzung sind wirksame Strategien, um wichtige Strukturen in Kleinprivatwäldern zu erhalten. Historische Nutzungsformen wie Niederwald hängen hingegen vom aktiven Engagement der Waldbesitzenden ab. Große, alte Laubbäume, Baummikrohabitate und Totholz spielen eine wichtige ökologische Rolle in Kleinprivatwäldern. Ihre Erhaltung und kontinuierliche Bereitstellung sollte daher hohe Priorität haben. Dem zunehmenden Nutzungsdruck muss hingegen mit gezielten politischen Maßnahmen begegnet werden, um die Naturschutzwerte in Kleinprivatwäldern zu schützen. Finanzielle Anreize, Aufklärung der Waldbesitzenden und Flächenschutz können sich hierbei als erfolgreich erweisen.

Solche Schutzmaßnahmen profitieren von Kenntnissen über die Situation der Waldbesitzenden und die räumliche Verteilung wertvoller Strukturen in ihren Wäldern. Analog zur Gesellschaft insgesamt unterliegen auch die Kleinprivatwald-Besitzenden soziodemografischen Veränderungen. In Zukunft müssen politische Entscheidungstragende ihre Gesetzgebung und Kommunikationsstrategien anpassen, um der wachsenden Vielfalt der Waldbesitzenden gerecht zu werden. Zu den sich abzeichnenden Trends unter Waldbesitzenden gehört eine größere Offenheit für die nichtwirtschaftliche Nutzung von Wäldern und die damit verbundenen Möglichkeiten für den Naturschutz. Besitzende größerer Flächen, die bisher vorwiegend mit Nadelholz bestockt waren, sollten bei der Umstellung ihrer Wälder hin zu mehr Vielfalt und Klimaresilienz wirksame Unterstützung und Beratung erhalten. Aufklärungsmaßnahmen und finanzielle Anreize können die oft bereits vorhandene Naturschutzorientierung von Waldbesitzenden mit laubwalddominierten Beständen stärken.

Frei zugängliche Geodaten können in Modellen genutzt werden, um Altwaldstrukturen auf Landschaftsebene vorhersagen. Isolierte Waldparzellen in gemischten Landschaften erbringen vielfältige Ökosystemleistungen für das umliegende Land, werden bei der Naturschutzplanung jedoch oft übersehen. Waldrandstrukturen und habitatreiche alte Laubbäume erhöhen die strukturelle Vielfalt und steigern den Wert von Landschaftsmosaiken. Diese Altbäume sind in gemischten Landschaften besonders wertvoll und sollten vorrangig geschützt werden. Kleinprivatwald-Besitzende und Naturschutzorganisationen benötigen Unterstützung bei ihren Schutzbemühungen. Durch Aufklärung über seltene Strukturen in den Waldbeständen kann das Bewusstsein für deren Wert für den Naturschutz geschärft werden. Präzise geografische Daten zur Verteilung wertvoller Strukturen können politische Entscheidungstragende bei der Planung von Schutzmaßnahmen und der Kommunikation mit den Waldbesitzenden unterstützen.

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Chapter 1

Introduction

This chapter introduces the thesis. After presenting the global context of intensifying crises that threaten various ecosystems (Section 1.1), it delves into the situation of small-scale private forests (SPFs), an important forest ownership class (Section 1.2). In Section 1.3, SPF owners are presented as an exceptionally heterogeneous group with diverging attitudes and changing demographics. Forest structures in SPFs are identified as relevant for forest nature conservation efforts, and current research gaps are identified (Section 1.4).

1.1 The global context: Crises affecting forest ecosystems

The well-being of human societies around the world depends on intact ecosystems. However, the health of these ecosystems and their ability to provide services to people are severely threatened by global crises, such as climate change and biodiversity loss. Increasing temperatures, changing precipitation patterns, human land use intensification, pollution, and the introduction of alien species challenge the functioning of ecosystems (Pörtner et al. 2023). Nevertheless, societies' demands on ecosystems, such as forests, are increasingly complex, and include for example the provision of timber supply and game animals, recreation, as well as water regulation and carbon sequestration. Forest landscapes face climatic and biodiversity challenges, while politics, also in Europe, struggles to develop a comprehensive legal approach securing the services forests provide (Winkel et al. 2022).

The consequences of climate change are becoming tangible everywhere. In Europe, the southern countries are especially threatened by catastrophic wildfires, but central and northern parts will also be vulnerable to fires during dry seasons. Bark beetles thrive in droughts caused by climate change and have destroyed vast coniferous woodlands worldwide. This has reduced urgently needed biomass and fueled further climate change. Human societies are reacting fragilely to these challenges, which are already causing political unrest (Hlásny et al. 2021). The incidence of droughts is also rising in Europe, putting ecosystem functioning at risk. Major drivers are the altered warm-season precipitation patterns with increased evapotranspiration (Markonis et al. 2021). Droughts affect all forest types, but younger plantations, conifer monocultures, and managed forests in general are more sensitive (Holtmann et al. 2024).

Climate change forces species to migrate, leading to novel species interactions. Limited ability to migrate or adapt, disappearing habitats, and species being trapped in climatic dead ends inevitably lead to biodiversity loss. Species and also biomass loss caused by human activities, such as changes in land use, deforestation, and pollution, lead to reductions in carbon storage and sink capacity, and increase CO_2 emissions (Pörtner et al. 2023).

Large forest landscapes harbor the greatest abundance and diversity of old-growth forest species, yet these forests are declining rapidly worldwide. Their protection is urgently needed, as strong economical forces drive conflicting land use changes (Potapov et al. 2017) and landscape fragmentation endangers forest sustainability (Schaich and Plieninger 2013). Intact forested landscapes are highly vulnerable to human interventions, which can easily threaten rare and specialized species (Betts et al. 2017). Forest species engage in complex interactions, and are mutually dependent. The resilience of these species can only withstand so much stress before unforeseen effects threaten the entire ecosystems (Ibarra et al. 2020).

1.2 The ecological importance of small-scale private forests

Large parts of Europe and North America are forested. The average forested area of six large European countries (France, Sweden, Germany, Finland, Norway, Poland) is 41.0 %, while the forested area of the USA is 28.3 %. The majority of these forests is owned by private organizations or individuals. This applies to 59.2 % of the forests in the aforementioned European countries and 62.6 % of US forests (UNECE and FAO 2020). A closer look at the situation in Germany reveals that 43.0 % of its forested area is in private hands, and around a fifth of all forests are private forests smaller than 20 ha (Statistisches Bundesamt 2023a; Statistisches Bundesamt 2023b; Thünen Institute 2022). The large accumulated area makes these SPFs an important target for conservation efforts.

Management differs between ownership types, leading to different structures and biodiversity patterns (Mölder et al. 2021). Low-intensity forest management or the cessation of management leads to increases in biodiversity and maturity indicators (Torras et al. 2012). European forest biodiversity depends heavily on old-growth structures, but also on structures of open forests that trace back to historical forms of use. Close relationships can be found between these structures and various taxon groups. This holds, for example, for vascular plants, fungi, epiphytic lichens, bryophytes, beetles, and birds (Blasi et al. 2010).

Exhaustive surveys of forest biodiversity quickly become impractical and uneconomical, so appropriate approximation techniques are necessary (Juutinen and Mönkkönen 2004; Caro and Girling 2010). Biodiversity monitoring can be supported by data on forest structural diversity. Quantitative diversity measures must consider a wide variety of structural aspects to identify essential habitats for a broad range of taxon groups (Storch et al. 2018). Strong correlations have been shown to exist between forest structural parameters and the abundance of many taxon groups (for example, vascular plants, bryophytes, lichens, beetles, ants, birds), but a large set of sampled structures is needed for predictions. Other taxon groups might depend on topography or management variables (Storch et al. 2023). Solid statistical evidence underscores the importance of old-growth structures, such as large broadleaf trees, deadwood, and wood cavities, for multiple important taxon groups (Zeller et al. 2023). However, these structures are strongly influenced by forest management, and are rare in production forests (Wagenaar et al. 2025).

Ownership type is an underused variable in assessments of structural differences between forest habitats. Its inclusion in European studies often sheds light on the distribution of valuable structures. For example, Finnish private forests have been shown to have higher structural diversity and a greater number of tree species than forests in other ownership types. This reflects differences in management, which is more diverse in forests in private hands (Maltamo et al. 1997). The same holds true in Latvia, where state forests are harvested more often and private forests have fewer roads, greater structural diversity, and more tree species (Rendenieks et al. 2015). Ownership has been shown to influence forest management, as well as biodiversity and carbon sequestration abilities, in some German forests. SPFs exhibited greater structural diversity, more deadwood, and higher carbon storage capacity due to less intensive management (Schaich and Plieninger 2013). Czech conifer monocultures have recently experienced large-scale disturbances, and experts agree that their homogeneous management results in uniform structures that eliminate important habitats for forest species (Kjučukov et al. 2022).

The high parcelization of SPFs offers diverse patches of forest in a cultural landscape with unique structures and long forest edges not found in other ownership classes (Wulf and Kolk 2014). Diverse management practices might include non-use and the restoration of open forest structures (Kjučukov et al. 2022), which are important for species that benefited from historical forms of forest use like coppicing. Different taxon groups react differently to the abundance of old-growth structures from various structural groups. Therefore, it is advisable to provide heterogeneous habitats at the landscape scale (Rigo et al. 2024). Forests taken out of management that are embedded in a connected forest landscape develop an increasing number of old-growth structures and can buffer rising temperatures (Adhikari et al. 2024). Native forests with complex structures provide a wider range and higher quality of ecosystem services than plantation systems (Hua et al. 2022). Remnants of historic forest use, such as wood pasture, that have survived in SPFs also exhibit high densities and qualities of old-growth structures (Lőrincz et al. 2024; Wolbeck et al. 2025).

Tree-related microhabitats (TreMs) are a group of old-growth structures that has gained attention in the past years. The survey of TreMs (Larrieu et al. 2018) is often used as a proxy for a wide range of forest taxon groups, including saproxylic beetles and fungi, spiders, bats, birds, and lichens. Although the study of these structures is a relatively new field (Asbeck et al. 2021), many strong relationships between TreMs and forest biodiversity have already been established (Dutta et al. 2025). Some TreMs play vital roles as key habitats for many taxon groups (Martin et al. 2022). The development of TreMs is a stochastic process that occurs over relatively long periods of time (Larrieu et al. 2022), and is therefore correlated with tree age and diameter (Kozák et al. 2023). This is especially true for ecologically important microhabitats (Kõrkjas et al. 2021), such as cavities in oaks, which are rare in production forests where trees are harvested before they can reach old individual ages (Ranius et al. 2009). TreMs differ depending on forest ownership type. Their density can be substantially higher in SPFs due to less regular management in non-production forests, which also fosters TreM diversity (Johann and Schaich 2016).

Another important forest structural group that depends on careful management is deadwood. Deadwood serves many roles in forests. It provides habitat, helps maintain the ecosystem health, reduces the effects of disturbances (Parisi et al. 2018), and stores carbon for relatively long time spans (Chivulescu et al. 2022). Similar to TreMs, deadwood can be used as an indicator of species diversity because it provides habitat for taxon groups such as bryophytes, lichens, fungi, invertebrates, small mammals, and birds (L Bujoczek et al. 2021).

1.3 Attitudes, sociodemographics, and outreach to small-scale private forest owners

Forest owner associations often portray their members as primarily pursuing economic interests and managing their forests with the main goal of timber production (Kronholm 2016). However, it is increasingly accepted that SPF owners are a heterogeneous group with a wide range of goals and associated activities (Westin et al. 2023). Very active, multi-objective owners can be contrasted to passive conservation-oriented owners. Conventionally managing owners, who focus solely on wood cutting, lie somewhere in between (Tiebel et al. 2024). Owners' objectives often far surpass simple harvesting. Urban, absentee, and other nontraditional owners challenge conventional notions of forest management (Weiss, Lawrence, Lidestav, et al. 2019). Changing demographics and the importance of inheritance as a means of acquiring forest ownership lead to more female-identifying people in charge of SPFs (Butler et al. 2016). A shifting demographic leads to a change in the values that SPF owners see in their forests. This will, in turn, lead to different management strategies applied in the future (Nordlund and Westin 2011). SPF owners in an aging society often cling to their property even when they have to scale back their engagement in their forests (Sass et al. 2023). SPF owners also differ in their willingness to implement management practices aimed at climate mitigation, adaptation, and biodiversity conservation (Husa and Kosenius 2021).

Large-scale societal shifts, such as urbanization, are driving the emergence of new forest ownership types. Politics has not kept up with this development and is missing opportunities to provide targeted support to new forest owners who would otherwise be willing to implement new management approaches (Weiss, Lawrence, Hujala, et al. 2019). To design targeted and effective outreach strategies that prepare SPFs for the crises of the future, it is necessary to understand the factors influencing their owners' attitudes and behaviors: To SPF owners, their forests mean much more than their economic value. They represent identity, family heritage, and responsibility for nature. On the downside, forest owners might perceive conservation programs as too restrictive and act in a counterproductive manner (Tiebel et al. 2021). Additionally, like society at large, they often choose to ignore disturbing ecological facts (Takala et al. 2022). Policymakers need to adapt and approach owners accordingly (Joa and Schraml 2020). SPF owners can cooperate and make management decisions at the landscape level. This offers several social and ecological advantages. Owners are more likely to work together if they share similar attitudes and mutual trust. They also need support from institutions with expertise and resources (Fischer et al. 2019). Policymakers face fewer obstacles implementing protection schemes when land ownership is concentrated rather than fragmented across many parcels. Compartmentalized mixed landscapes require special attention to facilitate collaboration with SPF owners and other stakeholders, such as nonprofit organizations operating in the region (Loeb and D'Amato 2020). Publicly owned forests may be easier targets for establishing reserves and securing the ecological continuity. However, SPFs can offer high diversities of both management strategies and associated forest structures (Mölder et al. 2021). High demand for firewood and initiatives that aim to increase wood mobilization in SPFs threaten the role these forests play in nature conservation. Efforts to support SPF owners in their low-intensity management are urgently needed (Schaich and Plieninger 2013).

1.4 Research gaps and motivation

The situation of SPFs is tightly interconnected with multiple related concepts and stakeholder groups. Global crises affect SPFs, but SPFs also harbor high biodiversity, which offers potential to counter the climate and biodiversity crises. While forest owners shape their forests, they are themselves influenced, for example, by other stakeholders, politics, and the structures present on their land. Forest scientists aim to inform politics and owners alike, and are dependent on adjacent scientific fields, but also on governmental and institutional support for their work. Figure 1.1 illustrates important concepts related to SPFs, together with all their possible interconnections. Note that most connections can possibly act in both directions, and that the graph shows only the most important concepts within the scope of this thesis. Next, I will zoom in on some of these interconnections and identify knowledge gaps that motivated our work.

Tree stands and structures on an SPF parcel are influenced by the surrounding landscape, the topographic characteristics, and the management history of the parcel up to the point when the current owner assumed responsibility. From this date on, the owner[1] can implement management strategies that reflect their goals and attitudes regarding their forest. However, structures of high conservation value often require long time spans to develop (Kõrkjas et al. 2021), or depend on random events, such as storms that damage tree crowns and lead to tree injuries (Larrieu et al. 2022). The amount of deadwood as an important habitat structure has been shown to be influenced partly by site characteristics (L Bujoczek and M Bujoczek 2022; Kennedy et al. 2008) and partly by management decisions on the parcels (Kapusta et al. 2020). The question concerning the relationship between (a) current SPF owner's goals, attitudes, and management activities, and (b) the structures and abundance of valuable habitats on their parcels is not settled.

Before new owners can begin developing their forests, they must make a variety of management decisions regarding which activities to perform. These decisions are in turn influenced by the owners' goals, their perception of feasibility, and possibly their attitude toward nature conservation. Current research is trying to shed light on the factors that influence management behavior, often examining a single influencing factor such as urbanity or ethnicity in detail (Caputo and Snyder 2023; Robillard et al. 2023). As a single factor, owner gender gained a lot of attention in research (Kuhlman et al. 2024; Böhling 2022; Umaerus et al. 2019) and practice (Lukacic et al. 2023; Carter

[1] Throughout this thesis, I do not assume participants' gender and use the singular pronouns *they/them* to refer to them.

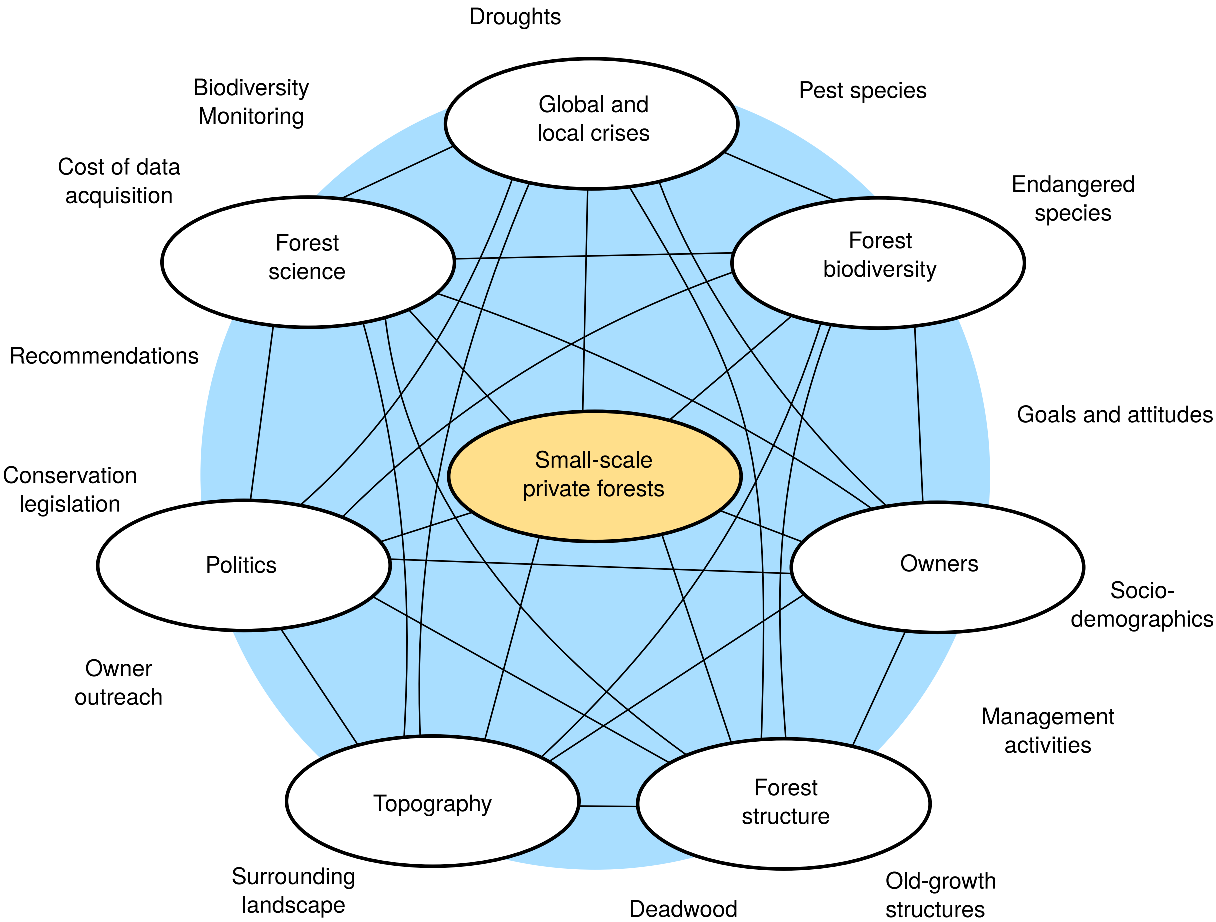

Figure 1.1: Relevant concepts (white shapes) in the context of small-scale private forests, and some related notions (periphery). All concepts are tightly interconnected, but the direction and intensity of these connections is often not clear. See also Figure 5.1.

2019). However, the question remains whether focusing on single influencing factors is expressive enough, and multifactorial research is gaining track (Floress et al. 2019; Côté et al. 2016). At the same time, existing work is restricted to viewing owner behavior as single answer variable. How the owners' goals and attitudes are evolving is still not sufficiently covered.

Forest structures of high conservation value can often be characterized as old-growth structures, and multiple taxon groups depend on them (Rigo et al. 2024; Storch et al. 2023). SPF owners can decide to protect such structures in their forests, if the already exist. In structurally poor forests, however, the owners can only create opportunities for old-growth structures to develop (Husa and Kosenius 2021; Johann and Schaich 2016), but this process takes long time spans (Ranius et al. 2009), often exceeding the engagement period of one single forest owner. Therefore, policymakers should develop outreach and policy instruments to secure the retention and development of old-growth structures. To accomplish this, policymakers need reliable spatial data to determine where to focus their efforts (Barredo et al. 2021). The heterogeneous ownership and non-professionalized management of SPFs leads to a lack of spatial data concerning forest structures and biodiversity. This creates a significant knowledge gap regarding old-growth structures and the accompanying species in SPFs. A method to predict the abundance of such structures from more easily obtain-able data would have a wide range of applications. For example, it could be used as a proxy for biodiversity, to target owner outreach, and as data basis for decision makers to help design targeted outreach and legislation for nature conservation.

1.5 Overview of own research

The preceding section identified the research gaps that established the foundation for the current work. From these gaps, I developed research hypotheses (Table 1.1) that set the framework for this thesis. These hypotheses provide a cohesive research outline and are revisited in the Synthesis (Chapter 5). Each hypothesis was used as the basis for a research article that was submitted to an international scientific journal. The three resulting papers are included in this thesis as Chapters 2, 3, and 4. These publications share a common methodological foundation: Mathematical models were used to illuminate one or several of the interconnections (Figure 1.1) between SPF owners, their land, and the forest structures on it. The work for these publications was embedded in the KLEIBER research project[2], which was carried out at NW-FVA and the University of Göttingen, Germany. In the project, a comprehensive SPF owner questionnaire (Tiebel et al. 2021; Tiebel et al. 2024) was deployed, whose responses I used for parts of my research. Research in the scope of the KLEIBER project used a model region in Lower Saxony, the Lower Saxon Hills, as study area (see Sections 2.2.1 and 4.2.2).

(H_1)	The distribution of forest structural elements on small-scale private forests, especially those that support rare and endangered forest species, is influenced by owner goals and management activities.
(H_2)	Management goals and activities are influenced by sociodemographic characteristics of small-scale private forest owners, and gender is important among them.
(H_3)	Old-growth forest structures are subject to strong influences from landscape-related variables. These can be used to predict old-growth structures in small-scale private forests on the landscape scale.

Table 1.1: Research hypotheses

The first research article (Chapter 2) deals with the influence that owners of SPF parcels have on relevant structures on their land. We clarify this and explicitly look at management goals the owners might pursue, and the management activities they perform in their forests. These goals and activities are expected to influence forest stand characteristics and the distribution of other structures of high conservation value. Thus, we formulate hypothesis H_1 (see Table 1.1) from the perspective of forest nature conservation. From this hypothesis, we expand on the premise that historically, the

[2] https://www.nw-fva.de/forschen/projekte/kleiber

current owner's influence only adds to further influences from site characteristics, or the surrounding landscape that shapes structures in SPFs.

The second article (Chapter 3) focuses on SPF owners' management behavior, goals, perceived obstacles to achieving these goals, and attitudes toward nature conservation. These characteristics may be influenced by sociodemographic variables, such as gender, age, or urbanity. We state our working hypothesis as H_2 (see Table 1.1). In line with current research, we use a multivariate framework to identify sets of predictors. Similar to the analyses in the first paper, we decided to include potential candidate predictors from the forest parcels' site characteristics, such as parcel size and forest age. These variables are expected to exert some influence on owner behavior.

The third article (Chapter 4) focuses on old-growth structures in SPFs. In order to explain their spatial distribution, we need to quantify the erratic and diverse occurrences of such structures. Then, solid predictors must identified. With this framework in place, models can be trained to make predictions. Our approach relies on the third hypothesis, H_3 (see Table 1.1), which is supported by results from the first publication. Using readily available predictor variables, the models can generate landscape-scale predictions, providing comprehensive coverage of the study area with a relatively small set of sampled SPF parcels.

1.6 Thesis structure

- This chapter presents global crises that endanger forest ecosystems, takes a closer look at the important ownership class of SPFs, and illuminates the situation of their owners, especially in Europe and North America. Research gaps are identified concerning SPF owners, structures in their forests, and differences in conservation values on their land.
- Chapter 2 pursues the question of how much influence the current owners have on forest structures on their land, especially taking structures of high conservation value into account. The chapter uses data from the overarching owner survey, field data collected in a subsample of SPF parcels, and topographic variables calculated from open datasets.
- The subsequent Chapter 3 uses owner survey data to shed light on the factors that influence SPF owner attitudes and behaviors. Motivated by the question about the influence of sociodemographic traits such as gender, we trace a wider arc, encompassing a variety of sociodemographic and landscape characteristics, and investigate influences on activities, attitudes, and goals of forest owners.
- Chapter 4 builds on strong influences of landscape-related parameters that we recognized. Important old-growth structures are captured in a novel forest parcel index, and we pursue the idea of building prediction models for such structures on SPF parcels.
- The synthesis in Chapter 5 brings together the experiences and results of the prior chapters, and unifies them into an outlook on SPFs from a nature conservation point of view. It closes with essential recommendations for policymakers.

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Chapter 2

Owner attitudes and landscape parameters drive stand structure and valuable habitats in small-scale private forests of Lower Saxony (Germany)

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Owner attitudes and landscape parameters drive stand structure and valuable habitats in small-scale private forests of Lower Saxony (Germany)

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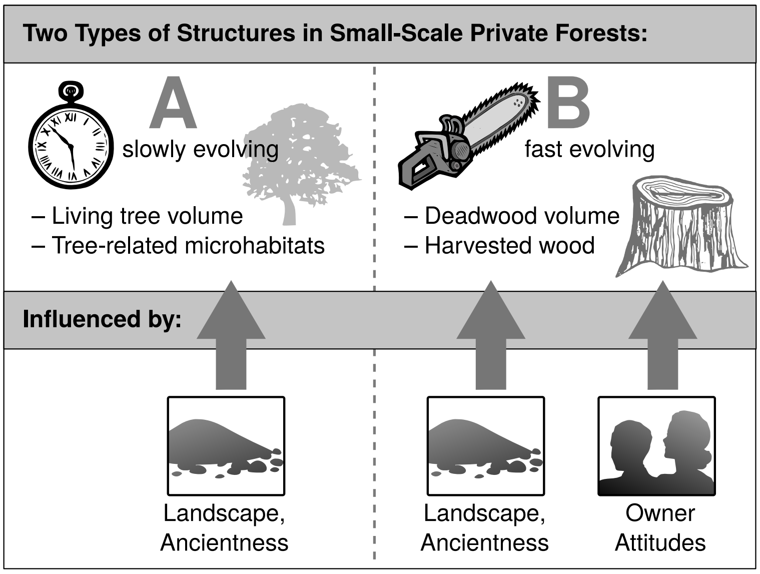
Abstract

Small-scale private forests cover large areas in Europe and often contain structures and habitats of high nature conservation value that are increasingly put under pressure due to a rising interest in fuelwood and wood products. We investigate the distribution of variables like living tree and deadwood volumes, management intensity, diversity and density of tree-related microhabitats recorded in 81 small-scale private forest parcels in the Lower Saxon Hills (northwest Germany). We provide an assessment of the influence of predictors like the individual forest owners' goals and activities, as stated by them in a quantitative survey, as well as landscape parameters like parcel size, slope, landscape fragmentation and forest continuity. Our results indicate that there are two types of structures of conservation value in small-scale private forests: slowly evolving structures (type A) like large-diameter living trees and tree-related microhabitats which mostly depend on landscape parameters that act on longer time scales, and fast evolving structures (type B) like deadwood that are influenced by both owner attitudes and landscape parameters. The resulting implications for integrative forest and conservation management are discussed. When considering the conservation of the slowly evolving type A structures, long-term commitments to conservation legislation, financial incentives and generation-spanning education of forest owners are necessary. Efforts to promote the faster evolving type B structures might prove particularly advantageous in small-scale private forests given the structural diversity of the stands, but also the often strong identification of owners with their land.

Graphical abstract



Keywords Small-scale private forests · Forest owner attitudes · Nature conservation values · Tree-related microhabitats · Landscape metrics

2.1 Introduction

When it comes to an effective conservation policy in forest landscapes, all types of ownership must be considered and integrated. This is especially true for landscapes with mixed ownership and a high proportion of privately owned forest land (Fischer et al. 2019; Loeb and D'Amato 2020). In Germany, half of the country's forested area is privately owned, distributed equally among owners possessing at least 20 ha, and small-scale private forest (SPF) owners with forest parcels smaller than 20 ha (BMEL 2014). While forestry in owner groups with larger properties (state and federal forests, communal forests, and larger private properties) has become more mechanized and commercially oriented in the past, SPF owners have often been less inclined to harvest timber from their forests. Furthermore, many SPFs in Germany are of very small sizes (average private forest parcel size of 3 ha) (BMEL 2014), often precluding economic use, especially by heavy machinery, and leading to significantly different forest structures in SPFs compared to other ownership types (Mölder et al. 2021). Most notably, SPFs have been shown to be characterized by higher structural diversity (Maltamo et al. 1997; Rendenieks et al. 2015; Schaich and Plieninger 2013) and biodiversity (Torras et al. 2012). Certain structures and habitats that are considered to be of high nature conservation value have been shown to occur there more frequently, like tree-related microhabitats (TreMs) (Johann and Schaich 2016) and deadwood (Schaich and Plieninger 2013).

With changing economic parameters like increasing demand for fuelwood, intensified forest management can also be expected in many regions with a high share of SPF (UNECE 2022). Extension services offered by state and private forestry associations are also increasingly encouraging wood extraction from small parcels (Takala et al. 2022), even though this might be questionable considering the carbon impact (Norton et al. 2019; Sterman et al. 2022). Another aspect to consider are the consequences for habitat structures and the species that depend on them (Kjučukov et al. 2022), i.e., the nature conservation values of forest lands. TreMs have been recognized as valuable for a plethora of species groups (Asbeck, Großmann, et al. 2021). They are relatively easy to survey and can be used as a proxy for the occurrence of species groups like saproxylic beetles, spiders, bats, birds, fungi and lichens (Martin et al. 2022). Many TreMs like different forms of cavities are known to develop over long time spans (Kõrkjas et al. 2021) and are therefore rare in many conventionally managed forests, where trees are mostly harvested before they can develop features like accumulated crown deadwood or tree cavities (Ranius et al. 2009). Due to lower management intensity, TreMs have a higher chance to develop in SPFs, but are now experiencing increased pressure with rising timber and particularly firewood extraction. This is particularly true for TreMs linked to large-diameter trees, which are important elements of conservation strategies (Kozák et al. 2023). Another feature of high importance to multiple forest functions and nature conservation value is deadwood, which improves forest soils, has a beneficial impact on water retention, and serves as medium-term carbon sink (Chivulescu et al. 2022; Parisi et al. 2018; Piaszczyk et al. 2021). Deadwood also provides the substrate and habitat for a range of organism groups, many of which are endangered and protected. Examples include bryophytes, lichens, fungi, invertebrates, small mammals and birds (L Bujoczek et al. 2021). Similar to TreMs, deadwood supplies in SPFs and related biodiversity can be put under pressure with increasing forest management intensity.

SPF owners are a heterogeneous group of people with a diverse set of motivations and goals concerning their land, resulting in a variety of strategies when managing their forests (Tiebel et al. 2024; Westin et al. 2023). While SPF owners are often assumed to have predominantly economic interests, there is actually a large variety in motivations. A substantial group of SPF owners is strongly interested in nature and cultural heritage conservation (Weiss et al. 2019). Likewise, the management activities of SPF owners are diverse and may comprise a wide range from industrialized wood harvesting, logging by horses, manually extracting single small stems as firewood for personal consumption, or even ceasing all felling activities for the sake of nature conservation, or due to lack of interest or long distances to their property (Bieling 2004; Tiebel et al. 2021; Weiss et al. 2019).

Many structures of conservation value in forests take a long time to develop (Kõrkjas et al. 2021) or may depend on random, unpredictable events (breaking of stems or parts of the crown, injuries, colonization by animals; Larrieu et al. (2022)). Therefore, it seems not to be easy to relate structures and habitats to current motivations and management goals of forest owners. The time span during which individual forest owners actively influence their forests is often short compared to natural processes in the forest ecosystem, and long-term influences for example from landscape characteristics of the forest parcels (elevation, slope, water and soil parameters) or their surroundings (fragmentation or location in large, closed forests) may play an equally important role in the development of valuable structures (L Bujoczek and M Bujoczek 2022; Kapusta et al. 2020; Kennedy et al. 2008).

To our knowledge, the relationships between small-scale private forest owner goals and activities, and structures and habitats in their respective forest parcels have not been investigated yet. To address this research gap, we performed analyses in SPFs smaller than 5 ha in a model region, the

Lower Saxon Hills in northwest Germany (see Fig. 2.1). We used the following data sets: (*a*) quantitative survey data about SPF owners' goals and activities; (*b*) field data collected on their parcels (data on forest structure and nature conservation values); and (*c*) data on landscape parameters of the parcels to address the following research questions:

1. What are the characteristics of the SPF parcels in our model region concerning stand structure variables and the distribution of valuable habitats?
2. What are the respective influences of owner goals and activities, and landscape parameters on these variables?
3. How can the possibly varying influences be explained, and which conclusions for integrative forest and conservation management in SPFs can be drawn?

2.2 Methods

2.2.1 Study area

Our study area is the Lower Saxon Hills geographic region (Fig. 2.1) in the German federal state of Lower Saxony, which consists of two discontiguous areas and includes adjacent administrative units (in total 14 228 km^2). Due to the uniform legal situation and consistent governmental forest administration, eventual regional differences in the support and treatment of SPF owners are kept to a minimum in this study. The Lower Saxon Hills are 33 % forested, with European beech (*Fagus sylvatica*, 35 %), Norway spruce (*Picea abies*, 29 %) and oaks (*Quercus robur* and *Quercus petraea*, 11 %) as the dominant tree species. Natural vegetation would consist mostly of European beech, while the admixture of Norway spruce, oaks and other broadleaf (e.g., sycamore *Acer pseudoplatanus*, wild cherry *Prunus avium*, birch *Betula pendula*, hornbeam *Carpinus betulus*) and conifer (e.g., Scots pine *Pinus sylvestris*, Douglas fir *Pseudotsuga menziesii*) tree species is largely due to anthropogenic influence. In privately owned forest parcels (43 % of the forested area), 22 % of the area consists of parcels with a size between 5 and 20 ha, and 23 % of the area is occupied by parcels of 5 ha or less (ML 2014). The distribution of forest ownership classes and small-scale structural diversity is comparable to many European countries (Mölder et al. 2021; Schmithüsen and Hirsch 2010), which allows for a transfer of our results.

The study area lies at the border between oceanic and humid continental climates (Köppen classifications Cfb and Dfb), with average annual precipitation on our research sites between 645 and 1042 mm, and annual mean temperatures between 8.2 and 10.3 °C (DWD 2018b; DWD 2018a). Bedrock is mostly Mesozoic limestone and sandstone, in part with a Quaternary loess cover, and occasionally evaporite (gypsum karst) (LBEG 2022). Despite the relatively high average rainfall, the study area has been affected by unusual heat and drought periods since 2018. This combined with severe storms in 2018 and 2020 led to increased damage by bark beetles and widespread tree mortalities in conifer stands (Rohde et al. 2021; Rohde et al. 2019).

2.2.2 Owner attitudes and forest parcels

To obtain insights into the attitudes of SPF owners in the study area, we used data from a quantitative mail survey that was conducted among the members of three local private forest owner associations. We sent out questionnaires by post to all 4204 members of these associations, and 1671 persons (39.8 %) returned usable answers by mail or online (Tiebel et al. 2021). For the present work, we recontacted those participants who had provided their contact details. We asked for the location of their largest forest parcel and for their approval to carry out field work. This call resulted in 91 answers, of which 81 provided useful geographic information about forest parcels (Fig. 2.1). These parcels range in size from 0.1 to 3.8 ha (mean: 1.21 ha, median: 1.01 ha, SD: 0.89 ha).

Owner goals concerning their forests were queried in the questionnaire with a list of 16 possible goals, with the possibility to rate their respective influence on a five-point Likert scale (details given in the Appendix, Section 2.6.1). These goals were then categorized into four types (Tiebel et al. 2021), namely goals referring to the promotion of certain ecosystem services (regulating, cultural and provisioning), and purely financial goals (Table 2.1). For each goal type consisting of several sub-goals, a value of agreement between 0 and 1 was calculated. The forest management activities of SPF owners (Table 2.1) were captured using a checklist of 26 possible choices and categorized into five activity types (1. classical silvicultural, 2. close-to-nature silvicultural, 3. traditional silvicultural, 4. active conservation, and 5. passive conservation activities). Agreement with each type of activity was again expressed as a fractional value between 0 and 1.

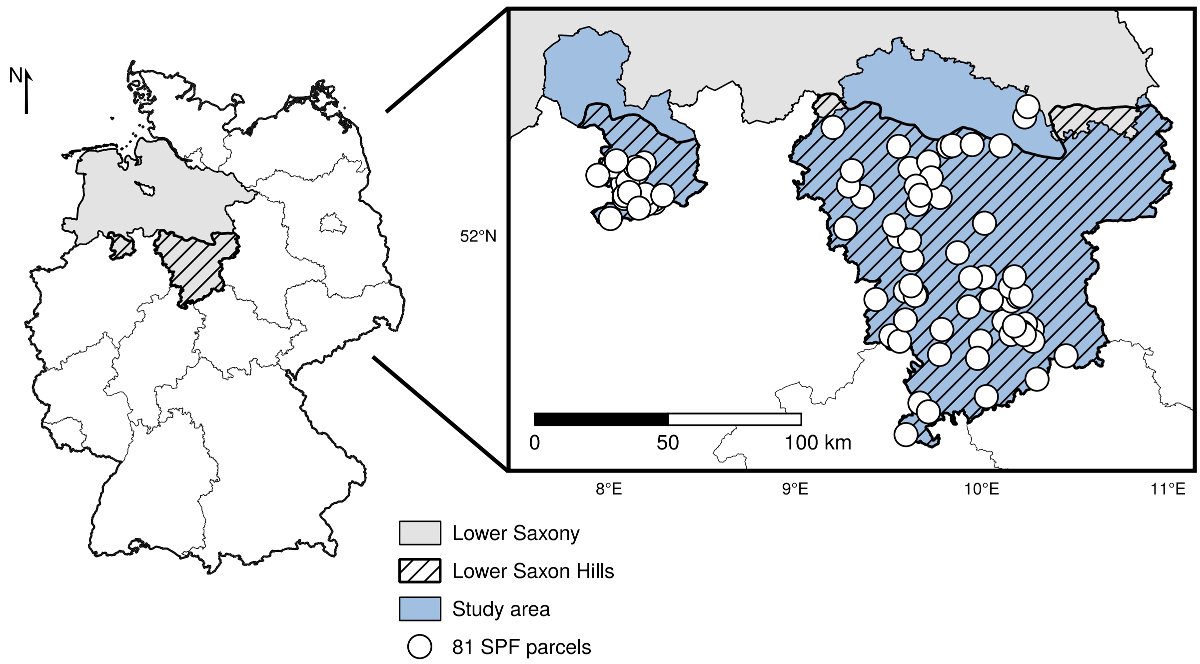


Figure 2.1: The study area is located in the federal state of Lower Saxony (Germany) and consists of a set of administrative units (dark blue) to closely resemble the Lower Saxon hills geographic region (hatched). Data: Lower Saxony Forest Planning Agency (NFP), GADM (https://gadm.org/).

Table 2.1: Predictors: Owner attitudes and landscape parameters.

Owner attitude	**Min**	**Max**	**Mean**	**SD**
Identification with regulating goals	0	1	0.860	0.245
with cultural goals	0.350	0.900	0.660	0.118
with provisioning goals	0.200	1	0.651	0.212
with financial goals	0.200	1	0.519	0.217
Implementation of classical silvicultural activities	0	1	0.520	0.269
of close-to-nature silvicultural activities	0	1	0.504	0.214
of traditional silvicultural activities	0	0.500	0.062	0.166
of active conservation activities	0	0.857	0.215	0.235
of passive conservation activities	0	0.750	0.315	0.249
Landscape parameter	**Min**	**Max**	**Mean**	**SD**
Parcel size (ha)	0.14	3.80	1.21	0.886
Elevation (m a.s.l.)	55	403	194	83.8
Slope (%)	0.2	55.3	13.8	10.8
Water availability (0–3)	0	3	1.01	0.461
Nutrient availability (0–2)	0	2	1.26	0.628
Distance to paved road (m)	0	1096	299	275
Ancient broadleaf forest	0	1	0.165	0.367
Ancient mixed forest	0	1	0.277	0.436
Ancient conifer forest	0	1	0.162	0.362
Open land within 2 km radius	0.011	0.998	0.716	0.312
Proportion of border with open land	0	1	0.650	0.357

2.2.3 Landscape parameters

Based on the literature and expert knowledge, we identified landscape parameters (Table 2.1) that were expected to influence forest structure and the distribution of valuable habitats. Elevation, slope and aspect of the individual parcels were derived from a digital terrain model (LGLN 2022). We used data about water availability (given on a scale from 0 = dry to 3 = wet) and nutrient availability (0 = oligotrophic, 1 = mesotrophic, 2 = eutrophic) to further characterize the parcels (LBEG 2022). Connection to infrastructure was expressed by the distance to the nearest paved road (OpenStreetMap contributors 2022). Corine land cover data (European Environment Agency 2018) was used to calculate the proportion of open land surrounding a parcel within a radius of 2 km (Verga et al. 2021); this value was pre-selected from a series of logarithmically scaled possible radii of 50–5000 m, based on correlations of the predictor with the response variables (Jackson and Fahrig 2015). The percentage of each forest parcel border that coincides with open land was calculated from Corine data. We used data about the presence of forests in Lower Saxony on historical maps (NFP 2010) to classify the parcels as either recent forest, or ancient forest (more than 200 years of continuous forest cover) of broadleaf, conifer or mixed character, respectively.

Figure 2.2: Selection of structural features and management situations found in SPFs in the study area. **a** Remnants of historical usage: old coppice stool in a formerly coppiced European beech (*Fagus sylvatica*) stand. **b** Extreme habitats: European beech forest on shallow soil over limestone in steep terrain. **c** Habitat trees: limb breakage with exposed heartwood (pedunculate oak, *Quercus robur*). **d** Small-scale harvesting of firewood, mainly European beech. Photographs: Peter Hansen.

2.2.4 Forest structure and valuable habitats

Forest structural data (Table 2.2) were collected on circular plots of 500 m^2 (r = 12.62 m), generally following the methodology in Meyer and Fricke (2018). Parcels below 1.5 ha were equipped with one plot, larger plots received two (below 3 ha) or three plots. The center of a single plot was placed at the centroid of the forest parcel in a Geographic Information System (with some leeway for concavely shaped parcels), while two or three plots were placed to provide the maximum distance from one another and the border of the parcel. Standing trees (living or dead) with a diameter at breast height (dbh) of at least 7 cm were recorded with dbh and tree species. For each tree species and each plot, nine height measurements were taken if possible from trees in three different height classes using a handheld laser rangefinder (LTI TruPulse 360B). Stumps with a diameter of at least 7 cm and lying deadwood with a diameter of at least 20 cm were recorded, too. Deadwood was classified as either broadleaf or conifer deadwood and as sawn and non-sawn. In addition, the stage of decay (four classes: 1 = freshly dead to 4 = identifiable, but completely soft) was determined.

After data collection on the plots, the whole forest parcel was assessed for disturbances (for example, excessive logging trails, signs of recreational use, storm damage; each classified on a scale from 0 = not present, to 3 = strong influence). Trees of at least 50 cm dbh were recorded and

Table 2.2: Response variables: Forest structure and nature conservation values. To describe forest management intensity on the parcels, we use the index ForMI (Kahl and Bauhus 2014), consisting of three components (iHarv = proportion of harvested volume to total volume; iNonat = proportion of volume of non-natural species to total volume; iDwcut = proportion of sawn deadwood to total deadwood volume).

Forest structural parameters	**Min**	**Max**	**Mean**	**SD**
Living tree volume (m^3 ha^{-1})	0	990	258	227
Broadleaf	0	877	210	227
Conifer	0	580	48.1	110
Deadwood (m^3 ha^{-1})	0	276	30.4	44.5
Broadleaf	0	124	11.2	22.1
Conifer	0	204	19.2	38.8
Sawn	0	65.4	11.1	13
Non-sawn	0	239	19.3	40.5
Accumulated harvested volume (m^3 ha^{-1})	0	1087	260	272
Broadleaf	0	1029	94.2	169
Conifer	0	1087	166	274
ForMI index value (0–3)	0	2.95	1.39	0.869
iHarv component (0–1)	0	0.978	0.41	0.328
iNonat component (0–1)	0	1	0.406	0.436
iDwcut component (0–1)	0	1	0.574	0.394
Other nature conservation parameters	**Min**	**Max**	**Mean**	**SD**
Biotope value points (0–24)	6	23	14.1	4.28
Number of tree and shrub species on plot	0	10	3.77	2.07
Mean stand age (years)	12.5	112.5	46.5	31.9
TreM density (ha^{-1})	0	118	12.6	22.7
TreM trees (ha^{-1})	0	72.3	10	17.3
Trees dbh $\geq$ 50 cm (ha^{-1})	0	163	18.1	30

assessed for TreMs following the field key by Larrieu et al. (2018) to calculate TreM density (per ha), the abundance of trees with TreMs (per ha), and the abundance of trees with a dbh $\geq$ 50 cm (per ha). For each forest parcel, the prevailing stand age was classified into 25-year classes (0–25 yrs, 26–50 yrs, and so on) by expert estimation in the field. Height and dbh data from the trees with measured heights were used to calculate individual Näslund height curves for each tree species on each plot (Mehtätalo et al. 2015) in order to interpolate the heights of the remaining trees from dbh measurements alone. Wood volumes were calculated from dbh and height data using species-specific form factors. Accumulated harvested volumes were calculated from stump data: To this aim, stump diameters were first extrapolated to dbh using a uniform tapering value of 1 cm/m, and then standard form factors were applied. Harvested volumes therefore constitute an integral over the stump persistence time of the wood volume that was taken from the forest.

To quantify human influence on forest development, we calculated the forest management intensity index (ForMI) (Kahl and Bauhus 2014). Non-native tree species as used in the context of the ForMI were understood to also encompass species planted outside their natural range, for example *Picea abies* (Norway spruce). On each parcel, the three most important biotope types in terms of surface area were identified (Drachenfels 2021) and translated to area-weighted biotope values ranging from 0 to 24 points (low to high, see Table 2.4) according to the German federal regulation on the avoidance and compensation of interventions into nature and landscape (BKompV 2020). An impression of the diverse situations encountered in SPFs is given in Fig. 2.2.

2.2.5 Data analysis

To assess the respective influence of owner attitudes and landscape parameters on the response variables forest structure and nature conservation values, we used ordinary least squares (OLS) regression analysis (compare Lange et al. (2022), Przepióra and Ciach (2022)). For each response variable (Table 2.2), we calculated a linear model using all predictors from landscape parameters and owner attitudes (Table 2.1). Multicollinearity among the predictors was relatively weak, with variance inflation factors below 4, and we decided not to remove any predictors (Naimi et al. 2014; Wooldridge 2013). We calculate semipartial correlations (Grömping 2015) as a measure of the effect size of individual predictors, and quote R^2 values to assess the relative explanatory power of the models. All analyses were carried out using R 4.0.3 (R Core Team 2020).

2.3 Results

Descriptive statistics of the response variables are presented in Table 2.2. In this section, we focus on the OLS regression analysis. Relevant results are summarized in Table 2.3. Each row corresponds to an individual OLS regression computed for a single response variable (first column). To compare the explanatory power of the models, we used R^2 values, as stated in column 2. The remaining columns express the individual contributions of the predictors to the model at hand. In the following, we group the results concerning living tree volumes, deadwood, harvested volumes, management intensity, and nature conservation values.

2.3.1 Living tree volumes

The model for broadleaf, conifer and total living tree volumes showed relatively high R^2 values (Table 2.3). Owner attitudes had no significant influences on the response variables, while several landscape parameters exhibited significant influences. Living broadleaf tree volume was positively connected to ancient broadleaf and ancient mixed forest sites. The proportion of border length with open land also showed a positive correlation. For living conifer tree volumes, the amount of open land within a 2 km radius displayed a strong negative influence. The total living tree volume was strongly positively influenced by ancient mixed forest sites, while there was only a weak positive influence of broadleaf forest sites and the border length with open land.

2.3.2 Deadwood volumes

The picture for deadwood volumes as an important nature conservation value was different (Table 2.3), with forest owner attitudes acting as relevant influences. Deadwood was found in all decay stages, but recent deadwood prevailed (decay stage 1: 66.4 %, stage 2: 21.3 %, stage 3: 10.1 %, stage 4: 2.1 % of the volume). Total deadwood volume showed a strong dependency on the slope of the forest parcels, with additional influence by the implementation of close-to-nature silviculture. The respective influences became clearer if we discerned between broadleaf (63.2 % of the deadwood volume) and conifer (36.8 %) deadwood volumes. Broadleaf deadwood showed a slight positive influence by close-to-nature silviculture, the slope and ancient broadleaf forest sites, while parcel size had a negative influence. For conifer deadwood, we found a strong positive effect of slope. We also discerned between deadwood of anthropogenic (sawn) and natural origin (deadwood without saw marks). The occurrence of anthropogenic deadwood was highly dependent on owners' attitudes. We found a strong positive influence of close-to-nature silviculture activities, a slight positive influence of the identification with regulating goals, and a slight negative influence of the implementation of active conservation measures. Landscape parameters played an important role as well, with a strong positive influence of ancient conifer forest sites. For deadwood of natural origin, slope was the sole but strong positive driver.

2.3.3 Accumulated harvested wood volumes and management intensity

For accumulated harvested wood volumes and the closely related management intensity, owner attitudes showed significant effects (Table 2.3). Total harvested wood volume, while most strongly influenced by ancient conifer forest sites, was fostered by the implementation of classical silvicultural activities (and slightly influenced by close-to-nature forestry activities). For broadleaf harvested volumes, ancient mixed forest sites had a strong positive influence, while the distance to the next paved road and the adoption of close-to-nature silvicultural activities also had positive influences. We saw a more pronounced influence of owner attitudes on harvested conifer volumes. Classical silvicultural activities were promotors, while the identification with provisioning goals and the pursuit of passive nature conservation hampered them. The strongest effect was a positive influence of ancient conifer forest sites.

For management intensity, we found positive effects of the support for cultural goals and the implementation of classical silvicultural activities. Passive conservation measures showed a negative influence. We additionally identified a strong positive effect of ancient conifer forest sites. The proportion of harvested to total wood volume (Iharv) showed a similar pattern. The volume proportion of non-natural tree species (Inonat) was slightly negatively influenced by ancient broadleaf forest sites and the amount of open land within a 2 km radius, while ancient conifer sites showed a positive effect. The volume proportion of anthropogenic deadwood (Idwcut) showed a different pattern: It was slightly positively influenced by the identification with cultural goals and the adoption of classical silvicultural activities.

Table 2.3: Influences of predictors on response variables. Each line corresponds to a linear model for the response variable given in the first column. The second column lists the R^2 value of each model. The predictors are given in the remaining columns. Significant influences are given in bold face. If a predictor represents a significant contribution to the model, it is shown in this table with its semipartial correlation value and an indication of the $\Pr(>|t|)$ value p: "(*)" for $p \leq 0.1$, "$*$" for $p \leq 0.05$, "$**$" for $p \leq 0.01$, "$***$" for $p \leq 0.001$; otherwise, a placeholder "·" is shown. An exhaustive version can be found in Table 2.6.

Answer variable	R^2	Forest owner goals and activities									Topographical parameters										
		Regulating goals	Cultural goals	Provision. goals	Financial goals	Classical silvic.	Close-to-nature silvic.	Traditional silvic.	Active conser-vation	Passive conser-vation	Parcel size	Elevation	Slope	Water avail.	Nutrient avail.	Distance to road	Ancient broadleaf	Ancient mixed	Ancient conifer	Open land within 2km	Border w/ open land
Living wood volume																					
Total	0.40	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	$0.17^{(*)}$	$\mathbf{0.29}^{**}$	·	·	$0.18^{(*)}$
Broadleaf	0.42	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	$\mathbf{0.24}^{*}$	$\mathbf{0.22}^{*}$	·	·	$0.18^{(*)}$
Conifer	0.43	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	$\mathbf{-0.33}^{**}$	·
Deadwood volume																					
Total	0.36	·	·	·	·	·	$0.18^{(*)}$	·	·	·	·	·	$\mathbf{0.42}^{***}$	·	·	·	·	·	·	·	·
Broadleaf	0.30	·	·	·	·	·	$0.20^{(*)}$	·	·	·	$\mathbf{-0.25}^{*}$	·	$0.20^{(*)}$	·	·	·	$0.20^{(*)}$	·	·	·	·
Conifer	0.34	·	·	·	·	·	·	·	·	·	·	·	$\mathbf{0.37}^{***}$	·	·	·	·	·	·	·	·
Sawn	0.43	$0.18^{(*)}$	·	·	·	·	$\mathbf{0.27}^{**}$	·	$-0.18^{(*)}$	·	·	·	·	·	·	·	·	·	$\mathbf{0.34}^{**}$	·	·
Non-sawn	0.33	·	·	·	·	·	·	·	·	·	·	·	$\mathbf{0.44}^{***}$	·	·	·	·	·	·	·	·
Harvested wood volumes																					
Total	0.45	·	·	·	·	$\mathbf{0.20}^{*}$	$0.19^{(*)}$	·	·	·	·	·	·	·	·	·	·	·	$\mathbf{0.37}^{***}$	·	·
Broadleaf	0.37	·	·	·	·	·	$\mathbf{0.24}^{*}$	·	·	·	$-0.20^{(*)}$	·	·	·	·	$\mathbf{0.22}^{*}$	·	$\mathbf{0.31}^{**}$	·	·	·
Conifer	0.54	·	·	$\mathbf{-0.20}^{*}$	·	$\mathbf{0.18}^{*}$	·	·	·	·	·	·	·	·	·	·	·	·	$\mathbf{0.36}^{***}$	·	·
ForMI	0.50	·	$\mathbf{0.20}^{*}$	·	·	$\mathbf{0.20}^{*}$	$0.17^{(*)}$	·	·	$\mathbf{-0.22}^{*}$	·	·	·	·	·	·	·	·	$\mathbf{0.36}^{***}$	·	·
Iharv	0.50	·	·	$-0.16^{(*)}$	·	$\mathbf{0.19}^{*}$	$\mathbf{0.20}^{*}$	·	·	$\mathbf{-0.23}^{*}$	·	·	·	·	·	·	·	·	$\mathbf{0.42}^{***}$	·	·
Inonat	0.51	·	·	·	·	·	·	·	·	·	·	·	·	·	$-0.16^{(*)}$	·	$-0.18^{(*)}$	·	$\mathbf{0.29}^{**}$	$-0.18^{(*)}$	·
Idwcut	0.30	·	$\mathbf{0.24}^{*}$	·	·	$0.21^{(*)}$	·	·	·	·	·	·	$-0.20^{(*)}$	·	·	·	·	$0.19^{(*)}$	·	·	·
Other nature conservation values																					
Biotope value	0.48	$-0.18^{(*)}$	·	·	·	·	·	·	·	·	·	·	·	·	·	·	$\mathbf{0.21}^{*}$	$0.17^{(*)}$	·	$\mathbf{0.19}^{*}$	·
# of tree species	0.27	·	·	·	$\mathbf{-0.25}^{*}$	·	·	$\mathbf{0.23}^{*}$	·	·	·	·	·	·	$0.20^{(*)}$	·	·	·	·	·	·
Mean stand age	0.42	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	$\mathbf{0.26}^{*}$	$\mathbf{0.25}^{*}$	·	·	·
TreM density	0.34	·	·	·	·	·	·	·	·	·	$-0.18^{(*)}$	·	·	·	·	·	$\mathbf{0.32}^{**}$	$\mathbf{0.21}^{*}$	·	·	·
TreM tree density	0.34	·	·	·	·	·	·	·	·	·	$-0.18^{(*)}$	·	·	·	·	·	$\mathbf{0.31}^{**}$	$\mathbf{0.21}^{*}$	·	·	·
Trees dbh $\geq$ 50 cm	0.32	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	$\mathbf{0.27}^{*}$	$\mathbf{0.25}^{*}$	·	·	$\mathbf{0.26}^{*}$

2.3.4 Other nature conservation values

Within the group of nature conservation values apart from the various wood volumes, landscape parameters showed strong influences. Ancient broadleaf forest sites and the amount of open land within a 2 km radius exhibited a positive influence on biotope values. The mean stand age showed positive influences by both ancient broadleaf and mixed forest sites. Regarding TreMs, the most abundant TreM categories found in the field were crown deadwood and concavities (see Table 2.5 in the Appendix), and European beech (61.2 %) and oaks (28.4 %) were the main TreM-bearing trees. The mean diameter of the inventoried TreM-bearing trees was 65.0 cm (median 60.0 cm). Concerning the abundance of TreMs, the models showed patterns similar to the mean stand age model. Parcel size had a slightly negative effect, while the location on ancient broadleaf and mixed forest sites was positively correlated. Note the positive influence of the border length with open land for the density of large-diameter trees. Owner attitudes were only sparsely correlated with nature conservation values. Except for the model for the number of tree species (which reached only marginal explanatory power), almost no owner attitude variable exhibited significant influence on these models.

2.4 Discussion

In this study, we adopted a novel methodological approach to shed light on the effect of small-scale private forest owners' attitudes on the structures of their forest stands, especially taking into account nature conservation values. Since we expected owner attitudes to only partly explain the variance seen in the response variables (note that the survey cast only a spotlight on a single time point in the long history of a parcel's owners and their attitudes), several landscape parameters were included as well. We found that landscape parameters played an important role as predictive variables in almost all of the models that we considered. Such patterns are similar to those found in previous studies (Asbeck, Kozák, et al. 2021; Kapusta et al. 2020; Kennedy et al. 2008; Levers et al. 2014). Concerning the influence of owner attitudes in the models, we found that some response variables are indeed correlated with forest owner attitudes, while others are mostly unrelated to the owners' goals and activities. We propose that these two groups of response variables describe two underlying types of structures with distinct characteristics. We sort these structures as belonging into either “type A” or “type B”, as described as in the following (Fig. 2.3):

- **Type A** Structures addressed as belonging to type A show strong correlations with several landscape parameters, but are mostly unrelated to owner attitudes. We postulate that these structures are evolving very slowly, such that the goals and activities of the current forest owner play only a minor role. Landscape parameters continuously persist over long time spans and are therefore plausible influence factors for the development of type A structures.
- **Type B** Structures of this type show correlations with landscape parameters, but they are also prominently correlated with owner attitudes. We regard such structures as fast evolving and readily susceptible to the individual forest owner's influence.

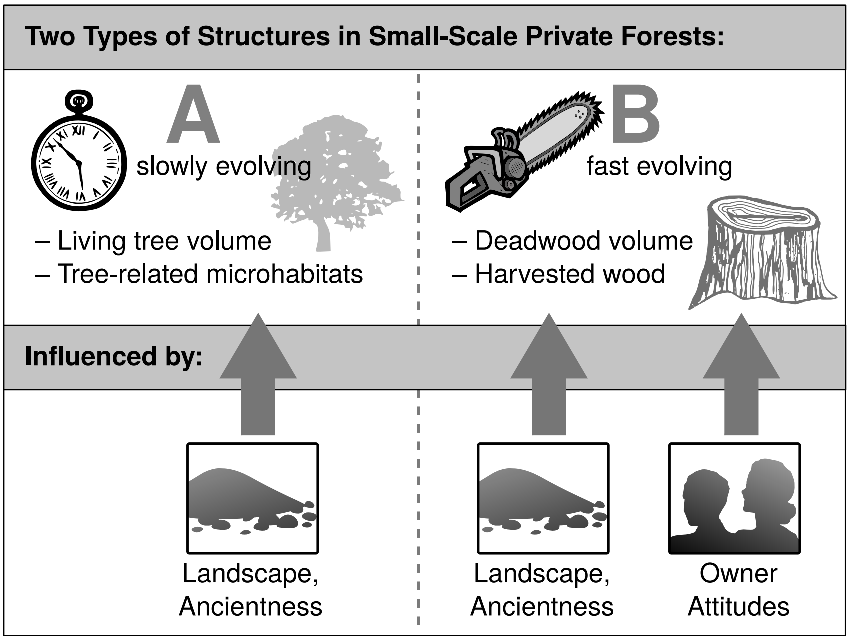


Figure 2.3: Overview of the two types of structures that we discerned: Slowly evolving type A structures like living tree volume or the density of tree-related microhabitats were not influenced by owner attitudes, but showed a correlation with landscape parameters. Fast evolving type B structures like the amount of deadwood or harvested wood were influenced by both landscape parameters, and owner goals and activities.

In the following, we take a closer look at the individual response variables and propose a classification into either type A or type B and finally highlight crucial points concerning the integration of our results in forest conservation planning.

2.4.1 Wood volumes and valuable habitats (type A, slowly evolving structures)

The amount of living tree volume is determined mostly by high-diameter trees which take long time spans to mature. Consequently, current forest owner attitudes show minimal influence on wood volumes, supporting a classification of all response variables concerning living tree volumes into type A (slowly evolving structures). While the total living tree volume already shows correlations with ancient forest sites, it proved beneficial to discern between broadleaf and conifer volumes (which is also reasonable given their different habitat properties).

Ancient conifer sites do not seem to promote today's conifer volume, in line with evidence for greater climate resilience of mixed stands (Honkaniemi et al. 2020). The dwindling of conifers on ancient conifer sites might be due to water stress and extensive damage by storms and bark beetles in spruce monocultures often present on such sites (L Bujoczek et al. 2021; Kharuk et al. 2016). The strongest correlation of conifer wood volume is a negative one with the amount of open land within a 2 km radius. Historically, conifer plantations in the study area tended to cover large, contiguous areas and were planted on less valuable land. Smaller conifer patches in open land are more exposed to adverse climatic and biotic conditions like storm gusts, bark beetle swarming (Stříbrská et al. 2022), and drought (Buras et al. 2018).

Living broadleaf tree volumes are closely interrelated with the occurrence of TreMs and large-diameter trees (dbh $\geq$ 50 cm), and both benefit from a long continuity of forest cover (ancient broadleaf or mixed forest sites). Broadleaf wood volume correlated with parcels' direct borders with open land, which also holds for large-diameter trees. The positive influence of forest border structures can be explained by the occurrence of old, large-diameter trees that were intentionally left in place and historically marked the border between forest and agricultural land. Such trees are prone to develop a variety of TreMs, and today belong to the oldest individuals ('champion trees') on many parcels, making forest borders and forest patches in agricultural landscapes a highly valuable habitat (Froidevaux et al. 2022; Orłowski and Nowak 2007). This is further supported by TreM density being negatively correlated with parcel size. In contrast to findings by Larrieu et al. (2022), neither elevation nor slope showed any significant correlation with TreM densities.

Biotope values as defined by BKompV (2020) can also be classified as type A structures. They lack correlations with owner attitudes but show correlations with ancient broadleaf sites and the amount of open land around the parcels. This is not surprising, as sites embedded in a fragmented landscape are likely to be covered by broadleaf forest, reaching high biotope values (Table 2.4 in the Appendix). Such sites have already been identified to be promising ecosystem service providers (Decocq et al. 2016; Varela et al. 2018). Lastly, the number of tree species did not fit in any of the type A or type B categories.

2.4.2 Deadwood, harvested volume and management intensity (type B, fast evolving structures)

The mean amount of deadwood (30.4 m^3 ha^{-1}) reached several threshold values for the survival of different forest species groups as evaluated by Müller and Bütler (2010), who for instance recommend to establish forest stands with deadwood amounts > 20–50 m^3 ha^{-1} in a network of forest landscapes. Variables related to deadwood amounts show significant influences of owner attitude variables and can be classified as type B (fast evolving structures). Across the models, we see positive influences of the forest owners' implementation of close-to-nature silviculture, especially on sawn deadwood. Doerfler et al. (2017) found management intensity to be a driver of deadwood volume, with deadwood increasing up to a certain maximum and then decreasing with management intensity. We observed this behavior only for conifer deadwood, while broadleaf deadwood was uniformly negatively correlated to management intensity. Concerning the landscape parameters, consistent with L Bujoczek et al. (2021), slope plays a major role for non-sawn (conifer) deadwood, but an influence of elevation as proposed in Kennedy et al. (2008) was not observed (possibly due to a lower elevation range among our sites). The influence of slope can be explained by more difficult access to steep, wind-thrown parcels, where accumulating deadwood cannot be easily extracted.

When looking at harvested wood volumes, strong influences by owner attitudes lead to a classification in type B as well. Especially conifer harvested volume is affected by owner attitudes like the implementation of classical silvicultural measures. The related forest management intensity index also shows a distinct type B pattern, with forest owner attitudes playing a major role in the models' ability to explain variance in the response variables. Provisioning goals are negatively correlated with the sub-index Iharv (the proportion of harvested to total wood volume). It can be assumed that provisioning goals become less important as owners' stands are more affected by storm damage. The implementation of passive conservation measures exerts a strong negative influence on management intensity. This is in line with research pointing at high management intensities being negatively correlated with most forest ecosystem services except for the production of biomass (Sing et al. 2018). High agreement with cultural goals might be perceived as characteristic of recreationalist forest owners (Blanco et al. 2015); however, our results reveal a correlation with forest management intensity. A possible explanation might be that forest owners who invest more time in management are more inclined to value cultural ecosystem services than more passive owners. Landscape parameters do not show strong influences on management intensity apart from the importance of ancient conifer forest sites.

2.4.3 Consequences for nature conservation

In the face of today's ecological crises, management of forests is challenged to provide wood products and fuelwood while at the same time fostering a multitude of other forest ecosystem services. Integrative forest management has proven to be a suitable way to meet these requirements (Kraus and Krumm 2013; Krumm et al. 2020), and within this framework, the conservation of forest biodiversity is a prime concern and depends on certain specific structures and habitats. We found that structures of high conservation value in SPFs can be separated into two types: the slowly evolving type A structures, and structures of the relatively fast evolving type B. It is therefore advisable to take these characteristics into account when designing nature conservation efforts in SPFs.

As development times of valuable type A structures (among them living tree volumes especially of broadleaf trees and TreMs) amount to decades and longer, conservation measures are able to protect already existing structures, but cannot be expected to support their formation on a short-term basis. Conservation efforts might target the protection of habitat trees (for instance, 'champion trees' that we often localized near border structures in the landscape), e.g., through contract-based conservation programs (Demant et al. 2020). Over the course of such a tree's life, economical pressure might rise, leading to it being harvested at some point—especially considering the increasing demand for firewood. A continuous educational process will be needed to persuade forest owners of the inherent value of old broadleaf trees (Salomaa et al. 2016). When it comes to promoting the development of valuable structures like large-diameter trees or accompanying TreMs, very long-term commitments that transcend the individual forest owners would be beneficial, like the designation of protected areas. Apart from the naturally slow formation of TreMs, approaches to actively create TreM-like structures like artificial cavities or high stumps should be promoted (Adelmann et al. 2021), but a widespread application would require strong intrinsic or extrinsic motivation of forest owners (see Tiebel et al. (2024) for examples).

Valuable type B structures in SPFs include different sorts of deadwood which are readily influenced by the individual forest owners. SPFs are often endowed with a large pool of deadwood, and they are less liable to the economic pressures of the timber market (Eggers et al. 2014). Consequently, deadwood structures could be a primary target of individualized conservation efforts to reach out to SPF owners. Management intensity is also influenced by owner attitudes: The application of more extensive forms of forest management, but also of traditional, nowadays mostly abandoned forms of management with high importance for biodiversity protection in cultural landscapes, like coppicing or coppicing with standards, would be desirable from a nature conservation perspective (Buckley 2020). Extremely structure-rich remnants of formerly coppiced forests are still found throughout our study area in SPFs (Mölder 2016; Mölder et al. 2021), but need appropriate management lest they become lost in the conversion to high forest (Buckley 2020).

In contrast to forests in other ownership types, SPF owners are an exceptionally heterogeneous group (Blanco et al. 2015; Deuffic et al. 2018; Weiss et al. 2019; Westin et al. 2023), and it might prove beneficial to develop differentiated policy instruments to address different owner types. Many forest owners in our study area value the conservation of biodiversity higher than resource use or the generation of income, but this attitude is not readily translated into consequential behavior (Tiebel et al. 2024). We developed a typology based on the stated activities owners perform in their forests, and discern between multiple-use-oriented forest owners who would benefit from consultation by forestry stakeholders and contract-based conservation the most; conventional forest owners with a focus on wood production who would mostly adopt measures with a low trade-off, but are open to financial incentives; and conservation-oriented forest owners who are mostly passive in their management and would benefit from practice-oriented consultation to implement active measures (Tiebel et al. 2024). SPF owners, especially of the last type, might be an elusive group (Fairchild et al. 2022) and difficult to reach for private conservation initiatives due to lack of or scattering of organization, but their stands offer many possibilities for the conservation and development of valuable habitat structures, also given SPF owners' high identification with their property (Tiebel et al. 2022).

Concerning financial incentives for nature conservation, activities like the provisioning and retention of deadwood, the promotive management of habitat trees, or the resumption of coppicing, are very promising candidates for contract-based nature conservation in private forests (Demant et al. 2020), and SPF owners are often inclined to embrace such initiatives (Juutinen et al. 2020). Financial incentives to guide forest management decisions are regarded as a key ingredient in adapting forests to climatic change (Bauhus 2022). Until recently, they have played a minor role in Germany, especially in SPFs (Franz et al. 2018), but this is changing (VNPWaldR 2021). Policy makers, forestry and nature conservation organizations should be aware of the high but threatened nature conservational values present in SPFs.

2.5 Conclusion

We proposed a novel method to assess the distribution of forest structural (living and harvested wood volumes, management intensity) and nature conservational (diversity, quantities of deadwood and microhabitats) variables in small-scale private forests in Germany's Lower Saxon Hills. To this aim, we used predictors generated by a forest owner questionnaire (owners' goals and management measures), and landscape parameters. We separated the response variables into two types, and interpret these as slowly evolving structures (type A) and fast evolving structures (type B). Easily obtainable landscape parameters explain a large proportion of the variance seen in type A structures in SPFs, like broadleaf wood volume and tree-related microhabitats. Structural data about such forests is often missing due to the SPF owners' low level of institutional organization Hence, leveraging data on landscape parameters might prove useful in predicting conservation values to reduce potential field work to identify structural hotspots. Type B structures were shown to be influenced by landscape parameters but also, for the first time, prominently by owner attitudes.

Concerning the success of nature conservation in SPFs, the multitude of owner types is increasingly recognized as a decisive factor, but differing characteristics of the target structures in the forests need to be taken into account as well. Slowly evolving structures (type A) depend on long-term commitments to conservation legislation, financial incentives and generation-spanning education of forest owners. Efforts to promote faster evolving valuable structures (type B) like broadleaf deadwood, or the resumption of traditional forms of management might prove particularly advantageous in small-scale private forests given the structural diversity of the stands, but also the often strong identification of owners with their land.

2.6 Appendix

2.6.1 Private forest owner questionnaire, translated version

Remark: The order of the individual sub-questions was changed to group together questions related to the same goal type (Q1) or activity type (Q2). Additional information not present in the original questionnaire is given in brackets.

Question 1: How important do you perceive the following objectives regarding your forest?

For each row, please check the answer that applies to you.

[type of goal]		*not important*	*rather unimportant*	*neither*	*rather important*	*very important*	*no opinion*
[fostering regulating ecosystem services]	Long-term preservation of a stable and healthy forest stand	☐	☐	☐	☐	☐	☐
	Protection of soil, water, air quality	☐	☐	☐	☐	☐	☐
	Biodiversity conservation	☐	☐	☐	☐	☐	☐
	Carbon sequestration, conservation of carbon sinks	☐	☐	☐	☐	☐	☐
[fostering cultural ecosystem services]	Protection as a cultural asset	☐	☐	☐	☐	☐	☐
	Preservation of family heritage	☐	☐	☐	☐	☐	☐
	Safeguarding or enhancement of landscape beauty	☐	☐	☐	☐	☐	☐
	Possibility for nature observation	☐	☐	☐	☐	☐	☐
	Possibility for own recreation	☐	☐	☐	☐	☐	☐
	Preservation as a place of education	☐	☐	☐	☐	☐	☐
	Possibility for hunting	☐	☐	☐	☐	☐	☐
[fostering provisioning ecosystem services]	Wood production for personal consumption	☐	☐	☐	☐	☐	☐
	Wood production for selling	☐	☐	☐	☐	☐	☐
	Collection of non-wood products	☐	☐	☐	☐	☐	☐
[financial goals]	Preservation for financial security	☐	☐	☐	☐	☐	☐
	Profit maximization	☐	☐	☐	☐	☐	☐

Question 2: Which of the following activities are carried out in your forest (both by you and by third parties)?

Please check all that apply.

[Type of activity]		
[Classical silvicultural]	☐	Thinning (e.g., felling of competitive trees, extraction of firewood)
	☐	Protection of young plants against browsing (e.g., by fences)
	☐	Timber sale
	☐	Planting/promotion of native tree species (e.g., common oak, sessile oak, European beach, Norway spruce, Scots pine)
	☐	Planting/promotion of introduced tree species (e.g., Douglas fir, northern red oak, grand fir)
	☐	Harvest of single mature trees
	☐	Pruning (removal of branches for higher economic value)
[Close-to-nature silvicultural]	☐	Reduction of damage due to logging
	☐	Avoidance of chemical pesticides
	☐	Promotion of broadleaf trees in coniferous forests
	☐	Use of logging horses
	☐	Promotion of natural tree regeneration
	☐	Avoiding clear-cuts
[Traditional silvicultural]	☐	Coppicing/coppicing with standards
	☐	Wood pasture
[Active conservation]	☐	Promotion of a shrub layer
	☐	Protection/restoration of light stand structures (open/light areas)
	☐	Protection/maintenance of special structures (e.g., bizarre growth forms)
	☐	Promotion of rare native tree and shrub species (e.g., European crab apple, wild service tree, common yew)
	☐	Species protection measures (e.g., for bats or birds)
	☐	Habitat restoration (e.g., peat bogs, flowing waters, stagnant waters)
	☐	Removal of introduced species (e.g., black cherry, giant hogweed, Japanese knotweed)
[Passive conservation]	☐	Protection of habitat trees
	☐	Protection of dead wood
	☐	Non-use of parts of the stand
	☐	None of the above

2.6.2 Encountered biotopes and their values

Table 2.4: Biotope codes (Drachenfels 2021) used in the surveys, translation given according to BKompV (2020).

Biotope code	Biotope	Value (0–30 yrs)	Value (> 30–80 yrs)	Value (> 80 yrs)
BMS	mesophilic *Crataegus* shrub	13	13	13
WAR	nutrient-rich *Alnus* swamp forest	14	20	23
WCE	medium-wet *Quercus*/*Carpinus* forest, base-poor	15	20	23
WCR	wet *Quercus*/*Carpinus* forest, base-rich	15	20	23
WEG	*Alnus*/*Fraxinus* riparian forest	12	15	18
WGF	wet mixed non-*Quercus*/*Fagus* forest, base-rich	15	19	22
WGM	medium-wet mixed non-*Quercus*/*Fagus* forest, base-rich	14	16	18
WJL	young-age broadleaf forest	11	11	11
WJN	young-age conifer forest	9	9	9
WKC	lichen-rich *Pinus sylvestris* forest on nutrient-poor dry sand	14	19	22
WLB	acidophilic hill/mountain *Fagus sylvatica* forest	14	17	20
WLM	acidophilic lowland *Fagus sylvatica* forest on clay	14	17	20
WMB	mesophilic hill/mountain *Fagus sylvatica* forest, base-poor	14	17	20
WMK	mesophilic hill/mountain *Fagus sylvatica* forest, base-rich	14	16	18
WMT	mesophilic lowland *Fagus sylvatica* forest, base-poor	14	17	20
WNS	miscellaneous swamp forest	15	18	21
WPB	*Betula*/*Populus tremula* pioneer forest	13	13	13
WPE	*Acer*/*Fraxinus* pioneer forest	13	13	13
WPS	miscellaneous pioneer forest	13	13	13
WQE	miscellaneous acidophilic *Quercus* mixed forest	15	19	22
WQF	medium-wet *Quercus* mixed forest on sand	15	20	23
WRM	highly structured forest border, average locations	16	16	16
WRT	highly structured forest border, dry, warm, base-rich	16	16	16
WRW	highly structured forest border with hedge bank	16	16	16
WSS	medium-wet ravine forest on silicate	15	17	20
WTB	*Fagus sylvatica* forest on dry, warm limestone	15	19	22
WXH	plantation of native broadleaf trees	11	13	16
WZD	plantation of *Pseudotsuga menziesii*	6	10	12
WZF	plantation of *Picea abies*	9	11	14
WZK	plantation of *Pinus sylvestris*	9	11	14
WZL	plantation of *Larix decidua*	9	11	14
WZS	miscellaneous plantation of non-native species	6	10	12
Wn	coppice forest	19	19	19

2.6.3 Tree-related microhabitats

Table 2.5: TreM categories as defined in Larrieu et al. (2018), number of occurrences.

Form	Group	Number	%
Cavities	Woodpecker breeding cavities	8	1.0
	Rot-holes	74	8.8
	Insect galleries	0	0.0
	Concavities	167	19.9
Tree injuries and exposed wood	Exposed sapwood only	17	2.0
	Exposed sapwood and heartwood	52	6.2
Crown deadwood	Crown deadwood	434	51.7
Excrescences	Twig tangles	34	4.1
	Burrs and cankers	4	0.5
Fruiting bodies of saprophytic fungi	Perennial fungal fruiting bodies	9	1.1
	Ephemeral fungal fruiting bodies	0	0.0
Epiphytic and epixylic structures	Epiphytic and parasitic crypto- and phanerogams	28	3.3
	Nests	5	0.6
	Microsoils	4	0.5
Exudates	Exudates	3	0.4

Table 2.6: Influences of predictors on response variables (full version of Table 2.3). Each line corresponds to a linear model for the response variable given in the first column. The second column lists the R^2 value of each model. The predictors are given in the remaining columns. Significant influences are given in bold face. If a predictor represents a significant contribution to the model, it is shown in this table with its semipartial correlation value and an indication of the Pr($>|t|$) value p: "$(*)$" for $p \leq 0.1$, "$*$" for $p \leq 0.05$, "$**$" for $p \leq 0.01$, "$***$" for $p \leq 0.001$.

Answer variable	R^2	**Forest owner goals and activities**									**Topographical parameters**										
		Regulating goals	Cultural goals	Provision. goals	Financial goals	Classical silvic.	Close-to-nature silvic.	Traditional silvic.	Active conservation	Passive conservation	Parcel size	Elevation	Slope	Water avail.	Nutrient avail.	Distance to road	Ancient broadleaf	Ancient mixed	Ancient conifer	Open land within 2km	Border w/ open land
Living wood volume																					
Total	0.40	–0.10	–0.04	0.07	–0.02	–0.13	0.00	–0.09	–0.04	0.05	–0.08	–0.07	–0.03	0.02	0.03	0.05	$0.17^{(*)}$	$\mathbf{0.29^{**}}$	–0.14	–0.01	$0.18^{(*)}$
Broadleaf	0.42	–0.16	–0.06	0.00	–0.01	–0.07	0.05	–0.03	–0.01	0.01	–0.15	–0.06	0.02	0.01	0.10	0.12	$\mathbf{0.24^{*}}$	$\mathbf{0.22^{*}}$	–0.08	0.15	$0.18^{(*)}$
Conifer	0.43	0.12	0.05	0.15	–0.02	–0.12	–0.11	–0.13	–0.07	0.08	0.16	–0.02	–0.10	0.03	–0.16	–0.13	–0.15	0.16	–0.12	$\mathbf{-0.33^{**}}$	0.01
Deadwood volume																					
Total	0.36	0.08	–0.08	–0.05	0.09	–0.06	$0.18^{(*)}$	–0.11	–0.14	–0.02	0.00	–0.05	$\mathbf{0.42^{***}}$	0.09	0.04	–0.08	0.04	–0.03	0.11	0.05	–0.09
Broadleaf	0.30	0.07	–0.15	0.00	0.09	–0.02	$0.20^{(*)}$	–0.07	–0.04	0.06	$\mathbf{-0.25^{*}}$	0.01	$0.20^{(*)}$	0.09	–0.13	–0.04	$0.20^{(*)}$	0.17	–0.02	0.11	0.04
Conifer	0.34	0.05	–0.01	–0.06	0.05	–0.06	0.09	–0.08	–0.13	–0.06	0.15	–0.06	$\mathbf{0.37^{***}}$	0.06	0.12	–0.07	–0.06	–0.13	0.14	0.00	–0.12
Sawn	0.43	$0.18^{(*)}$	–0.02	–0.05	–0.03	0.13	$\mathbf{0.27^{**}}$	–0.15	$-0.18^{(*)}$	–0.05	–0.14	–0.02	0.09	0.04	0.12	–0.11	–0.03	0.10	$\mathbf{0.34^{**}}$	–0.13	–0.03
Non-sawn	0.33	0.03	–0.08	–0.04	0.10	–0.11	0.11	–0.07	–0.09	–0.01	0.05	–0.05	$\mathbf{0.44^{***}}$	0.09	0.01	–0.05	0.05	–0.07	0.01	0.10	–0.09
Harvested wood volumes																					
Total	0.45	0.08	0.02	–0.15	0.12	$\mathbf{0.20^{*}}$	$0.19^{(*)}$	–0.12	–0.11	–0.13	–0.02	–0.05	–0.01	0.06	–0.03	0.11	–0.03	0.10	$\mathbf{0.37^{***}}$	–0.05	–0.05
Broadleaf	0.37	–0.06	–0.14	0.08	0.05	0.03	$\mathbf{0.24^{*}}$	–0.04	–0.04	0.02	$-0.20^{(*)}$	–0.06	0.04	–0.05	–0.04	$\mathbf{0.22^{*}}$	0.13	$\mathbf{0.31^{**}}$	0.00	0.12	0.08
Conifer	0.54	0.12	0.11	$\mathbf{-0.20^{*}}$	0.09	$\mathbf{0.18^{*}}$	0.04	–0.09	–0.09	–0.14	0.10	–0.01	–0.03	0.09	–0.01	–0.02	–0.11	–0.09	$\mathbf{0.36^{***}}$	–0.12	–0.10
ForMI	0.50	0.09	$\mathbf{0.20^{*}}$	–0.15	0.02	$\mathbf{0.20^{*}}$	$0.17^{(*)}$	–0.09	0.00	$\mathbf{-0.22^{*}}$	0.09	0.00	–0.14	–0.07	–0.09	0.02	–0.04	0.08	$\mathbf{0.36^{***}}$	–0.15	–0.02
Iharv	0.50	0.06	0.08	$-0.16^{(*)}$	0.10	$\mathbf{0.19^{*}}$	$\mathbf{0.20^{*}}$	–0.04	0.01	$\mathbf{-0.23^{*}}$	0.04	–0.03	–0.08	–0.05	–0.05	0.06	–0.03	0.06	$\mathbf{0.42^{***}}$	0.00	–0.07
Inonat	0.51	0.15	0.12	–0.13	0.02	0.07	0.07	–0.14	–0.09	–0.14	0.15	–0.04	–0.03	0.04	$-0.16^{(*)}$	–0.10	$-0.18^{(*)}$	–0.06	$\mathbf{0.29^{**}}$	$-0.18^{(*)}$	–0.07
Idwcut	0.30	–0.01	$\mathbf{0.24^{*}}$	–0.04	–0.07	$0.21^{(*)}$	0.13	0.00	0.08	–0.13	0.00	0.06	$-0.20^{(*)}$	–0.16	0.01	0.10	0.15	$0.19^{(*)}$	0.13	–0.14	0.10
Other nature conservation values																					
Biotope value	0.48	$-0.18^{(*)}$	0.02	–0.02	0.07	–0.03	0.09	0.05	–0.07	0.02	–0.08	–0.08	0.06	–0.15	0.03	0.06	$\mathbf{0.21^{*}}$	$0.17^{(*)}$	–0.15	$\mathbf{0.19^{*}}$	0.10
# of tree species	0.27	–0.08	–0.03	0.10	$\mathbf{-0.25^{*}}$	0.06	–0.10	$\mathbf{0.23^{*}}$	0.13	0.05	–0.03	0.00	–0.05	–0.06	$0.20^{(*)}$	–0.05	0.04	–0.02	0.05	–0.08	0.01
Mean stand age	0.42	–0.08	0.00	0.05	–0.01	0.01	0.11	–0.02	–0.16	0.09	–0.08	–0.09	0.05	–0.09	0.05	0.05	$\mathbf{0.26^{*}}$	$\mathbf{0.25^{*}}$	–0.04	0.09	0.12
TreM density	0.34	0.05	–0.01	–0.06	–0.05	0.03	–0.09	0.00	0.16	–0.09	$-0.18^{(*)}$	–0.11	–0.01	0.08	0.10	0.03	$\mathbf{0.32^{**}}$	$\mathbf{0.21^{*}}$	0.00	0.01	0.11
TreM tree density	0.34	0.01	0.01	–0.06	–0.03	0.02	–0.05	–0.01	0.10	–0.09	$-0.18^{(*)}$	–0.08	–0.04	0.10	0.10	0.03	$\mathbf{0.31^{**}}$	$\mathbf{0.21^{*}}$	–0.01	0.02	0.15
Trees dbh $\geq$ 50 cm	0.32	–0.03	0.06	–0.04	0.03	–0.05	0.03	–0.05	–0.05	0.00	–0.14	–0.02	–0.09	0.06	0.13	0.01	$\mathbf{0.27^{*}}$	$\mathbf{0.25^{*}}$	0.02	0.06	$\mathbf{0.26^{*}}$

2.6.4 Closing statements

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Declarations

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Chapter 3

Does gender really matter? How demographics and site characteristics influence behavior and attitudes of German small-scale private forest owners

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Does gender really matter? How demographics and site characteristics influence behavior and attitudes of German small-scale private forest owners

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Highlights

- Drivers of private forest owners' management behavior and attitudes are identified.
- Economic goals and activities are promoted by large forest holdings.
- High levels of broadleaf forest encourage conservation decisions.
- Gender-specific outreach should be complemented by targeting specific forest owner groups.

Abstract

When analyzing management behaviors of small-scale private forest owners, demographic variables such as income, age, or profession, and land characteristics such as forest holding size often emerge as important drivers. However, gender is frequently used in targeted outreach, even though the other variables regularly show higher predictive power. To shed light on this discussion, we examined the influences of a broad set of predictors including both land characteristics and sociodemographic factors such as gender on management activities, owner goals, perceived obstacles, and conservation attitudes as response variables. We used a questionnaire survey to collect quantitative data from 1268 small-scale private forest owners in northwestern Germany. Random forest models were used to predict the responses and to rank the predictors according to their variable importance. We found that the size of forest holdings often had a strong influence on economic activities, while the amount of broadleaf forest was important for conservation-oriented management decisions. While gender-specific outreach is a strong tool to empower formerly marginalized forest owner groups, gender was not found to be an important predictor of forest management activities in our analyses. We advocate considering other characteristics when conceiving communication with forest owners.

In order to design carefully targeted policy instruments and outreach to forest owners, we propose a set of easily accessible owner parameters and land characteristics. These factors can guide more individualized conservation outreach strategies in small-scale private forests that are embedded in the overall livelihood systems of their owners.

Keywords Non-industrial private forest owners · Forest livelihoods · Sociodemographic factors · Random forest model · Feminist political ecologies · Forest management activities

3.1 Introduction

Today's forests face a variety of crises (Pörtner et al. 2023). The climate crisis is affecting forests in many ways, causing global changes such as increased likelihoods of wildfires, more insect pests, and longer periods of drought (El Garroussi et al. 2024; Hlásny et al. 2021; Markonis et al. 2021). The biodiversity crisis, fueled by a continuous loss of old-growth forest structures (Potapov et al. 2017), affects rare and specialized forest species (Betts et al. 2017). As large pools of carbon sequestration and biological diversity, forests are needed in solving global crises, and their resilience will continue to depend on the conservation of their biodiversity (Ibarra et al. 2020). At the same time, society's demands on forest ecosystems are becoming increasingly complex (Winkel et al. 2022). In large parts of Europe and the USA, much of the forest is owned by private organizations and individuals (UNECE and FAO 2020). This is also the case in Germany, where 43.0 % of the total forest area is privately owned, and 18.4 % of the total forest area is divided into small-scale private forest (SPF) of less than 20 ha (Destatis 2023b; Destatis 2023a). The group of SPF owners is large and diverse, with widely varying attitudes and management strategies (Tiebel et al. 2024; Weiss, Lawrence, Lidestav, et al. 2019). While private forest owner associations often convey a relatively uniform view of their members as primarily pursuing economic goals, other goals such as recreation or nature conservation have become increasingly important to SPF owners in recent times (Weiss, Lawrence, Lidestav, et al. 2019; Weiss, Lawrence, Hujala, et al. 2019). SPFs in Germany often comprise a diverse mosaic of tree species, age classes, structures, and different management approaches, often leading to high structural and habitat diversity on the landscape scale (Hansen et al. 2023; Johann and Schaich 2016). However, the lack of institutional organization among many SPF owners can also be an obstacle when it comes to offering advice and help or promoting new policy tools (Joa and Schraml 2020).

Against this background, research has sought to identify factors that are major predictors of SPF owners' goals and ultimately management decisions. It was found that sociodemographic factors are particularly important variables influencing SPF behavior. As prominent characteristics of SPF owners such as gender distribution, age, or urbanity are changing (BJ Butler et al. 2016; Eggers et al. 2014; Sass et al. 2023), impacts on SPF management activities can be expected (Nordlund and Westin 2011). Understanding the factors that influence the attitudes and behavior of SPF owners is essential for designing targeted outreach strategies to engage them in promoting mitigation and adaptation to a changing environment to ensure the provision of vital ecosystem services. Current research has focused on individual single factors, such as gender, ethnicity (Robillard et al. 2023), geographic distance (Caputo and Snyder 2023), or forest parcel size (BJ Butler et al. 2021), and provided in-depth analyses of their relationship to target variables, such as forest owner behavior.

A large body of research has attempted to characterize owners according to whether they identify as female or male. It was established that female forest owners have more positive attitudes toward nature conservation (Kuhlman et al. 2022; Tiebel et al. 2022; Umaerus et al. 2019), and that they identify more with aesthetic perspectives regarding their property (Tiebel et al. 2022). They cut less timber (Lidestav 1998; Lidestav and Ekström 2000) than their male counterparts, while being more price-sensitive (Follo et al. 2017) and wanting to maintain their property in the best possible way (Krause and Enzensbach 2008; Redmore and Tynon 2011). On the other hand, it has been suggested that female owners value timber production as much as male owners (Böhling 2022), but that they are additionally interested in recreational and social values, and are open to alternative business ideas such as tourism (Umaerus et al. 2019). Careful forest management is seen as a high priority for female forest owners (Schlecht and Westermeyer 2010), and while being more likely to admit a personal lack of information, they might seek support more likely than male owners (Andersson and Lidestav 2016; Hamunen et al. 2020; Schlecht and Westermeyer 2010). Female forest owners express a greater need for assistance and learning opportunities, and more concern about invasive species (Berget and Dwivedi 2024). In addition to economic activities, active forest ownership for female owners involves taking care of forests and their species (Kuhlman et al. 2024). Gender-specific outreach for women is presented as a way to increase their engagement in an environment that is described as male-dominated and intimidating (Carter 2019; Lukacic et al. 2023; Miner et al. 2021).

Table 3.1: Multifactorial work on the influences of demographics, site characteristics, market drivers, and policy instruments on different activities of forest owners. The key predictors are listed.

Work	Response variable	Important predictors
Binkley (1981)	Timber harvesting	Parcel size, timber price, profession, income
Beach et al. (2005)	Timber harvesting	Parcel size, stock quality, timber price
Joshi and Arano (2009)	Timber harvesting	Profession, education, income, age
Kuuluvainen et al. (2014)	Timber harvesting	Parcel size, stock quality, profession, age
Silver et al. (2015)	Timber harvesting	Parcel size, stock quality, timber price, management plan, education
Côté et al. (2016)	Timber harvesting	Parcel size, length of tenure, management plan, gender, urbanity
Beach et al. (2005)	Reforestation	Policy instruments
Beach et al. (2005)	Silvicultural treatments	Parcel size, education, income, age, urbanity
Eggers et al. (2014)	Management strategies	Parcel size, profession
Juutinen et al. (2020)	Management strategies	Profession, gender, education, age, urbanity
Floress et al. (2019)	Management behavior	Parcel size, knowledge, past behavior, attitude
Husa and Kosenius (2021)	Willingness to apply activities	Parcel size, education, income, age
Joshi and Arano (2009)	Managing for wildlife	Type of acquisition, income, age, urbanity

However, it can be asked whether a strong focus on a single characteristic of forest owners is sufficient when trying to efficiently identify owner groups for targeted outreach and policy instruments. This question has been raised, for example, by SM Butler et al. (2017) in relation to gender as a potential driver of differences in forest management activities. Research has taken on a multifactorial approach to identify factors that influence SPF owners' management activities such as timber harvesting, which is considered one of the most important activities performed in forests (Table 3.1). In a seminal work by Binkley (1981), the probability of timber harvesting was influenced by multiple sociodemographic factors like profession and income of the owner, but also by site characteristics (forest parcel size) and market drivers (timber prices). Through a review of the literature, Beach et al. (2005) analyzed timber harvesting patterns and related silvicultural activities like reforestation. They found that logging activity depends on parcel size, stock quality, and market prices, while activities such as reforestation are strongly linked to policy instruments like government cost sharing. In addition, silvicultural treatments, such as timber stand improvement and young growth tending, depend on parcel size, but also on sociodemographic factors like income, age, education, and urbanity of the owners (Beach et al. 2005). In a study by Kuuluvainen et al. (2014), the harvesting behavior of Finnish SPF owners was mainly influenced by stock quality, parcel size, and the age and occupation of the owner. Silver et al. (2015) identified market prices, the existence of a management plan, education, timber stock quality, and parcel size as drivers of timber harvesting. Size, urbanity, the existence of a management plan, gender, and length of tenure were important predictors of timber harvesting in Côté et al. (2016).

Other authors focused on more complex behavioral variables, such as different management strategies that SPF owners use on their property. Eggers et al. (2014) looked at predictors of five different management strategies, and again parcel size was identified as an important predictor. Among owner demographic variables, forestry profession played a small role, but other variables such as gender and urbanity did not show a strong correlation with the management strategies. A different set of management strategies was studied by Juutinen et al. (2020), who contrasted traditional strategies with more modern approaches such as uneven-aged management. The forest owner's profession, urbanity, education, age, and gender had strong influences on the choice of strategy. Husa and Kosenius (2021) investigated the willingness of forest owners to adopt different management practices that affect timber production, biodiversity, carbon sequestration, and adaptation to climate change. Important predictors of response variables include age, education level, and income of forest owners, as well as parcel size. A broader set of activities related to harvesting, silviculture, property management, and care for wildlife and recreation was examined by Joshi and Arano (2009). Here, forest owner age, education, profession, and income were identified as predictors of harvesting and related silvicultural practices, while property management for wildlife and recreation depended on the type of acquisition and owner's income, age, and urbanity. In a literature review of factors influencing 13 different categories of behavior related to forest management, Floress et al. (2019) described a variety of influences from factors such as parcel size, knowledge, and past behavior. Owners' attitudes, such as their concern for the environment, were identified as good candidate predictors, while owners' goals showed poor correlation with their actual behavior. In summary, existing multifactorial research on the determinants of SPF owner activity has identified a number of relevant variables, including sociodemographic traits, site characteristics, market drivers, and management goals.

The focus of this study is to identify predictors not only of SPF owners' behavior, but also of their management goals, perceived obstacles to their goals, and attitudes toward conservation. As predictors, we use sociodemographic variables, such as gender, age, and urbanity, and site characteristics like forest parcel size, stand age, and proportion of broadleaf trees. By combining a broad set of predictors in multivariate models, the relative importance of each variable will be assessed, attempting to answer the question of which individual factors (e.g., gender) are actually driving the response variables. For organizations designing policy or outreach instruments for SPF owners, it will be convenient that our variables are either already available or relatively easy to collect from the target group. We aim to answer the following research questions:

- How can the management activities of SPF owners be predicted from easily accessible sociodemographic data and forest parcel characteristics?
- Can this approach be extended to the owners' goals, perceived obstacles, and conservation attitudes?
- What are the most important predictors of the activities, goals, obstacles, and conservation attitudes of SPF owners?

Based on these results, we will discuss the implications for owner outreach and the conservation promotion in small-scale private forests.

3.2 Methods

3.2.1 Quantitative survey

The present analysis uses quantitative data collected through a postal and online questionnaire sent to all 4202 private forest owners in parts of Lower Saxony (Germany) in 2020 (Tiebel et al. 2024; Tiebel et al. 2021) who are organized in three local forest owners' associations. The Lower Saxon Hills region was chosen as the study area because of its consistent legal situation and uniform forest administration. 43 % of the forest in the study area is privately owned, of which 91 % consists of parcels smaller than 20 ha; this is comparable to many Western and Central European countries (ML 2014). The survey followed Dillman's Tailored Design Method (Dillman et al. 2014) and consisted of 26 questions related to sociodemographic parameters, site characteristics, owner attitudes, and framework conditions (Tiebel et al. 2021). Of the 1671 original responses (response rate 39.8 %), only those SPF owners with a total property area of at most 20 ha were selected for the present study, resulting in a dataset of size $n = 1268$. The upper threshold of 20 ha was chosen to meet the definition of small-scale private forest in Germany (ML 2014). It is possible that there is some non-response bias in the result set. Individuals with less interest in the topics of the questionnaire may have been less likely to participate in the study, while people with more interest or free time may have been over-represented. This needs to be taken into account when generalizing the results. The representativeness of the dataset used in our study was examined in detail in Tiebel et al. (2021), where we conclude that the assessed ownership and forest structures are comparable to German-wide data (Feil et al. 2019) and European surveys (Schmithüsen and Hirsch 2010). In terms of sociodemographic factors, our participants show a similar gender and age distribution, but a more rural orientation than private forest owners in Germany as a whole, while being comparable at the European level.

3.2.2 Predictors and response variables

From the questionnaire, we selected a set of 13 variables related to forest parcel characteristics and owner demographics that are commonly understood to potentially influence owner goals, attitudes, and behaviors (Table 3.2). The granularity of the variables differed in the questionnaire, e.g., the proportion of broadleaf forest was sampled using four classes (below 25 %; 25–50 %; 50–75 %; above 75 %), while there were three possible responses to the question on forest age (below 40 years; 40–100 years; above 100 years). During preliminary model runs, it was observed that predictors with finer granularity were over-selected by the models (see also Section 3.4.4). To eliminate this effect and to facilitate comparisons between driving variables, the data for each predictor were dichotomized into two classes, sacrificing some of the information originally present in the data and turning the predictors into binary variables (see Sass et al. (2023) for a similar approach). The aggregation was performed so that the sizes of the two resulting classes per variable were as equal as possible to allow the regression or classification algorithm to extract as much information as possible from a binary predictor. It was verified that this aggregation step had negligible influence on the predictive power of the models.

We analyzed the influence of the driving variables on the response variable groups management activities, owners' goals, perceived obstacles, and attitudes toward conservation (see Table 3.3 and Appendix Table 3.4). Goals and attitudes were queried using a 5-point Likert scale (1 = strongly disagree; 2 = rather disagree; 3 = neutral; 4 = rather agree; 5 = strongly agree), while questions for activities and obstacles could be answered yes or no.

Missing values in our dataset (i.e., the respondent did not select an answer to the question at all) were replaced by modeled values using 3NN imputation (Templ et al. 2022). Nulls were relatively rare in the data, with the following average percentages per category: predictors (2.4 %), management activities (0.0 %), goals (4.7 %), perceived obstacles (2.2 %), attitudes toward conservation (14.7 %).

3.2.3 Bivariate statistics

To assess linear correlations between each predictor and each response variable, we calculated bivariate correlations using Kendall's τ. In addition to their absolute value, these measures indicate the direction of influence (positive or negative) of a predictor on a response variable.

Table 3.2: Predictors as assessed in the questionnaire and coded as either 0 or 1, after 3NN imputation.

Predictor	Description	Mean
Broadleaf	Equals 1 if the amount of broadleaf forest property is larger than 50%, 0 otherwise	0.620
Forest age	Equals 1 if the average stand age is over 40 years, 0 otherwise	0.746
Total size	Equals 1 if the total forest property size is over 2.5 ha, 0 otherwise	0.501
Number of parcels	Equals 1 if owner owns more than one forest parcel, 0 otherwise	0.567
Bought or leased	Equals 1 if the forest land is bought or leased (as opposed to inherited, gifted, etc.), 0 otherwise	0.272
Distance	Equals 1 if the owner lives more than 10 km away from their forest, 0 otherwise	0.188
Formal training forestry	Equals 1 if the owner has a formal (professional or university level) training in forestry, 0 otherwise	0.068
Female	Equals 1 if the owner identifies with female gender, 0 otherwise	0.194
Owner age	Equals 1 if the owner is older than 65 years, 0 otherwise	0.353
Professional qualification	Equals 1 if the owner has completed a professional training program (as opposed to only having finished secondary school), 0 otherwise	0.710
Agriculture/forestry	Equals 1 if the owner is a professional in agriculture or forestry, 0 otherwise	0.306
Time in forest	Equals 1 if the owner spends time in their forest during job or leisure, 0 otherwise	0.692
Settlement size	Equals 1 if the owner has spent most of their time in a settlement of over 5000 inhabitants, 0 otherwise	0.306

3.2.4 Multivariate analyses: Random forest classification and regression

For each response variable, we built a random forest model (number of trees: 501) that included all the predictors. Models were trained and evaluated using 5-fold cross-validation (Kuhn et al. 2023). We used two different quality criteria to assess the predictive power of the overall final model, depending on the response variables: Regression models for Likert-scale response variables (goals and conservation attitudes) were assessed by their R^2 value. For binary response variables (management activities and perceived obstacles), the classification models were assessed using Cohen's kappa (κ). While R^2 values and κ values both provide information on the predictive power of models, i.e. the amount of variance that they explain, some care is needed when interpreting such values. Relatively low numerical R^2 values such as 0.090 might already express a medium effect size (Cohen 1988), while a κ value of 0.200 is needed to speak of fair agreement strengths (Landis and Koch 1977). Some authors set the bar even higher (Shrout 1998).

Regarding the importance of individual predictors in a model, random forest models provide a natural ranking of these variables (Archer and Kimes 2008), where the most important predictor is assigned a value of 100 %, and the others are subsequently assigned smaller percentage values according to their importance in building the decision trees of the model. For visualization purposes, we weighted the importance of the driving variables by the predictive power of the model (R^2 or κ values), e.g., a predictor with 80 % importance in a model with a κ value of 0.080 would appear with an importance measure of 6.4 in our final results. All analyses were performed using R 4.4.1

Table 3.3: Response variables (management activities, owner goals, perceived obstacles, and attitudes toward conservation). For details, see Table 3.4 in the Appendix.

Response variable group	**Response variables**	**Coding**
Management activities (carried out)	Pruning; thinning; protection of young plants against deer browsing; timber sale; planting/promotion of native tree species; planting/promotion of introduced tree species; protection of habitat trees; reduction of damage due to logging; avoidance of chemical pesticides; coppicing/coppicing with standards; wood pasture; promotion of a shrub layer; promotion of broadleaf trees in coniferous forests; protection/restoration of light stand structures; protection/maintenance of special structures; use of logging horses; promotion of rare native tree and shrub species; promotion of natural tree regeneration; avoiding clearcuts; protection of dead wood; harvest of single mature trees; species protection measures; biotope restoration; removal of introduced species; non-use of parts of the stand; none	0 or 1
Owner goals (importance of)	Wood production for selling; wood production for personal consumption; collection of non-wood products; possibility for own recreation; possibility for hunting; protection as a cultural asset; safeguarding or enhancement of landscape beauty; preservation as a place of education; possibility for nature observation; long-term preservation of a stable and healthy forest stand; carbon sequestration, conservation of carbon sinks; biodiversity conservation; protection of soil, water, air quality; preservation for financial security; profit maximization; preservation of family heritage	5-point Likert
Obstacles (perceived)	Lack of time; lack of money; lack of technical equipment; lack of skills; lack of knowledge; lack of information; lack of family labor force; forest size is too small; unclear boundaries of the forest; unknown contact persons; poor accessibility through forest roads; uncertainty about the location of the forest; distance between forest and living place; too much effort; lack of interest; initial stand conditions unfavorable for my objectives; no notable restrictions	0 or 1
Attitudes concerning nature conservation (agreement with)	Structures with high conservation value are present in my forest; my management ensures natural forest conditions; even without financial support, I am willing to promote nature conservation; my forest provides no other benefit to me, which is why I promote nature conservation; nature conservation in my forest continues the family tradition; nature conservation in my forest implies refraining from any use; extraction of renewable resources is more meaningful than nature conservation; conservation in my forest can limit recreational uses; conservation in my forest prevents a visually beautiful impression; conservation in my forest threatens my personal freedom of decision; conservation in my forest creates high costs; I do not perform management due to difficult forest stand conditions; I would like to see higher involvement in decision making processes about conservation; I perceive the management restrictions as too strict	5-point Likert

(R Core Team 2020). Multicollinearity testing of the predictors was done by calculating variance inflation factors, which were below 1.3 for all tested variables.

3.2.5 Presentation of results

We examined the random forest models for each variable in the four response variable groups and ranked the models by their predictive power (Fig. 3.1), starting with the model with the highest predictive power in each group. We report the R^2 or Cohen's kappa (κ) value of the model and its most important predictors. Variable importance (*vi*) values are given as integers, with 100 used for the single most important variable, and subsequently less important variables receiving smaller values. For visual comparability, the *vi* values in Fig. 3.1 were weighted by the predictive power of the model and given a sign according to the direction of the bivariate correlation of the individual predictor and the response variable. When an important predictor was identified, the distribution of that variable in the population of SPF owners in our sample is described in the results section (see also Table 3.5 in the Appendix). For binary responses (activities, obstacles), the percentage of "yes" responses is given. For Likert responses (goals, attitudes), Likert scores "rather important (4)" and "very important (5)" were combined, and the percentage of those responses is given.

3.3 Results

3.3.1 Management activities

Variables related to different management activities (Fig. 3.1a) were given as binary yes/no answers in the questionnaire. We used Cohen's kappa (κ) values as a measure of the predictive power of the models. The predictive power of the management activity models was often relatively strong, with an average κ value of 0.075, and eleven of the 26 models having κ values above 0.050. These are presented in the following, along with their strongest predictors.

The response variable scoring highest was *timber sale* (κ = 0.340), which the random forest model was very successful in predicting from our driving variables. It was most influenced by *total size* (*vi* = 100) and *broadleaf* (*vi* = 71). Owners of more than 2.5 ha of forest land sold timber in 75.6 % of the cases, while only 46.6 % of owners of smaller parcels sold timber. Ownership of forests with predominantly broadleaf trees reduced timber sales, with 52.7 % of their owners selling compared to 74.9 % of owners of predominantly coniferous forests. *Habitat-tree protection* (κ = 0.236) was influenced with almost equal strength by the variables *broadleaf* (*vi* = 100) and *bought/leased* (*vi* = 97). Owners of broadleaf-dominated forests were inclined to protect habitat trees in 50.6 % of the cases, while only 32.8 % of owners of conifer-dominated stands did so. Owners who bought or leased their land were more likely to protect habitat trees (58.3 %), while 38.5 % of the owners who passively came into possession of their forest chose to protect. The model for *reduce logging damage* (κ = 0.226) showed a single strong influence by *total size* (*vi* = 100). 63.3 % of owners of parcels larger than 2.5 ha try to reduce damage from logging, while the percentage for owners of smaller parcels is 39.8 %. *Harvest of single mature trees* (κ = 0.226) was influenced by the predictors *agriculture/forestry* (*vi* = 100) and *forest age* (*vi* = 62). The activity was more frequently chosen by agricultural or forestry professionals (64.9 %), with only 39.9 % of the other owners choosing this strategy. The model for *promotion of natural tree regeneration* (κ = 0.210) was influenced by the predictor *total size* (*vi* = 100), but almost equally strongly by *time in forest* (*vi* = 90).

Figure 3.1: Weighted variable importance of the 13 predictors in random forest models for (a) management activities, (b) owner goals, (c) perceived obstacles, and (d) conservation attitudes. Negative sign if the bivariate correlation coefficient is negative. Weighting is done by multiplying the variable importance given by the random forest model by the model's predictive power [Cohen's kappa for (a), (c); R^2 for (b), (d)]. Models with predictive powers lower than 0.01 are not shown. The bubble diameter is proportional to the absolute value of the weighted variable importance.

Owners of parcels larger than 2.5 ha were more likely (66.6 %) to rely on natural regeneration, compared to 45.8 % of owners of smaller parcels. This strategy was also chosen by 62.6 % of people who spend time in forests, compared to 41.8 % of people who do not visit forests during job or leisure. A similar situation was found for the model of *protection of young plants against deer browsing* (κ = 0.200), with *total size* (*vi* = 100) and *time in forest* (*vi* = 80) as the most important predictors. Larger-scale owners protected against browsing in 55.3 % of the cases, compared to 35.7 % of the other owners. Of those people who spend time in forests, 51.1 % protected against browsing compared to 32.8 % of others. The activity of *planting/promotion of introduced tree species* (κ = 0.125) was influenced almost equally by the predictors *broadleaf* (*vi* = 100) and *total size* (*vi* = 98). Owners of predominantly broadleaf forests preferred not to plant foreign species (only 21.6 % did so), while 41.1 % of the other owners performed this activity. On the other hand, parcel size had a positive influence, with 39.7 % of owners of larger parcels planting introduced species, compared to only 18.3 % of owners of smaller parcels. *Planting/promotion of native tree species* (κ = 0.116) depended on *total size* (*vi* = 100), but also on *time in forest* (*vi* = 67). While 73.2 % of the larger-scale owners planted native species, 55.8 % of the others did so. Spending time in forests also increased the likelihood of planting native species, with 69.2 % of forest-visiting owners doing so, compared with 53.8 % of the others. *Protection of dead wood* (κ = 0.110) was mostly dependent on *broadleaf* (*vi* = 100). 50.9 % of the owners of predominantly broadleaf forests managed for deadwood, while only 35.1 % of the other owners did so. A similar situation was found for the activity of *avoiding clearcuts* (κ = 0.096), which also depended mostly on *broadleaf* (*vi* = 100). Owners of broadleaf forest avoided clearcutting in 73.4 % of the cases, while 53.1 % of the other owners avoided it. The activity *promotion of broadleaf trees in coniferous forests* (κ = 0.090) was negatively influenced by *broadleaf* (*vi* = 100), but promoted by *total size* (*vi* = 87). Owners of predominantly broadleaf forests reported this activity in 39.1 % of the cases, compared to 50.8 % of the owners of predominantly coniferous forests. Owners of parcels larger than 2.5 ha promoted broadleaf trees in 49.3 % of the cases, compared to 37.8 % of the other owners. Models for the remaining activities had predictive powers below 0.05 and are not described here.

3.3.2 Owner goals

The importance of different forest management goals (Fig. 3.1b) had been rated by the SPF owners on a 5-point Likert scale, and accordingly, we calculated R^2 scores to examine the predictive power of the random forest models. In general, predictions were rather unassertive. Among the 16 models, the average R^2 score was 0.039, and four goals reached predictive powers exceeding 0.050: *wood production for selling*; *wood production for personal consumption*; *profit maximization*; and *possibility for hunting*. The most important predictors for the goal of wood production for selling (R^2 = 0.173) were *agriculture/forestry* (*vi* = 100), followed by *total size* (*vi* = 81). 78.1 % of the agricultural or forestry professionals perceived the goal as important compared to 51.0 % of the other owners. Here and in the following, we use the term "important" to combine the Likert scores "rather important (4)" and "very important (5)", similar to SM Butler et al. (2017). Owners with a total forest size of more than 2.5 ha agreed with the importance of this goal in 70.2 % of the cases, compared to 48.3 % of the owners of smaller lots. Regarding *wood production for personal consumption* (R^2 = 0.145), the importance of this goal decreased with the *distance* (*vi* = 100) between the residence and the forest plot. 73.3 % of owners living within 10 km of their forest supported this goal, compared to 46.4 % of those living further away. *Settlement size* (*vi* = 66) also played a negative role, with 46.6 % of people living in places with more than 5000 inhabitants supporting this goal, compared to 73.3 % of people living in smaller communities. The goal of *profit maximization* (R^2 = 0.104) was important for 43.6 % of the agricultural or forestry professionals (*vi* = 100), while only 19.8 % of the other owners supported it. The goal *possibility for hunting* (R^2 = 0.072) reached the lowest predictive power out of all goals that still lie above 0.050, and was most strongly influenced by the variable *total size* (*vi* = 100). Owners of parcels larger than 2.5 ha considered this goal as important in 34.3 % of the cases, while owners of smaller properties did so in only 19.4 % of the cases.

3.3.3 Perceived obstacles

Several possible obstacles to the owners' goals (Fig. 3.1c) had to be rated using yes/no answers in the questionnaire, and Cohen's kappa values were used to assess the models' predictive power. The average κ value among the response variables was 0.048, but only three out of 17 obstacles allowed for prediction using our determinant variables: *distance between forest and living place*; *lack of time*; and *forest size is too small*. All other models had κ values below 0.050 and are not considered in the following. The model for the obstacle *distance* (κ = 0.408) is the model with the highest overall predictive power and is uniquely dependent on *distance* (*vi* = 100). Forest owners who live more than 10 km from their forest perceived this distance as an obstacle to their management goals in 47.7 % of the cases, compared to 1.3 % of the owners who live closer. The model for *lack of time* (κ = 0.255) also showed a relatively high predictive power and depends on the variable *owner age* (*vi* = 100). Owners over the age of 65 reported a lack of time in only 19.9 % of the cases, while for younger owners, this obstacle hampered their management in 52.2 % of the cases. The model for the obstacle *too small* (κ = 0.112) was also dominated by the influence of a single predictor, *total size* (*vi* = 100). Owners of more than 2.5 ha of forest land perceived the size of their property as an obstacle in only 21.7 % of the cases, while for 46.9 % of the smaller-scale owners, property size was a limiting factor in their management. Other perceived obstacles could not be successfully predicted by our set of predictors.

3.3.4 Conservation attitudes

Attitudes toward various aspects of nature conservation (see Fig. 3.1d) were assessed by measuring individual agreement with 14 statements on a 5-point Likert scale. As for the importance of management goals, we aggregated the Likert scores "rather strong agreement (4)" and "very strong agreement (5)". The predictive power of the models for conservation attitudes was rather poor, with an average R^2 value of 0.040, and only five models reaching a threshold of R^2 = 0.050. The corresponding attitude statements were the following: *my forest provides no other benefit to me, which is why I promote nature conservation*; *nature conservation in my forest implies refraining from any use*; *I perceive the management restrictions as too strict*; *conservation in my forest creates high costs*;

conservation in my forest threatens my personal freedom of decision. The model for the attitude *no other benefit* (R^2 = 0.095) showed influences of the variables *female vi* = 100) and *total size vi* = 74). Forest owners who identified as female agreed with this statement in 35.8 % of the cases, compared to 20.5 % for owners who identified as male. Owners of parcels larger than 2.5 ha were less likely to agree, with a percentage of 18.7 %, compared to 28.1 % of the owners of smaller-scale parcels. The attitude *refrain from use* (R^2 = 0.085) was equally influenced by the predictors *female vi* = 100) and *total size vi* = 89). While people who identified as female supported the statement in 13.0 % of the cases, 5.6 % of the male-identifying owners did so. In larger-scale owners, the statement found 4.3 % agreement, while smaller-scale owners agreed in 9.8 % of the cases. The attitude *restrictions too strict* (R^2 = 0.084) had a single most important determinant, *number of parcels vi* = 100). Owners of multiple parcels supported the statement in 53.8 % of the cases, while 34.1 % of the single-parcel owners showed agreement. *High costs* (R^2 = 0.083) showed equally strong influences from three predictors, *total size*, *number of parcels*, and *agriculture/forestry*, while the attitude *threatens freedom* (R^2 = 0.078) was influenced mostly by *agriculture/forestry vi* = 100) and *number of parcels vi* = 61).

3.4 Discussion

The gender of small-scale private forest (SPF) owners is often considered an important driver of their management decisions. Consistent with a body of research using multifactorial models to explain owner activities, we analyzed the respective influence of six forest characteristics and seven owner demographic parameters, including gender. We used these variables to also predict owner goals, perceived obstacles, and conservation attitudes.

3.4.1 Prediction of management activities

Among our models predicting management activities, we found a large percentage of comparably strong models. This was in line with previous studies that have focused mostly on predicting forest owner activities such as timber harvesting in the past (Beach et al. 2005; Joshi and Arano 2009; Kuuluvainen et al. 2014) and identified important influences, such as parcel size, timber prices, and owner education (Côté et al. 2016; Silver et al. 2015), see also Table 3.1. The questionnaire used for the current study asked for five of the six variables that have been most often identified as strong predictors of forest owner behavior (parcel size, profession, education, income, age, urbanity). In addition, we included the variables types of acquisition and gender, which were less important overall. Driving influences varied among our response variables, but we were able to identify recurring patterns:

(1) Seven management activities (*timber sale*; *reduction of damage due to logging*; *promotion of natural tree regeneration*; *protection of young plants against deer browsing*; *planting/promotion of introduced tree species*; *planting/promotion of native tree species*; *promotion of broadleaf trees in coniferous forest*) were strongly and positively dependent on the total size of forest

owned. The activities in this group can be characterized as either classical or close-to-nature silvicultural activities (Tiebel et al. 2024), aiming at the maintenance and economic use of the forest. We found negative influences of the amount of broadleaf forest on *timber sale*, *planting/promotion of introduced tree species*, and *promotion of broadleaf trees in coniferous forests*, and conclude that these activities are preferred by owners of large parcels with predominantly coniferous forests. Owners' profession and the amount of time they spend in their forests also played a role as predictors, underscoring the business-related nature of these activities.

(2) A different pattern was found for a second set of activities (*protection of habitat trees*; *protection of dead wood*; *avoiding clearcuts*). These activities can be characterized as passive conservation and close-to-nature silvicultural activities according to Tiebel et al. (2024). They were preferentially practiced in broadleaf forests, while other predictors such as total size, number of parcels, or owner profession did not show noticeable influences here. Comparing our results with the literature (see Table 3.1), we were able to confirm the strong influence of parcel size on harvesting activity. Previously observed effects of owner profession were also seen in our data, but we could not support influences by age, education, or urbanity, which showed only very weak influences in our analyses. The only noticeable influence of gender was found when looking at the activity *harvest of single mature trees*, which did not fall into any of the groups described above, but was mostly dependent on being an agricultural or forestry professional.

3.4.2 Prediction of goals, obstacles, and conservation attitudes

In contrast to the strong models for management activities, only four of the surveyed owner goals were influenced by our predictors to a noticeable degree. Three of them (*wood production for selling*; *profit maximization*; *possibility for hunting*) showed a similar pattern as the economically oriented activities mentioned above, being mostly influenced by owner profession and parcel size. The fourth goal, *wood production for personal consumption*, was favored mostly by small-town dwellers (settlement size) and hindered by long distances to their forests, which is reasonable given the often family-based and local nature of self-sufficient firewood production (Warde 2019).

The models of perceived obstacles to forest owners' management goals performed well in three cases, but provided little insight into the predictors of obstacles in general. The obstacles *distance between forest and living place and forest size is too small* were almost exclusively driven by the predictors distance and size, respectively. This was to be expected and at least validates our method. The obstacle *lack of time* was most strongly predicted by the age of the owner being younger than 65 years, suggesting that older and mostly retired people may not perceive a lack of time as an obstacle to their management. Again, this was to be expected to some extent, and other variables did not play a noticeable role in our analyses of obstacles to management goals.

The models of the response variable group of conservation attitudes scored relatively low on the scale of predictive power, but we found five above our threshold. It is interesting to note that these attitudes were not only influenced by the ubiquitous parcel size as well as number of parcels and profession, but that we also found influences of gender here, at least for the agreement with two statements (*my forest provides no other benefit to me, which is why I promote nature conservation*; *nature conservation in my forest implies refraining from any use*). Such a stronger support for conservation (Kuhlman et al. 2022; Tiebel et al. 2022; Umaerus et al. 2019), as well as higher passivity (Schlecht and Westermeyer 2010) in female forest owners have been described in the literature. Coming into an inheritance late in a forest owner's life might play a role in explaining passive attitudes, and female forest owners are known to have inherited their property more often (Kuhlman et al. 2023). Regarding forest owners' attitudes toward conservation, Tiebel et al. (2021) found differences related to the location of the owner's parcel inside or outside of protected areas. Policy instruments such as protection status, as well as other external factors such as market drivers have been shown to influence owners' activities (see Table 3.1), but were not the focus of the present study.

3.4.3 Gender differences

Gender differences in forest owner attitudes and behaviors have been the subject of much research (see Section 3.1 for an overview). Based on our results, we ask whether these differences call for different approaches when targeting female and male forest owners. Consistent with the existing literature (Floress et al. 2019; Husa and Kosenius 2021; Silver et al. 2015), we found that salient behavioral variables were mostly indifferent to forest owner gender, and parameters such as goals, obstacles, and conservation attitudes showed mostly the same pattern among forest owners who identified as female and male. It is important to note that statistical differences by gender do not imply causality, nor do they support an understanding of innate "feminine" character traits or concepts (e.g., concepts such as active forest ownership are often misleadingly understood as "masculine" compared to "feminine" concepts such as taking care (Kuhlman et al. 2024)). Gender differences among the surveyed SPF owners may be indicative of an underlying context: Caputo and Snyder (2023) pointed out that absentee owners are less active. The commonplace that female-identifying owners are more passive may not be an innate female trait, but a sign of an underlying cause. For various reasons, such as more frequent inheritances, female owners tend to live farther away from their property, which makes active management more difficult (30.1 % of female owners in our dataset live more than 10 km away from their forest, compared to 16.1 % of male owners). Looking at the occupation of the owner (Pieper et al. 2023), we find that 16.3 % of female owners identify themselves as agricultural or forestry professionals, compared to 34.1 % of male owners. Strong influences of such professions (Hogl et al. 2005) on management choices such as the harvesting of single mature trees, as we have seen in our results, may also explain seemingly strong influences of gender. Therefore, we advocate for a thoughtful presentation of research results. The approach of analyzing correlations of gender as a single factor can provide detailed information about gendered distributions of attitudes, behaviors, knowledge, or assets among forest owners. However, great care must be taken to avoid giving the impression of causality between (stated or attributed) gender and variables such as attitudes or behavior (Agarwal 1992).

3.4.4 Limitations and room for further research

The questionnaire used in the present study did not include some potentially interesting predictors, for example, on harvesting and other silvicultural behaviors. We also do not have data on the length of tenure (Côté et al. 2016; Kuuluvainen et al. 2014), which could be a proxy for the forest owners' emotional attachment to their property or feelings about forests as family heritage (Matilainen et al. 2019), or for their experience working in forests. Regarding financial influences, we did not control for market drivers such as timber prices, and we do not know the owners' income (Beach et al. 2005; Binkley 1981; Husa and Kosenius 2021; Joshi and Arano 2009) or what percentage of their income comes from timber sales. We also cannot assess whether owners make all decisions about the forest themselves, or whether they rely on a forester, contractor, or friends or relatives for advice and practical management. Possible influences of these factors, also in comparison to the predictors we have already assessed, could be the subject of further studies. Other types of determinants could also be considered. Owners' goals have been used as factors predicting future behavior, although such a link between the owners' goals and concrete actions in their forests has been shown to be weak, with the authors arguing for owners' attitudes instead (Floress et al. 2019). Concerning the statistical methodology, the choice of random forest models for predictions was guided by their ability to provide measures for variable importance. Variable importance is known to spuriously depend on the number of categories of predictors, as described in Section 3.2.2, or on their scale of measurement (Strobl et al. 2007). We decided on downsampling our predictors to binary categorical variables to prevent this, thereby tolerating some information loss. Downsampling in similar contexts could be avoided in future research by careful consideration of alternative variable importance measures (Archer and Kimes 2008; Strobl et al. 2007). While our research focused on identifying and evaluating predictors of behavior and attitudes of SPF owners, one must be careful not to interpret the findings as describing causal relationships. Further research work, possibly including the biographies of forest owners, will be essential to answer questions of causality.

3.4.5 Implications for outreach and conservation communication

When asked about their needs, SPF owners often express a desire for information, support, and empowerment in the practical management in their forests (Joa and Schraml 2020; Paloniemi and Vainio 2011). Especially female-identifying forest owners often express feelings of uncertainty and a greater wish for assistance (Berget and Dwivedi 2024). Female networks can be a beneficial tool to empower those forest owners who feel marginalized in a male-dominated environment. Empowerment by such networks of peers can change the discourse in forestry, providing for alternative safe spaces (Andersson and Lidestav 2016). Peer learning groups can also help people become more confident also in more diverse settings (Hamunen et al. 2020).

On the other hand, when planning outreach or policy instruments to promote nature conservation in SPFs, it is advisable to have a clear understanding of the target group in order to design carefully targeted interventions. The results of the current study, as well as the larger body of work dedicated to multifactorial analysis of predictors of forest owner activities (Silver et al. 2015; Floress et al. 2019; Husa and Kosenius 2021), see also Table 3.1, suggest that projects specifically targeting female-identifying forest owners (Hafner et al. 2021; Lukacic et al. 2023) may not be the tool of choice when trying to influence forest owners' attitudes and behavior. Rather, a more precise analysis of the forest owner population, its characteristics and specific needs could increase the net benefit and efficiency of outreach to forest owners. Our results suggest to distinguish between the following two easily identifiable groups of forest owners when promoting conservation ideas:

(1) Ownership of large forest parcels has been shown to be an important predictor for a number of classical or close-to-nature silvicultural activities. Some owners already engage in activities that are beneficial from a conservation perspective, such as promoting natural tree regeneration (Larsen et al. 2022) or planting native broadleaf species. Owners of larger SPF parcels should be encouraged to continue or expand this behavior, while they may need support and guidance with respect to the ongoing scientific debate on the planting of non-native or non-local tree provenances (Karrer et al. 2022; Pötzelsberger et al. 2020; Wessely et al. 2024). Owners will need to choose a transition strategy for their often conifer-dominated forests, and it will be important to point out that converting their forests toward mixed or broadleaf stands, although it may instinctively be opposed by some forest owners, is imperative given the climate trajectory and will also be economically beneficial in the long run.

(2) Our results show that owners of predominantly broadleaf forests often do the right thing from a conservation perspective. They protect habitat trees and deadwood in their forests and avoid clearcutting (Storch et al. 2020). These owners could be supported in their decisions. Education about the high conservation values already present in their forests could lead to even greater awareness (Baranovskis et al. 2022; Joa and Schraml 2020; Thorn et al. 2020), and policy instruments could provide incentives for conservation measures (e.g., BMEL (2022) for Germany), even in the face of more traditional forestry staff who promote forests' economic use.

3.5 Conclusion

Gender is often assumed to be an important driver of differences among small-scale private forest owners and the management decisions they make. We challenged this assumption by considering a larger set of easily accessible owner demographic variables as well as forest parcel characteristics. Analysis of questionnaire data from small-scale private forest owners allowed us to identify key predictors of different owner activities, as well as owner goals, perceived obstacles, and conservation attitudes. Strong models were built for important forest management activities, but also for different owner goals, obstacles to these goals, and, to a lesser extent, conservation attitudes. The predictors of our response variables varied, but some patterns emerged. Consistently, parcel size was a top predictor of many of our response variables, especially for economically important management activities, while broadleaf forest owners tended to have a more conservation-oriented management style. In general, owner gender was not an efficient predictor of our response variables. Peer networking and gender-specific outreach can still be great tools for empowering female-identifying forest owners, but in order to target communication to diverse groups, we argue for a set of readily available demographic and site characteristic variables that lend themselves to the design of outreach to forest owners. Careful target group analysis can lead to more individualized conservation outreach strategies in small-scale private forests that are embedded in the overall livelihood systems of their owners.

3.6 Appendix

3.6.1 Supplementary tables

Tables 3.4 and 3.5 were deferred to the Appendix.

Table 3.4: Details of the response variables.

Question	Nr.	Response range	Wording	Mean
Activity	1	0 or 1	Thinning	0.860
Activity	2	0 or 1	Protection of habitat trees	0.438
Activity	3	0 or 1	Protection of young plants against browsing	0.455
Activity	4	0 or 1	Reduction of damage due to logging	0.517
Activity	5	0 or 1	Avoidance of chemical pesticides	0.748
Activity	6	0 or 1	Coppicing/coppicing with standards	0.119
Activity	7	0 or 1	Wood pasture	0.014
Activity	8	0 or 1	Promotion of a shrub layer	0.146
Activity	9	0 or 1	Promotion of broadleaf trees in coniferous forests	0.435
Activity	10	0 or 1	Protection/restoration of light stand structures	0.232
Activity	11	0 or 1	Protection/maintenance of special structures	0.121
Activity	12	0 or 1	Use of logging horses	0.022
Activity	13	0 or 1	Timber sale	0.611
Activity	14	0 or 1	Planting/promotion of native tree species	0.645
Activity	15	0 or 1	Planting/promotion of introduced tree species	0.029
Activity	16	0 or 1	Promotion of rare native tree and shrub species	0.157
Activity	17	0 or 1	Promotion of natural tree regeneration	0.652
Activity	18	0 or 1	Avoiding clearcuts	0.657
Activity	19	0 or 1	Protection of dead wood	0.449
Activity	20	0 or 1	Harvest of single mature trees	0.476
Activity	21	0 or 1	Species protection measures	0.201
Activity	22	0 or 1	Pruning	0.158
Activity	23	0 or 1	Biotope restoration	0.046
Activity	24	0 or 1	Removal of introduced species	0.194
Activity	25	0 or 1	Non-use of parts of the stand	0.166
Activity	26	0 or 1	None	0.005
Goal	1	5-point Likert (1 to 5)	Collection of non-wood products	2.179
Goal	2	5-point Likert (1 to 5)	Possibility for own recreation	3.534
Goal	3	5-point Likert (1 to 5)	Wood production for selling	3.501
Goal	4	5-point Likert (1 to 5)	Wood production for personal consumption	3.772
Goal	5	5-point Likert (1 to 5)	Long-term preservation of a stable and healthy forest stand	4.729
Goal	6	5-point Likert (1 to 5)	Possibility for hunting	2.469
Goal	7	5-point Likert (1 to 5)	Safeguarding or enhancement of landscape beauty	3.898

Details of the response variables *(continued)*.

Question	Nr.	Response range	Wording	Mean
Goal	8	5-point Likert (1 to 5)	Protection as a cultural asset	4.226
Goal	9	5-point Likert (1 to 5)	Carbon sequestration, conservation of carbon sinks	4.306
Goal	10	5-point Likert (1 to 5)	Biodiversity conservation	4.403
Goal	11	5-point Likert (1 to 5)	Preservation for financial security	3.311
Goal	12	5-point Likert (1 to 5)	Profit maximization	2.611
Goal	13	5-point Likert (1 to 5)	Preservation of family heritage	4.211
Goal	14	5-point Likert (1 to 5)	Protection of soil, water, air quality	4.198
Goal	15	5-point Likert (1 to 5)	Preservation as a place of recreation	4.240
Goal	16	5-point Likert (1 to 5)	Possibility for nature observation	3.806
Obstacle	1	0 or 1	No notable restrictions	0.425
Obstacle	2	0 or 1	Lack of time	0.405
Obstacle	3	0 or 1	Lack of money	0.201
Obstacle	4	0 or 1	Lack of technical equipment	0.193
Obstacle	5	0 or 1	Lack of skills	0.144
Obstacle	6	0 or 1	Lack of knowledge	0.221
Obstacle	7	0 or 1	Lack of information	0.129
Obstacle	8	0 or 1	Lack of family labor force	0.323
Obstacle	9	0 or 1	Forest size is too small	0.346
Obstacle	10	0 or 1	Unclear boundaries of the forest	0.056
Obstacle	11	0 or 1	Unknown contact persons	0.039
Obstacle	12	0 or 1	Poor accessibility through forest roads	0.081
Obstacle	13	0 or 1	Uncertainty about the location of the forest	0.016
Obstacle	14	0 or 1	Distance between forest and living place	0.101
Obstacle	15	0 or 1	Too much effort	0.113
Obstacle	16	0 or 1	Lack of interest	0.021
Obstacle	17	0 or 1	Initial stand conditions unfavorable for my objectives	0.046
Attitude	1	5-point Likert (1 to 5)	Structures with high conservation value are present in my forest	3.888
Attitude	2	5-point Likert (1 to 5)	My management ensures natural forest conditions	3.796
Attitude	3	5-point Likert (1 to 5)	Even without financial support, I am willing to promote nature conservation	3.472
Attitude	4	5-point Likert (1 to 5)	My forest provides no other benefit to me, which is why I promote nature conservation	2.574
Attitude	5	5-point Likert (1 to 5)	Nature conservation in my forest continues the family tradition	3.148
Attitude	6	5-point Likert (1 to 5)	Nature conservation in my forest implies refraining from any use	1.763
Attitude	7	5-point Likert (1 to 5)	Extraction of renewable resources is more meaningful than nature conservation	2.616
Attitude	8	5-point Likert (1 to 5)	Conservation in my forest can limit recreational uses	2.782
Attitude	9	5-point Likert (1 to 5)	Conservation in my forest prevents a visually beautiful impression	2.195
Attitude	10	5-point Likert (1 to 5)	Conservation in my forest threatens my personal freedom of decision	2.973
Attitude	11	5-point Likert (1 to 5)	Conservation in my forest creates high costs	2.884
Attitude	12	5-point Likert (1 to 5)	I do not perform management due to difficult forest stand conditions	2.153
Attitude	13	5-point Likert (1 to 5)	I would like to see higher involvement in decision making processes about conservation	3.397
Attitude	14	5-point Likert (1 to 5)	I perceive the management restrictions as too strict	3.400

Table 3.5: Distribution of response variables (activities, goals, obstacles, and attitudes) with respect to the predictors. For binary responses (activities, obstacles), the percentage of "yes" responses is given. For Likert responses (goals, attitudes), Likert scores "rather important (4)" and "very important (5)" are combined, and the percentage of those responses is given.

Question	Nr.	Forest age		Bought/leased		Broadleaf		Total size		Nr. of parcels		Distance		Forestry training		Female		Owner age		Prof. qualific.		Agric./forestry		Time in forest		Settlem. size	
		0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
Activity	1	81.1	87.8	85.6	87.5	88.4	84.7	79.8	92.4	78.9	91.7	87.6	79.9	85.8	90.7	88	78.5	87.3	83.9	88.6	85.1	83.4	92.3	80	88.8	88.6	80.4
Activity	2	39.8	45.2	38.5	58.3	32.8	50.6	38.7	49	40.4	46.5	45.5	36.8	42.9	57	46.4	33.3	45.2	41.3	44.8	43.4	41.5	49.2	34.4	48.1	45.3	40.5
Activity	3	54	42.6	41.8	55.4	47.1	44.5	35.7	55.3	37.9	51.3	46.6	40.6	44.8	54.7	47.5	37.4	45.4	45.8	42.9	46.6	41.9	53.6	32.8	51.1	47.3	41.5
Activity	4	47.5	53.2	51.1	53.3	57.1	48.5	39.8	63.6	43.9	57.7	52.7	47.7	51.4	55.8	52.7	47.6	53.9	47.8	51.1	52	48.2	59.8	41.3	56.4	52	51
Activity	5	76.1	74.3	74.4	75.7	69.9	77.7	77.4	72.1	77	73	75.3	72.4	74.8	74.4	75	73.6	77.3	70.1	76.9	73.9	77.3	69.1	74.9	74.7	73.9	76.8
Activity	6	14.9	10.9	11.8	12.2	13.1	11.2	10.7	13.1	9.1	14	13	7.1	11.3	19.8	12.4	9.8	11.5	12.7	11.4	12.1	10.2	15.7	7.9	13.7	12.5	10.6
Activity	7	1.6	1.4	1.4	1.4	1.9	1.1	1.6	1.3	1.6	1.3	1.3	2.1	1.5	0	1.6	0.8	2.1	0.2	1.1	1.6	1.4	1.5	1	1.6	1.3	1.8
Activity	8	17.4	8.2	9.2	14.2	6.4	13.1	10.7	10.4	9.8	11.1	9.4	15.5	10.2	15.1	10.8	9.8	9.6	12.3	7.9	11.7	11.4	8.8	8.2	11.6	9.9	12.1
Activity	9	48.4	41.9	40.6	51.3	50.8	39.1	37.8	49.3	40.3	46	43.1	45.6	43.1	50	44.3	40.2	41.7	46.9	42.4	44	42.2	46.6	37.2	46.4	42.8	45.1
Activity	10	22	23.6	23.5	22.3	24.7	22.3	20.7	25.7	21.3	24.6	23.7	20.9	23.1	24.4	22.8	24.8	22.8	23.9	22	23.7	24.4	20.4	23.6	23	23.5	22.4
Activity	11	12.4	11.9	11.1	14.8	11	12.7	10.7	13.4	11.1	12.8	12.3	10.9	11.2	24.4	12.8	8.9	12.7	10.9	11.4	12.3	11.9	12.4	8.7	13.6	12	12.1
Activity	12	0.6	2.7	1.4	4.3	2.7	1.9	1.9	2.5	1.6	2.6	2.4	1.3	1.9	7	2.2	2.4	0.6	5.1	3	1.9	2	2.6	1.5	2.5	2.3	2.1
Activity	13	50.6	64.7	60.7	62.3	74.9	52.7	46.6	75.6	48.5	70.8	60.3	64.9	60.7	66.3	62.7	54.5	61.2	60.9	57.6	62.6	55.7	73.5	52.3	65	61.6	60.1
Activity	14	73.6	61.4	60.9	74.2	65.8	63.7	55.8	73.2	57.2	70.1	65.4	60.7	64	70.9	66.1	57.7	66.5	60.9	61.7	65.7	63.1	67.8	53.8	69.2	65.7	61.9
Activity	15	32	28	27.5	33	41.1	21.6	18.3	39.7	22.8	33.8	30.1	24.3	28	43	30.6	22.4	29.1	28.8	27.7	29.6	24.3	39.7	20.8	32.7	30	26.8
Activity	16	24.5	12.7	11.6	26.7	13.3	17.2	12.2	19.2	12	18.5	15.9	14.6	14.7	29.1	16.4	12.6	14.6	17.6	12.5	17	14.3	18.8	9.5	18.5	15.5	16.2
Activity	17	49.4	58.6	53.4	63.8	53.7	57.8	45.8	66.6	47.2	63.1	58.2	47.7	55.3	68.6	58.6	46.3	57.4	54	54.9	56.8	52.4	64.9	41.8	62.6	58.8	50.5
Activity	18	56.2	68.9	63.7	71	53.1	73.4	65.6	65.8	68.3	63.7	66.5	62.3	64.7	79.1	67.6	57.7	66.7	63.8	68.2	64.7	64.9	67.5	60.5	68	64.8	67.8
Activity	19	45.7	44.6	41.6	53.6	35.1	50.9	44.7	45	48.8	41.9	44.3	47.3	43.8	59.3	45	44.3	46.7	41.5	43.2	45.6	45.3	43.8	41	46.6	44.4	45.9
Activity	20	32.9	52.5	45.6	52.8	44.6	49.4	39.8	55.3	38.3	54.7	49.7	38.5	47	55.8	51.4	31.7	48.5	45.8	47.8	47.4	39.9	64.9	36.9	52.3	50.2	41.5
Activity	21	23	19.1	16.7	29.3	14.9	23.3	20.2	20	19.9	20.3	21.5	14.2	19.5	27.9	20.7	17.5	19	22.1	20.7	19.9	18.5	23.7	15.4	22.2	20.9	18.3
Activity	22	23.6	13.1	13.7	21.4	17.6	14.6	11.2	20.3	11.8	18.8	16.8	11.3	15.7	17.4	17.5	8.5	16	15.4	16.3	15.6	13.8	20.4	8.7	18.9	17.4	12.1
Activity	23	5.3	4.3	3.7	7	5.4	4.1	4.6	4.6	4.2	4.9	4.9	3.3	4.4	7	4.8	3.7	4	5.6	3.3	5.1	4.3	5.2	2.1	5.7	4.1	5.7
Activity	24	20.5	19	16.4	27.5	19.5	19.3	16.7	22	16.4	21.7	20.7	13.8	18.4	33.7	20.6	14.2	18.2	21.7	17.4	20.2	16.8	25.3	10.8	23.2	20.7	16.5
Activity	25	16.5	16.7	15.5	19.7	13.7	18.4	16.3	17	17.7	15.9	16.2	18.4	16.3	20.9	16.4	17.5	16.7	16.5	12.5	18.3	17.2	15.5	12.6	18.5	15.9	18.3
Activity	26	0.3	0.5	0.5	0.3	0.6	0.4	0.9	0	0.7	0.3	0.4	0.8	0.3	2.3	0.4	0.8	0.2	0.9	0.3	0.6	0.5	0.5	1	0.2	0.7	0
Goal	1	15.2	11.7	11.8	14.8	11.6	13.2	13	12.3	11.8	13.2	12.5	13	12.9	9.3	10.8	20.3	12.2	13.4	14.1	12	14.5	8.2	11	13.3	12.2	13.7
Goal	2	57.5	50.8	49.4	60.9	50.4	53.8	52.6	52.4	50.3	54.2	54.4	44.4	52.8	48.8	52.8	51.2	52.3	52.9	57.6	50.4	54.2	48.7	46.9	55	52	53.6
Goal	3	55.3	60.7	60.2	56.8	66.8	54.7	48.3	70.2	49.4	66.9	60.4	54.4	58.5	70.9	61.7	49.2	58.3	61.2	60.9	58.7	51	78.1	50.3	63.3	61.7	53.9
Goal	4	60.9	70.7	66	74.2	61	72.6	63.3	73.1	61.4	73.4	73.3	46.4	67.7	75.6	71.8	53.3	71.8	61.6	72.6	66.4	64.5	76.5	58.2	72.7	73.5	56.2
Goal	5	96	97.4	96.6	98	96.3	97.5	95.6	98.4	95.3	98.3	97.2	96.2	97	97.7	97.2	96.3	97.1	96.9	97.8	96.7	96.4	98.5	95.1	97.8	96.9	97.2
Goal	6	25.5	27.4	27.2	26.1	23.4	29	19.4	34.3	22.6	30.2	29.1	17.6	26.1	37.2	27.9	22.8	25.2	29.9	28.5	26.2	22.3	37.4	19.2	30.3	29.3	21.4
Goal	7	74.8	71.6	72.2	73	69.3	74.3	73	71.8	74.1	71.1	73	69.9	72.8	66.3	71.1	77.6	72	73.2	75.3	71.2	73	71.1	69.7	73.6	73	71.1
Goal	8	84.5	84.2	84.7	83.2	84.6	84.1	85	83.6	85.6	83.3	84.5	83.7	84.5	81.4	83.5	87.8	82.9	86.8	87.2	83.1	84.5	83.8	81.3	85.6	84.7	83.5
Goal	9	86.3	85.3	84.9	87.2	85.3	85.8	85.9	85.2	85.2	85.8	85.7	84.9	85.8	82.6	84.9	88.2	83.4	89.5	88.9	84.2	85.6	85.6	83.6	86.4	85.3	86.1
Goal	10	91	90.3	91	89	88.2	91.9	90.2	90.7	89.3	91.4	91.3	87	90.6	88.4	89.8	93.1	91	89.5	90.2	90.6	90.3	90.7	88.2	91.5	90.6	90.2
Goal	11	45.7	48.2	45.2	53.9	51.9	44.9	39.3	55.7	41	52.6	48.1	45.2	47.5	48.8	48.5	43.5	46.5	49.6	51.1	46.1	41.8	60.6	38.7	51.5	50.2	41.5
Goal	12	23.3	28.3	26.9	27.5	33.6	23	19	35.1	21.7	31.2	29.2	18	26.9	29.1	28.7	20.3	24.6	31.5	32.9	24.7	19.8	43.6	17.7	31.2	29.8	20.9
Goal	13	80.4	84.6	87.3	73.3	83.6	83.5	79.6	87.4	81.1	85.4	83.9	82	83.6	82.6	84.2	80.5	82.9	84.6	84	83.3	81.2	88.7	81	84.6	86.1	77.6
Goal	14	91.3	92.8	93.1	90.7	92.3	92.5	91.3	93.5	91.3	93.3	92.7	91.2	92.6	90.7	92	94.3	91.7	93.8	93.5	92	92.2	93	89.5	93.7	92	93.3
Goal	15	49.1	48	46.8	52.2	46.7	49.2	48.7	47.9	47	49.2	48.1	49	48.3	47.7	46.8	54.5	46	52.5	54.1	45.9	49.8	44.8	41.8	51.1	47.7	49.5
Goal	16	67.4	68.3	67	71	64.3	70.4	68.1	68	66.7	69.1	69.3	62.8	68.2	66.3	66.7	73.6	68.4	67.4	69.8	67.3	71	61.3	63.3	70.2	66.7	71.1
Obstacle	1	34.2	27.4	28.6	30.4	25.3	31.4	30.3	27.9	32.8	26.3	31.8	17.6	29.1	29.1	29.3	28.5	24.5	37.5	35.9	26.3	28.8	29.9	21.5	32.5	30.5	26

Distribution of response variables (activities, goals, obstacles, and attitudes) with respect to the predictors *(continued)*.

Question	Nr.	Forest age		Bought/leased		Broadleaf		Total size		Nr. of parcels		Distance		Forestry training		Female		Owner age		Prof. qualific.		Agric./forestry		Time in forest		Settlem. size	
		0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
Obstacle	2	37.3	41.5	40.7	39.7	45.2	37.5	34	46.9	33.3	45.9	39.7	43.5	40.3	43	41.8	35	52.2	19	28.8	45.2	38.3	45.4	42.3	39.6	40.5	40.5
Obstacle	3	19.6	20.3	21.8	15.7	25.9	16.5	17.4	22.8	17.9	21.8	20.3	19.2	20.3	17.4	19.6	22.4	22.8	15.2	18.8	20.7	19.1	22.4	22.3	19.1	20.2	19.8
Obstacle	4	17.1	20.1	19.7	18.3	21.6	17.9	19.4	19.2	19.3	19.3	18.9	21.3	19.7	14	18.2	24	21.3	15.6	18.2	19.8	20.3	17	24.6	17	19.5	18.8
Obstacle	5	15.2	14.2	15	13	14.1	14.6	14.5	14.3	15.1	13.9	12.4	23	14.7	10.5	10.8	29.7	14.8	13.8	12.2	15.3	17.6	7.2	22.6	10.8	12.5	18.8
Obstacle	6	20.8	22.5	22.8	20.3	24.1	20.9	23.9	20.3	20.8	23.1	19.6	32.6	22.7	14	20	30.9	24.9	17	19	23.3	26.8	11.3	34.6	16.5	20.5	25.8
Obstacle	7	10.9	13.5	12.9	12.8	13.5	12.5	13.3	12.4	12.9	12.8	12.2	15.5	13.3	7	12.5	14.2	13.7	11.4	12.2	13.1	14.1	10.1	17.4	10.8	11.8	15.2
Obstacle	8	32	32.5	33.8	28.4	38.2	28.8	27.2	37.5	27.5	36	32.3	32.6	32.7	27.9	31.5	35.8	32.6	31.9	29.9	33.3	31	35.3	34.9	31.2	32.8	31.2
Obstacle	9	30.4	35.6	35.4	31.3	29.7	37.2	46.9	21.7	39.9	30	32.7	41.4	34.4	32.6	34	35.8	33.5	35.7	29.9	36.1	35.7	31.2	45.6	29.3	34.8	33.2
Obstacle	10	2.2	6.8	4.9	7.5	4.6	6.2	7.1	4.1	3.8	7	5.1	7.9	5.8	2.3	5.2	7.3	5.4	6	5.2	5.8	6.1	4.4	7.7	4.7	4.8	7.5
Obstacle	11	3.1	4.2	3.8	4.3	3.3	4.3	4.3	3.6	3.6	4.2	3.3	6.7	4.1	2.3	3.5	5.7	4.5	2.9	3.3	4.2	5.1	1.3	5.9	3.1	3.5	4.9
Obstacle	12	5.6	9	7.4	10.1	8.7	7.8	7.3	9	5.5	10.2	8.1	8.4	8.1	8.1	8.8	5.3	8.5	7.4	8.7	7.9	6.7	11.3	4.9	9.6	9.3	5.4
Obstacle	13	0.6	1.9	1.7	1.2	1.9	1.4	1.6	1.6	1.5	1.7	0.9	4.6	1.7	0	1.3	2.8	1.6	1.6	0.3	2.1	2	0.5	2.3	1.3	1.3	2.3
Obstacle	14	8.1	10.7	10.7	8.1	11	9.4	12.5	7.6	10.7	9.5	1.3	47.7	10.1	9.3	8.3	17.1	9	11.8	5.7	11.8	12.7	3.9	15.6	7.5	5.9	19.3
Obstacle	15	8.7	12.2	12.4	8.4	14.9	9	10.4	12.1	9.7	12.5	10.1	16.3	11.2	12.8	10.7	13.8	11.7	10.5	9.5	12	10.8	12.4	13.6	10.3	10.1	13.9
Obstacle	16	1.9	2.2	2.6	0.9	2.5	1.9	2.2	2	2.6	1.8	1.8	3.3	2.2	1.2	1.7	4.1	2.3	1.8	1.9	2.2	2.7	0.8	4.9	0.9	1.9	2.6
Obstacle	17	3.1	4.4	4	4.3	5.2	3.4	4.7	3.5	5.1	3.3	3.9	5	4.1	4.7	4.1	4.1	4.9	2.7	3.3	4.4	4.2	3.9	6.2	3.2	3.9	4.6
Attitude	1	49.4	43.6	41.4	54.8	38.2	49.2	44.7	45.4	44.4	45.5	44.8	46	44.9	46.5	45.4	43.5	44.8	45.5	42.9	45.9	46.1	42.5	40	47.3	45	45.1
Attitude	2	77.6	75.7	74.8	80	68.5	80.9	78.4	74	75.8	76.5	76.7	74.1	75.7	82.6	76.9	73.2	76.1	76.3	79.3	74.9	76.7	75	73.6	77.3	76.5	75.5
Attitude	3	57.5	52.7	51.9	59.4	50.8	55.9	56.2	51.7	58.1	50.8	53.5	55.6	53.8	55.8	53.3	56.5	54.4	53.1	54.1	53.9	57.8	45.1	53.1	54.3	52.3	57.7
Attitude	4	23.3	23.5	24.6	20.3	23.7	23.3	28.1	18.7	29.1	19.1	21	33.9	23.5	22.1	20.5	35.8	19.9	29.9	26.4	22.2	26.9	15.5	28.5	21.2	20.9	29.1
Attitude	5	38.2	46.5	46	40	42.9	45.3	42.8	46	43	45.5	44.1	45.6	44.6	41.9	43.5	48	43.2	46.7	46.5	43.6	44.3	44.6	42.1	45.4	43.3	46.9
Attitude	6	7.8	6.8	7.5	5.8	6	7.6	9.8	4.3	10.2	4.6	5.6	13	7	7	5.6	13	7.4	6.2	6.2	7.3	8.6	3.4	10.3	5.6	4.9	11.9
Attitude	7	19.6	22.6	21.9	21.7	21	22.4	19.4	24.3	19.1	23.9	22.7	18	21.7	23.3	22.6	18.7	20.7	23.9	23.6	21.1	16.8	33.2	16.4	24.3	22.8	19.6
Attitude	8	23	27.6	24.9	30.4	24.9	27.4	24	28.8	23.5	28.7	26.8	24.7	26.4	26.7	26.7	25.2	28	23.4	25.3	26.9	25	29.6	25.4	26.9	26.1	27.1
Attitude	9	11.8	12.4	11.9	13	12.4	12.1	10	14.5	9.5	14.3	13	8.8	12.5	8.1	13.3	7.7	11.1	14.3	14.9	11.1	9.5	18.3	9.7	13.3	13.8	8.8
Attitude	10	30.4	42	38.7	40	38.6	39.3	31.4	46.6	31.9	44.5	41.2	29.7	38.8	41.9	43.1	22.4	40.2	36.8	41	38.2	32.4	54.1	34.1	41.2	40.9	34.8
Attitude	11	24.2	32.7	30.7	30.1	32.6	29.3	22	39.1	22	37	32	24.3	30.5	31.4	33	20.3	31.6	28.6	29.1	31.1	24.4	44.3	22.6	34.1	32.8	25.3
Attitude	12	16.8	15.6	16.4	14.8	14.9	16.5	16.1	15.7	17.1	15	14.1	23.8	15.8	17.4	14.4	22.4	14.9	17.9	16.3	15.8	16.1	15.5	19	14.6	15.9	16
Attitude	13	49.7	52.3	49.5	57.4	51	52	48.5	54.8	46.6	55.5	52	50.2	51.4	55.8	53.1	45.5	53.9	47.5	49.5	52.6	49.9	55.7	46.7	53.9	51	53.1
Attitude	14	33.5	49.3	44.9	46.4	46.3	44.7	37.6	52.9	34.1	53.8	46.9	38.1	44.9	50	48.1	33.3	47.7	40.8	42.1	46.6	40.2	56.7	38.5	48.3	47.5	40.2

3.6.2 Closing statements

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Chapter 4

Predicting old-growth structures in temperate small-scale private forests using landscape data

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Predicting old-growth structures in temperate small-scale private forests using landscape data

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Abstract

Key message Old-growth forest structures in small-scale private forests are strongly shaped by landscape context and can be reliably predicted using freely available spatial data. Remnant forest patches within mixed cultural landscapes act as important reservoirs and connectivity elements for forest biodiversity and should be prioritized in conservation and management planning.

Context Many forest species of high conservation concern depend on old-growth structures, which are often rare in contemporary production forests. In small-scale private forests, these structures are fostered by inactive owners and influenced by parcel topography.

Aims We attempt to quantify the abundance of old-growth structures in small-scale private forests in Lower Saxony, Germany. Landscape-related predictors are employed to model spatial distribution patterns.

Methods The *Parcel Index of Conservation Attributes* (PICA) was calculated from forest structural data and modeled using a gradient boosting tree model. Independent survey data was used to evaluate its performance externally. The predictions are shown in the form of a spatial distribution map.

Results The prediction identified parcels with a high abundance of old-growth structures. These were mostly found outside of large, more intensively managed forest regions and consisted of stands rich in broadleaf trees situated in semi-open, mixed-use cultural landscapes.

Conclusion Predictions about the spatial distribution of valuable habitats can be made using freely available landscape-scale data. Verifying these predictions using small samples increases the trust-

worthiness of the model. Forest patches in fragmented agricultural landscapes can act as islands of old-growth structures. These patches are vital for rare forest species and must be urgently protected.

Keywords Biodiversity hotspots, Forest management, Forest ownership, Predictive modeling, Machine learning, Fragmented cultural landscapes

4.1 Introduction

The biodiversity of European forests largely consists of species groups that depend on old-growth structures, which are mainly found in unmanaged, mature forests. Examples include bryophytes, lichens, saproxylic fungi and beetles, as well as bats and birds (Blasi et al. 2010; Rigo et al. 2024; Storch et al. 2023). Forests that are rich in old-growth structures are recognized as supporting a variety of forest ecosystem services and providing diverse habitats for forest species (Storch et al. 2018; Wagenaar et al. 2025; Zeller et al. 2023).

Old-growth structures include lying or standing deadwood (Henneberg et al. 2025), old trees approaching the end of their lives (Gilhen-Baker et al. 2022), high biomass pools, structural variation in tree sizes and canopy layers (Bauhus et al. 2009), and tree-related microhabitats (Martin et al. 2022). These structures are rare in production forests, which are typically managed with relatively short rotation periods (Barredo et al. 2021). Primary forests without anthropogenic influences have virtually disappeared from most of Europe (Sabatini et al. 2018). However, old-growth structures can develop in secondary forests if they are left undisturbed (Barredo et al. 2021), or if they are managed in a semi-natural way (Bauhus et al. 2009). But these structures take long periods of time to develop.

In Germany, large forest holdings under public or private ownership are primarily managed by professionals, while small properties often undergo more irregular management. Small-scale private forest parcels—cadastral units owned by individuals—of up to 20 ha account for 22.8% of Germany's total forested area (Thünen Institute 2022a). Systematic forestry is often not possible in the economies of small-scale private forests. Individual owners who do not depend on income from wood sales often pursue non-economic objectives, such as preserving natural or cultural values, or even non-management (Husa and Kosenius 2021; Tiebel et al. 2024). This behavior increases the likelihood of old-growth structures developing and persisting in such forests (Johann and Schaich 2016). However, their long-term protection is not reliably guaranteed (Svensson et al. 2025).

The continuous retention of old-growth structures, i.e. ecological or habitat continuity, is essential for the long-term survival of specialized forest species (Wysocki et al. 2025). This emphasizes the crucial role of forest management that is aware of old-growth structures, which hinges on precise spatial data (Barredo et al. 2021). Targeted outreach and policy instruments, such as protection legislation, incentives or conservation contracts (Demant et al. 2020), can safeguard such structures in private forests, but decision makers are in need of dependable spatial distribution data to implement these measures effectively.

Spatial data on old-growth habitats and the biodiversity that depends on them is usually unavailable due to the diverse ownership and the non-professionalized nature of small-scale private forests. This lack of actionable data presents a major research gap in the understanding of small-scale private forest structures and biodiversity (Thompson et al. 2022). A landscape-scale inventory of old-growth structures would be transformative, as it would allow decision makers to pinpoint their conservation actions. Precise and complete maps of old-growth forest structures could serve as a valuable substitute to field surveys of old-growth biodiversity (Martin et al. 2022), which are often prohibitively costly (Juutinen and Mönkkönen 2004).

As old-growth structures can manifest in a variety of ways, it is challenging to compare the nature conservation value of different small-scale private forest parcels. Therefore, a numerical index that takes various old-growth structures into account would be useful for assessing the spatial distribution of high-conservation-value structures among small-scale private forest parcels, especially at a landscape scale. In the present study, we propose a numerical index we call the *Parcel Index of Conservation Attributes* (PICA). PICA considers various forest structural variables known to be associated with old-growth forest biodiversity, including living and dead wood volumes and the number of large trees (Blasi et al. 2010; Storch et al. 2023).

Similar to other indices of structural characteristics (Di Filippo et al. 2017; Meyer et al. 2021; Reich et al. 2022), PICA can be calculated directly from field data obtained through forest structure surveys. However, for PICA to be useful at a landscape scale, it is preferable to model PICA values using data that is more easily accessible. In a previous study (Hansen et al. 2023), we identified predictors of old-growth forest structures in small-scale private forests. This study showed that old-growth structures were notably influenced by the landscape parameters of the forest parcels. The most important predictors were slope, distance to a road, ancient forest land and forest fragmentation metrics. These results suggested a method of predicting the abundance of old-growth forest structures in private forest parcels, substituting the need for comprehensive forest surveys with the ability to draw on already existing, blanket-coverage open landscape data. The final model should be able to produce a prediction map showing the spatial distribution of old-growth structures in small-scale forest parcels, as expressed by PICA values, at the landscape scale.

Specifically, our study addresses the following research questions:

- Can the *Parcel Index of Conservation Attributes* (PICA) be used to accurately quantify the abundance of valuable old-growth structures in small-scale private forests?
- To what extent are old-growth structures influenced by the landscape parameters of the individual forest parcels?
- What can be inferred from a spatial distribution model that predicts PICA values, and accordingly the abundance of old-growth structures, on the landscape scale?

4.2 Methods

4.2.1 Overview of the study design

Field data was collected on 78 small-scale private forest parcels in northwest Germany, and stored in a training dataset together with landscape data from open sources. A model m_1 was then trained using this dataset to predict PICA values. A control sample of 48 small-scale private forest parcels was surveyed to generate an independent testing dataset, which allowed for an external evaluation of the model's performance. Finally, a second predictive model m_2 was trained using both datasets to produce a raster-based prediction of PICA values in the study area (Fig. 4.1).

4.2.2 Study area

Fieldwork was conducted in the Lower Saxon Hills, a 14,228 km^2 geographic region consisting of two contiguous areas in the German federal state of Lower Saxony (Fig. 4.2). The region's private forest owners are subject to homogeneous legal and administrative conditions. Thirty-three percent of the region is forested, primarily with European beech (*Fagus sylvatica* L., 39%), which dominates the natural vegetation. Other common tree species include Norway spruce (*Picea abies* (L.) H. Karst., 18%), oaks (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl., 12%), sycamore maple (*Acer pseudoplatanus* L.), wild cherry (*Prunus avium* L.), birch (*Betula pendula* Roth), hornbeam (*Carpinus betulus* L.), Scots pine (*Pinus sylvestris* L.), and Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) (ML 2024). Private forests in the region account for 45% of the forested area. Nineteen percent of the private forest area is divided into small-scale private forests with a maximum size of 5 ha (ML 2024). The distribution of forest property is comparable to that of many other European countries (Schmithüsen and Hirsch 2010; UNECE and FAO 2020). The bedrock in the Lower Saxon Hills consists primarily of Mesozoic limestone and sandstone, partly with a Quaternary loess cover, and occasionally evaporite (gypsum karst) (LBEG 2022). The region's climate is oceanic to humid continental (Köppen classifications Cfb and Dfb), but it has experienced rising temperatures and more erratic precipitation patterns in recent years. The 2024 annual mean temperature on the parcels we studied ranged from 10.0 to 11.7 ℃, and the 2024 annual precipitation ranged from 744 to 1249 mm (DWD 2025a; DWD 2025b). Drought, elevated temperatures, and accompanying tree pests have impacted both conifer and broadleaf trees, rendering forestry in the study area highly vulnerable (George et al. 2022; Knutzen et al. 2025; Senf et al. 2020).

4.2.3 Study site selection and field work

Members of three local private forest owner associations who participated in a large-scale questionnaire survey in the Lower Saxon Hills region (Hansen et al. 2025; Hansen et al. 2023; Tiebel et al. 2021) and had provided contact information were asked for information about the exact location of their property. Eighty-eight owners of small-scale private forest parcels in the study area responded to this call, and 78 of them provided useful geographic information about their forest parcels. The 78 small-scale private forest parcels (sizes between 0.14 and 3.73 ha, average size: 1.16 ha) were visited during a first field campaign in 2021. Forest parcels exhibited a wide structural variety, ranging from deforested former conifer plantations to old broadleaf forests that have not undergone active management for several decades. On the sites, data on forest structure, management, and biotopes was collected. This resulted in the training dataset, d_{train} (Figs. 4.1 and 4.2). A model m_1 trained with this dataset was used to identify an additional set of 48 small-scale private forest parcels (see Section 4.2.6) in the study area (sizes between 0.15 and 2.31 ha, average size: 0.65 ha). A second

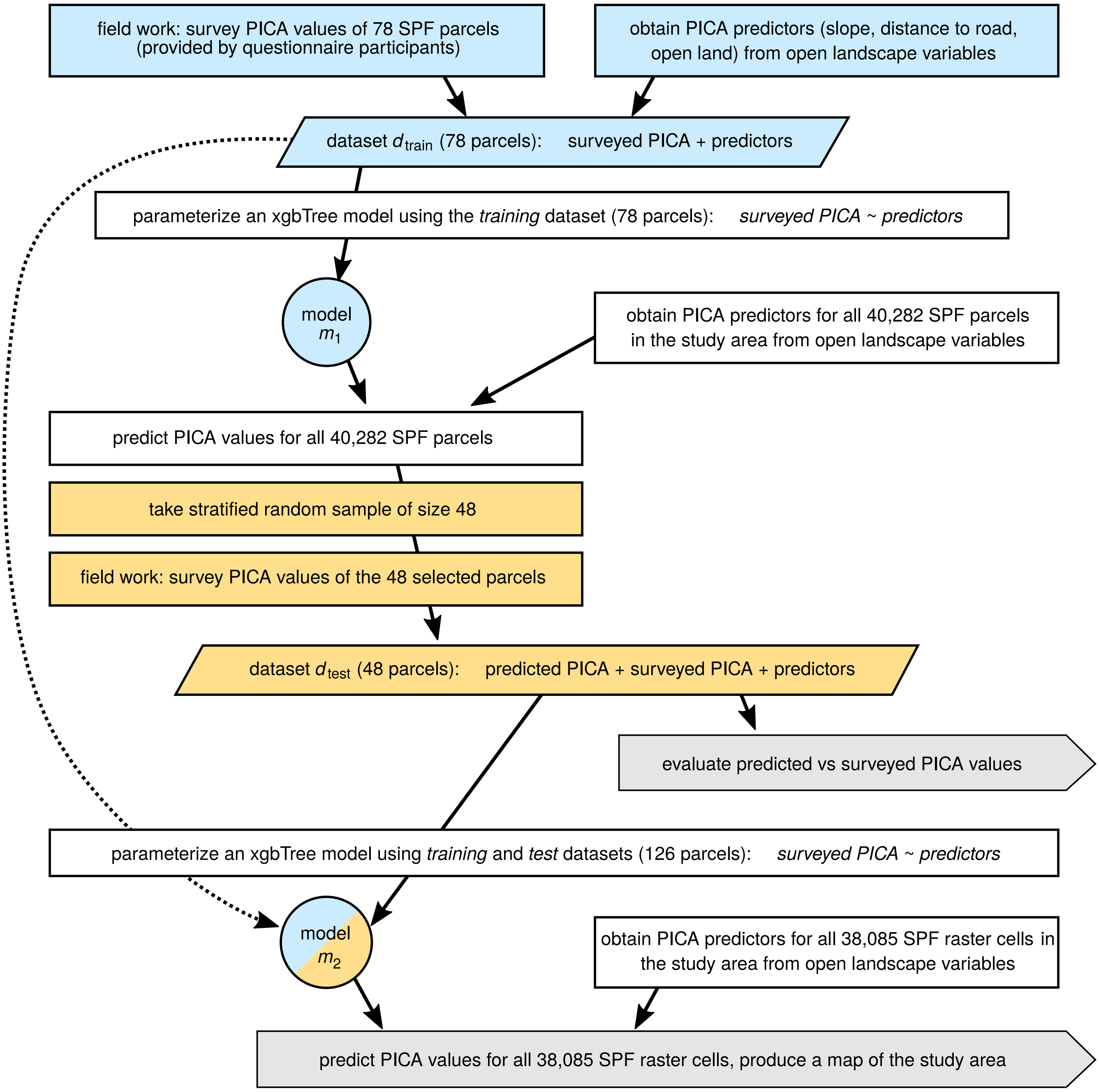

Figure 4.1: Flow chart of the study design. Blue color denotes elements related to the training dataset d_{train} (78 small-scale private forest parcels). Orange color denotes elements related to the testing dataset d_{test} (48 small-scale private forest parcels). Datasets shown as parallelograms, prediction models (xgbTree) shown as circles. Black arrows denote flow paths. Gray arrow boxes symbolize the primary outcomes of the overall design

field campaign was conducted in 2022 and 2023 to collect data on these parcels for external model evaluation, resulting in the test dataset, d_{test} (Figs. 4.1 and 4.2).

On each of the 126 small-scale private forest parcels, forest structural data was collected in one or several 500 m^2 circular plots ($r = 12.62$ m), according to Meyer and Fricke (2018). One plot was chosen for parcels smaller than 1.5 ha, two for parcels larger than 1.5 but smaller than 3 ha, and three for parcels of at least 3 ha. For single-plot parcels, parcel centroids were chosen as plot centers, allowing some flexibility for parcels with concave shapes. If a parcel had multiple plots, the plots were placed using repelling buffers in the geographic information system to maximize the distance from one another and from the parcel borders. We aggregated all plot data surveyed on multi-plot parcels by taking the mean. This removed within-parcel resolution but allowed us to treat these parcels the same way we treated parcels with a single plot. Additionally, estimation bias was lower on these parcels. Within each plot, all living or dead standing trees with a diameter at breast height (dbh, at 1.3 m) of at least 7 cm were recorded, along with their dbh and species. For each tree species, we grouped measured diameters into three classes and, from each class, selected three trees (when available) for height measurements ($n \leq 9$ total) using a handheld laser rangefinder (LTI TruPulse 360B). These data were used to fit individual Näslund height curves (Mehtätalo et al. 2015) for each tree species and each plot, which allowed us to interpolate the heights of unmeasured trees. Tree volume was calculated from dbh and height, using species-specific form factors. When surveying deadwood, we inventoried stumps with a diameter of at least 7 cm. We recorded their

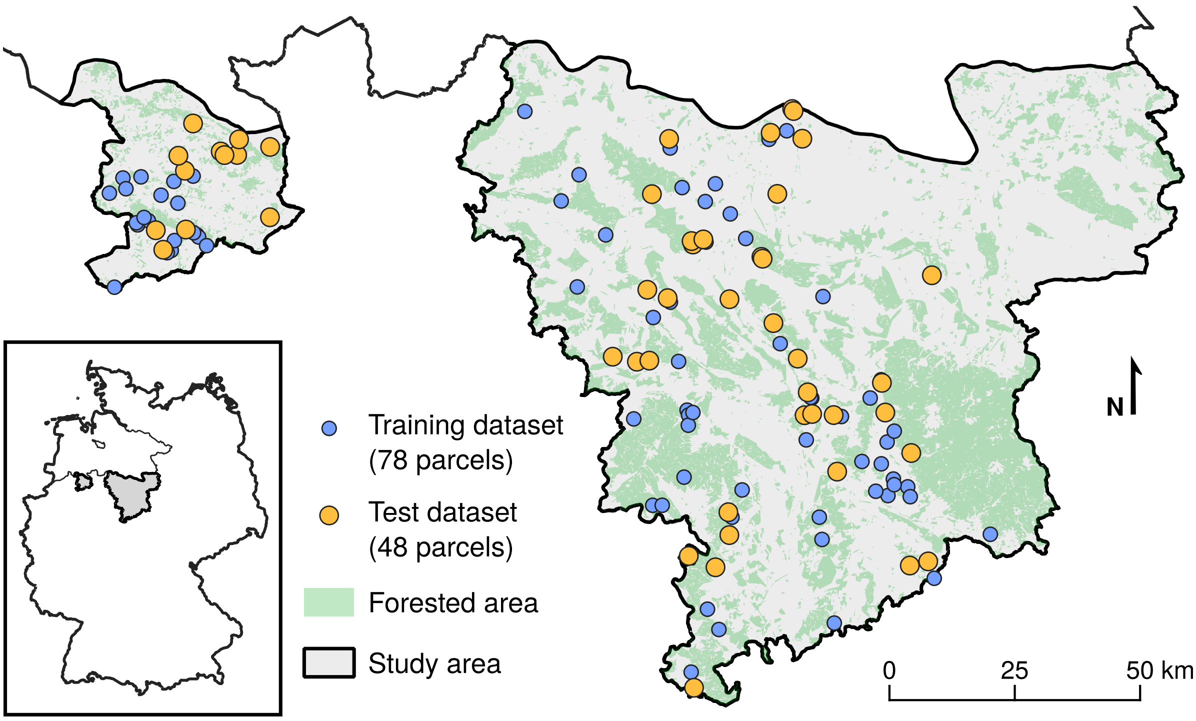

Figure 4.2: Map of the study area, the Lower Saxon Hills (14,228 km^2). Forest parcels in the training dataset d_{train} (small blue data points) were provided by owners who participated in a questionnaire. Parcels in the test dataset d_{test} (larger orange data points) were selected by a stratified random sampling process, see Section 4.2.6

diameter and height and classified them as conifer or broadleaf. Deadwood lying on the ground was inventoried if its diameter was at least 20 cm at the thicker end. The length and diameter at both ends were recorded, and each object was classified as either conifer or broadleaf, and as either of anthropogenic (showing saw marks) or natural origin. The volume of large objects, such as complete fallen trees, was calculated as it was for standing trees. The same was done for dead standing trees. All lying objects were recorded as if cut off at the plot border. The volume of harvested wood for each stump was calculated by first extrapolating the stump's diameter to dbh using a uniform tapering value of 1 cm/m. Then, the appropriate height curve and standard form factor were applied. Thus, the harvested wood volumes are the integral of the wood volume taken from the forest over the stump persistence time. These different wood volumes were used to calculate the Forest Management Index (ForMI) (Kahl and Bauhus 2014). We treated tree species planted outside their natural range, e.g., *Picea abies* (Norway spruce), as non-native. Several data were recorded not only in the plots, but also throughout the entire forest parcel. In this way, we recorded the occurrence of standing trees, whether living or dead, with a dbh of at least 50 cm throughout the entire parcel. Large-tree density was recorded at the parcel scale because these trees are rare, spatially clustered, and often absent from 500 m^2 plots. To evaluate the effects of parcel area, we examined the relationship between parcel size and large-tree density using Spearman's rank correlation coefficient. We also identified the three most important biotope types in terms of surface area (Drachenfels 2021). We assigned numerical "biotope values" to all biotope types present on the parcels (ranging from 0 = low to 24 = high), following the German federal regulation on avoiding and compensating for interventions in nature and landscapes (BKompV 2020) (see Hansen et al. (2023)). These numbers describe the standardized ecological value of biotope types, and favor old-growth and native forest types. We aggregated all biotope type values from a parcel, assigning weights based on the spatial extent of each biotope type. We used Wilcoxon rank sum tests to check for differences in structural data between the d_{train} and d_{test} datasets. Descriptive statistics of landscape parameters and field data are shown in Table 4.1.

4.2.4 Parcel Index of Conservation Attributes (PICA)

In the following, we define the *Parcel Index of Conservation Attributes* (PICA). This index attempts to quantify the abundance of old-growth structures on a forest parcel. PICA considers variables closely related to slowly-evolving and valuable old-growth habitat structures, that have been shown to be driven by the landscape parameters of the forest parcels (Hansen et al. (2023); see also Section 4.2.5). The components of the PICA include: (a) amount of living broadleaf wood; (b) amount of deadwood, particularly from broadleaf tree species; (c) low management intensity; (d) occurrences of rare, valuable biotopes; and (e) density of large-diameter trees. This choice was motivated by rapid applicability in common settings. Forest structural data that is standardly gathered in the field is mostly sufficient to calculate the index components. We chose to use the density of large-diameter trees (ρ_{ldtree}) on the parcels as one of the five individual components rather than the density of microhabitats or habitat-bearing trees (Larrieu et al. 2018). Surveying tree diameters is

Table 4.1: Descriptive statistics of data collected in the field; PICA values; and predictors (landscape parameters) for data sets d_{train} and d_{test}. Results of Wilcoxon rank sum tests are given as p-values. Significantly different means are marked $^{(a/b)}$

Variable	Dataset	Mean	SD	Min	Median	Max
Broadleaf living volume in m^3 ha^{-1}	d_{train}	210	228	0	116	877
(p-value: 0.270)	d_{test}	247	218	0	230	853
Broadleaf deadwood volume in m^3 ha^{-1}	d_{train}	11.2 ^{a}	21.9	0	3.03	124
(p-value: 0.042)	d_{test}	23.3 ^{b}	39.4	0	7.51	175
ForMI	d_{train}	0.462	0.292	0	0.402	0.984
(p-value: 0.156)	d_{test}	0.382	0.327	0	0.391	0.987
Biotope type value	d_{train}	14.3	4.18	6.0	13.0	23.0
(p-value: 0.193)	d_{test}	15.3	4.31	9.0	14.9	23.0
Trees at least 50 cm dbh per ha	d_{train}	18.4	30.5	0	4.39	163
(p-value: 0.113)	d_{test}	30.9	40.0	0	10.5	144
PICA value	d_{train}	0.436	0.226	0.078	0.436	0.905
(p-value: 0.090)	d_{test}	0.520	0.250	0.078	0.587	0.973
Slope in degree	d_{train}	7.8	5.8	0.1	6.3	27.9
(p-value: 0.558)	d_{test}	8.8	6.7	0.3	7.0	24.4
Broadleaf forest (n = 0, y = 1)	d_{train}	0.538	0.502	0	1	1
(p-value: 0.100)	d_{test}	0.688	0.468	0	1	1
Distance to road in m	d_{train}	373	280	24	303	1146
(p-value: 0.110)	d_{test}	562	479	32	435	1752
Open land in 200 m radius	d_{train}	0.398 ^{a}	0.336	0	0.376	1
(p-value: 0.023)	d_{test}	0.290 ^{b}	0.320	0	0.233	1
Open land in 2 km radius	d_{train}	0.541	0.190	0.048	0.564	0.814
(p-value: 0.612)	d_{test}	0.531	0.182	0.101	0.575	0.809

much more efficient than surveying microhabitats. Large-diameter trees are likely to already have microhabitats or develop them in the future (Kozák et al. 2023; Torres-García et al. 2024).

While (a), (b), and (c) were calculated from plot data, (d) and (e) were measured on the whole forest parcel. PICA values are unitless numbers ranging from 0 to 1, and the index is calculated as the mean of five components, each of which also ranges from 0 to 1. The forest structural parameters that define these components are as follows: (a) the volume of living broadleaf trees ($V_{\text{livingBrl}}$) given in m^3 ha^{-1}; (b) the volume of broadleaf deadwood (V_{deadBrl}) given in m^3 ha^{-1}; (c) the forest management intensity index (ForMI), defined to range from 0 to 3 by Kahl and Bauhus (2014), which uses standard inventory data of trees and deadwood to assess management intensity during the last 30–40 years of a stand; (d) biotope values ranging from 0 to 24 according to BKompV (2020); and (e) the density of large-diameter trees (ρ_{ldtree}), given in ha^{-1}. Since these five components do not fall within the range of 0 to 1, we applied transformations similar to those described by Storch et al. (2023). Biotope values were divided by 24. We considered high management intensities to be detrimental to old-growth structures and therefore subtracted the ForMI index values divided by three from one. To bring the broadleaf living volumes, broadleaf dead volumes, and habitat trees densities into the interval [0, 1], we use a saturation function s_h with the following properties: (a) $s_h(0) = 0$; (b) $s_h(h) = 0.5$; (c) $\lim_{x\to\infty} s_h(x) = 1$. A standard logistic function with an additional parameter h that satisfies these constraints is given by

$$s_h(x) = \frac{2}{1 + e^{-\ln(3)\frac{x}{h}}} - 1.$$

The value of h was chosen individually for each PICA component (broadleaf living volume, broadleaf dead volume, and density of large-diameter trees) according to the corresponding averages in our dataset and statewide inventory data (see Table 4.2). For example, consider the amount of broadleaf living volume, for which we chose $h = 250\text{m}^3$. Parcels with a broadleaf volume of 250 m^3 will receive a score of 0.5 on the broadleaf volume PICA component scale. The PICA value for an individual forest parcel is calculated as

$$\text{PICA} = \frac{1}{5}\left[s_{250}(V_{\text{livingBrl}}) + s_{20}(V_{\text{deadBrl}}) + \left(1 - \frac{\text{ForMI}}{3}\right) + \frac{\text{biotopeValue}}{24} + s_5(\rho_{\text{ldtree}})\right].$$

Table 4.2: Values of the h parameter for the different PICA components. Occurrences of old-growth structures close to h correspond to PICA component scores of 0.5

PICA component	Value of h chosen	Rationale
Broadleaf living volume	250 $\text{m}^3\ \text{ha}^{-1}$	The average in our dataset is 224 $\text{m}^3\ \text{ha}^{-1}$, median 158 $\text{m}^3\ \text{ha}^{-1}$. Average for all private forest sizes in Lower Saxony is 148 $\text{m}^3\ \text{ha}^{-1}$, for small-scale private forests 174 $\text{m}^3\ \text{ha}^{-1}$ (Thünen Institute 2022c).
Broadleaf deadwood volume	20 $\text{m}^3\ \text{ha}^{-1}$	The average in our dataset is 16.1 $\text{m}^3\ \text{ha}^{-1}$, median 6.0 $\text{m}^3\ \text{ha}^{-1}$. The average for all private forest sizes in Lower Saxony is 8.1 $\text{m}^3\ \text{ha}^{-1}$, and 11.5 $\text{m}^3\ \text{ha}^{-1}$ for small-scale private forests (Thünen Institute 2022b).
Density of large-diameter trees	5 ha^{-1}	The average in our dataset is 22.9 ha^{-1}, median 5.8 ha^{-1}. Lower Saxony recommendation for minimal density in Natura 2000 areas is 6 ha^{-1} (ML and MU 2019). For forests older than 100 years, Hesse state forest service recommends 10 ha^{-1}, and 15 ha^{-1} in Natura 2000 reserves (HMUKLV 2022).

4.2.5 Landscape-related predictor variables

Based on previous results (Hansen et al. 2023), we selected five landscape parameters of small-scale private forest parcels that have been shown to significantly influence our responses, i.e., the components of the PICA. The selected parameters were (1) terrain slope, calculated from a digital elevation model (variable *slope*) (GeoBasis-DE/LGLN 2025); (2) parcel status as broadleaf or conifer forest (variable *broadleaf*), sampled from CORINE land cover data (Copernicus Land Monitoring Service 2018) at the parcel centroid; (3) the parcel's distance to the nearest paved road (variable *distance to road*), calculated using a road network map (OpenStreetMap contributors 2022b); (4) the amount of open land within a 200 m radius of the parcel (variable *openland 200 m*); and (5) the amount of open land within a 2 km radius of the parcel (variable *openland 2 km*). The last two calculations were also based on CORINE land cover data (Copernicus Land Monitoring Service 2018). We decided on discarding the variables *parcel size*, *elevation*, *water availability*, and *nutrient availability*. While *parcel size* had to be removed for data licensing reasons (see Section 4.2.6), the other three variables had no influence on the relevant response variables. As we did not have clearance to disclose all small-scale private forest parcel geometries in the study area, polygon data were converted to raster data with a resolution of 100 m $\times$ 100 m to make study area-wide predictions. For prediction purposes, these raster cells were treated in the same manner as the land tenure parcels. Geospatial data were analyzed using QGIS 3.42 (QGIS Development Team 2025) and R 4.4.3 (R Core Team 2025).

4.2.6 Modeling and model evaluation

When evaluating a prediction model, it is possible to restrict oneself to an internal evaluation, using procedures such as cross-validation to extract as much information as possible from a limited data set. However, to determine whether a prediction model can generalize to new and different situations, a form of external validation is necessary (Ramspek et al. 2021). The dataset used to train a model may be biased; in our case, for example, it consists of owner-provided forest parcels. To address this issue, we employed a random sampling process to identify new, unseen forest parcels that may differ structurally from the training dataset. During external evaluation, we tested the model's predictions on these new parcels against independently surveyed ground truth. This allowed us to better understand the model's ability to generalize to new cases. Although costly, an external evaluation can greatly benefit the selection of a prediction model. It can assess generalizability to new data and detect overfitting, thus supporting the model's robustness and increasing trust in its predictions (Bowman and Robitaille 2005; Pearce and Ferrier 2000).

After completing the first field campaign to survey forest structural variables in the d_{train} dataset, we calculated PICA values (see Section 4.2.4) and topographic variables (see Section 4.2.5) for each of the 78 parcels. A gradient boosting tree (xgbTree) model m_1 (Chen and Guestrin 2016) was trained to predict the response variable (PICA values) from the predictors (the landscape variables), using manual fine-tuning of hyperparameters to achieve the best mean absolute error (Willmott and Matsuura 2005). Internal evaluation was performed using fivefold cross-validation, repeated five times (Hastie et al. 2017; Yates et al. 2023). Model m_1 was then used to predict PICA values for all 40,282 known private forest parcels of ≤ 4 ha size in the study area (Hansen et al. 2026). This threshold was chosen to avoid extrapolating beyond the parcel sizes in the training set d_{train}, which ranged from 0.142 ha to 3.805 ha. A stratified random sample of size 48 was taken from all these small-scale private forest parcels by randomly selecting 12 parcels from each predicted PICA quartile. This sampling method aimed to capture the PICA range in the study area, as opposed to random sampling, and differed from the sampling method used for d_{train}, thus providing a suitable foundation for the external evaluation (Ramspek et al. 2021). The 48 new parcels were surveyed on-site during our second field campaign, using the same methodology that was used before (see Section 4.2.3). PICA values were calculated from the components. The resulting data constituted the d_{test} dataset, which was used for the external evaluation of model m_1 (Fig. 4.1). In order to perform predictions using as much information as possible from the available data, a second gradient boosting tree model, m_2, was parameterized using the union of the d_{train} and d_{test} datasets (i.e. 126 small-scale private forest parcels), again employing repeated fivefold cross-validation. Hyperparameters were carried over from m_1 to prevent overfitting to the data. We expected m_2 to perform as well as model m_1 and to make better use of the available data. Our decision to use gradient boosting tree models was supported by several factors. We encountered nonlinearities in the responses early on, as seen in the slope response in Fig. 4.3. Like random forest models, gradient boosting tree models allow for high interpretability, for example by providing variable importance measures. Additionally, machine learning algorithms such as XGBoost are top performers for predicting tabular data (Grinsztajn et al. 2022; Januschowski et al. 2022). These algorithms can handle missing values, which could be important in situations involving incomplete surveys or missing landscape data.

A map showing all small-scale private forest parcels in the study area could not be released for licensing reasons. This prevented the use of parcel size as a predictor. Therefore, we assessed variable importance in model m_2 and used it to perform a rastered (100 m $\times$ 100 m) prediction of PICA values for all 38,085 raster cells in the study area containing known small-scale private forest parcels (Hansen et al. 2026).

4.3 Results

4.3.1 First field campaign: dataset d_{train}

The broadleaf living volumes on the 78 d_{train} parcels ranged from 0 to 877 $m^3\,ha^{-1}$ (see Table 4.1), with an average of 210 $m^3\,ha^{-1}$ (SD = 228 $m^3\,ha^{-1}$). Very large living broadleaf volumes were rare in the dataset, with 75% of the parcels having values below 350 $m^3\,ha^{-1}$. Broadleaf deadwood volumes (from natural and anthropogenic origins combined) also varied greatly, ranging from 0 to 124 $m^3\,ha^{-1}$. However, the average of 11.2 $m^3\,ha^{-1}$ (SD = 21.9 $m^3\,ha^{-1}$) was rather low, and was surpassed by only around 25% of parcels. Forest management intensity was captured by the ForMI index. Management intensities were distributed approximately uniformly in our dataset. The biotope types we encountered scored between six and 23 biotope value points, with an average of 14.3. The lowest values were assigned to young plantations of non-native tree species, such as Douglas fir, while the highest values were given to old oak and beech stands. Sampling of large-diameter trees took place throughout each small-scale private forest parcel. While such trees were absent or rare on most parcels (none were found on around a third of all parcels), 10% of the parcels had more than 50 trees per hectare with a diameter of at least 50 cm. In general, larger parcels tended to have slightly fewer large trees per hectare, but the effect size was small (Spearman's $\rho = -0.179$). PICA values were calculated from these numbers for the d_{train} dataset. These values were distributed uniformly between 0.078 and 0.905, with a mean and median of 0.436. The five landscape-related predictors were calculated from freely accessible sources (see Section 4.2.5). PICA values plotted against these predictors are shown in Fig. 4.3 (blue data points and curves, see also Section 4.3.3 for a closer characterization).

4.3.2 The first model m_1

Before training the model that will predict PICA values, we checked the landscape-related predictors (*slope*, *broadleaf*, *distance to road*, *openland 200 m*, *openland 2 km*) for multicollinearity by computing variance inflation factors (VIF). VIF values were very moderate, with a maximum of 1.49. Spearman correlation between the predictors was also low, with a maximum absolute value of 0.384 (see Table 4.3). The predictors were considered sufficiently unrelated and were all included in the subsequent analyses. Model m_1 was trained for lowest mean absolute error (MAE) using the d_{train} data. Some hyperparameters of the xgbTree model were manually tuned for low MAE: The maximum tree depth (*max_depth*) was set to three. The minimum sum of instance weight needed in a child node for a split (*min_child_weight*) was left at one, the default. The learning rate (*eta*) was set to 0.03. The minimum loss reduction (*gamma*) was set to zero. The subsample ratio of columns (*colsample_bytree*) was set to one. The subsample ratio of the training instances (*subsample*) was set to 0.8. The number of boosting rounds (*nrounds*) was set to 100.

PICA values in the dataset showed a standard deviation of 0.226, while the model achieved an MAE of 0.093 (root mean square error (RMSE) of 0.114), which represented 41.2% of the outcome standard deviation. The model's R^2 was 0.857, see the "training" results in Figure 4.4. It is worth noting here that this high performance is due to the fact that model m_1 was asked to predict data that it was trained on. Regarding the variable importance (*vi*, a numerical value between 0 = lowest and 100 = highest importance) of the predictors, we found that model m_1 favored the *broadleaf* predictor the most (*vi* = 100). *Distance to road* (*vi* = 79), *slope* (*vi* = 60), and *openland 200 m* (*vi* = 44) were also important predictors, whereas *openland 2 km* (*vi* = 0) did not contribute to the model's predictions. Model m_1 was used to predict preliminary PICA values for 40,282 small-scale private forest parcels in the study area.

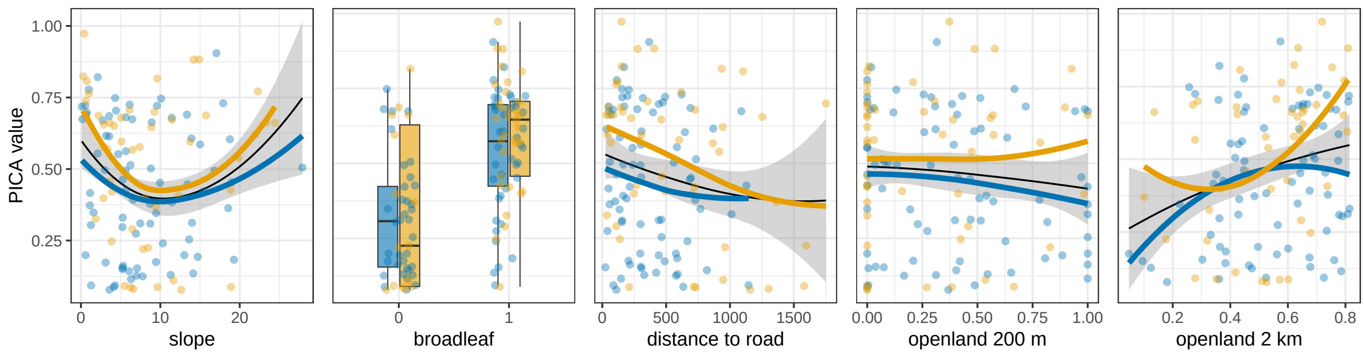

Figure 4.3: Scatter plots of the PICA values of datasets d_{train} (blue) and d_{test} (orange) against each of the five predictors. For the binary predictor *broadleaf*, boxplots are shown. For the other predictors, smoothing curves (LOESS) are given for d_{train} and d_{test}, while the black curve represents the response for the combined dataset of $d_{\text{train}} \cup d_{\text{test}}$. Confidence intervals (95%) are shown for the latter

4.3.3 Second field campaign: dataset d_{test}, PICA values and predictors

The 48 small-scale private forest parcels in the d_{test} dataset showed slightly higher amounts of living broadleaf volume, with mean and median values of 247 m^3 ha^{-1} and 230 m^3 ha^{-1}, respectively (see Table 4.1). The overall range (0 to 853 m^3 ha^{-1}) was comparable to the d_{train} dataset. Broadleaf deadwood was significantly more prevalent (Wilcoxon rank sum test, $p = 0.042$), with an average of 23.3 m^3 ha^{-1}, ranging from 0 to 175 m^3 ha^{-1}. Forest management intensity in the d_{test} dataset was slightly lower, averaging 0.382. The biotope values encountered on the new parcels were slightly higher than those in the training set, ranging from 9 to 23 and averaging 15.3. The density of large-diameter trees on the d_{test} parcels was slightly higher, with an average of 30.9 ha^{-1}. PICA values calculated from these components were slightly higher on average (0.520), though not significantly different from the d_{train} dataset (Wilcoxon $p = 0.090$, bootstrapped $(p_1 - p_2)$ PICA mean difference of -0.085 with 95% percentile confidence interval of -0.172 to 0.001, using 5000 replicates). The new data points appear in orange in Fig. 4.3, along with their accompanying smoothing curves. Black curves indicate a fit for the union of datasets d_{train} and d_{test} ($d_{\text{train}} \cup d_{\text{test}}$) and are equipped with 95% confidence bands. For both d_{train} and d_{test}, lying in a broadleaf forest was clearly associated with higher PICA values. *Slope* and *distance to road* showed tighter bands for smaller predictor values, as did *openland 200 m*. *Slope* showed hump-shaped curves for both datasets. Higher PICA values were observed on parcels with low or high slopes and lower PICA values for intermediate slopes. *Distance to road* exhibited a negative influence on PICA values, which was more pronounced in dataset d_{test}. *openland 200 m* exhibited a slightly negative influence; however, large *openland 200 m* values showed an anomaly in the d_{test} dataset. LOESS regression for *openland 2 km* was inconclusive, showing opposite directional hump-shaped curves between the datasets. Though the relation of PICA values and *openland 2 km* was overall positive, it showed looser confidence bands. This was also the only case in which the d_{train} and d_{test} data (blue and orange curves) differed considerably.

Table 4.3: Spearman correlation matrix of predictors

		Slope	**Broadleaf**	**Distance to road**	**Openland 200 m**
d_{train}	Slope	1.000			
	Broadleaf	−0.023	1.000		
	Distance to road	0.033	−0.103	1.000	
	Openland 200 m	0.219	−0.323	−0.014	1.000
	Openland 2 km	−0.013	0.112	0.028	0.348
$d_{\text{train}} \cup d_{\text{test}}$	Slope	1.000			
	Broadleaf	−0.088	1.000		
	Distance to road	0.066	−0.150	1.000	
	Openland 200 m	0.163	−0.291	−0.164	1.000
	Openland 2 km	−0.030	0.135	−0.151	0.388

4.3.4 Model evaluation

The most important test for our model was the external evaluation (Ramspek et al. 2021), in which we compared the predicted PICA values for the new parcel set, d_{test}, with the actual PICA values calculated from the field-measured component variables. The result is shown visually in the calibration plot in Fig. 4.4. In this plot, the actually measured PICA values are plotted against the PICA values predicted by model m_1. The blue data points correspond to parcels in the d_{train} dataset. Since these parcels were used to train the model, the blue data points scatter closely around the dashed line representing perfect predictions. Accordingly, the model achieved a low mean absolute error and a high R^2 value on the training data. The predictions for the test dataset d_{test} (orange data points) deviated more from the dashed line than in the case of d_{train}, resulting in a higher mean absolute error of 0.159 during external evaluation (with a root mean squared error of 0.188). This was still 36.4% below the standard deviation (0.250) of the actual field-measured PICA values in d_{test}. The R^2 value was 0.427, indicating an adequate fit of model m_1 to the test dataset d_{test}. The model generalizes relatively well, while overfitting some training patterns. The prediction errors are substantially smaller than the PICA standard deviation for both models; therefore, the predictions are informative, even though their absolute values carry uncertainty. Retraining model m_2 on the full dataset did not change the model errors. However, some of the variability in the data (visible in Fig. 4.3) remains unexplained by the model.

4.3.5 Updated model m_2 and predictions for the study area

To make predictions for the small-scale private forest parcels within the study area, we retrained a second gradient boosting tree model, m_2, using the union ($d_{train} \cup d_{test}$) of the datasets d_{train} and d_{test} to predict PICA values from the landscape-related predictor variables. We carried over the hyperparameter tuning that was optimized in model m_1. Regarding the variable importance (*vi*) of the predictors, we found that, similarly to model m_1, model m_2 favored the predictor *broadleaf* the most (*vi* = 100). *Distance to road* (*vi* = 68), *slope* (*vi* = 62), and *openland 200 m* (*vi* = 47) were also important predictors. *Openland 2 km* (*vi* = 0) did not contribute to the predictions. PICA values in $d_{train} \cup d_{test}$ showed a standard deviation of 0.238. The MAE of model m_2 was 0.099, with an RMSE of 0.121. This represented 41.6% of the outcome standard deviation. The R^2 value was 0.740. Note that this denotes a good model fit to the training data.

Since model m_2 was trained on a larger dataset ($d_{train} \cup d_{test}$) than model m_1, it was preferred for making final predictions of PICA values for all small-scale private forest parcels in the study area. We used model m_2 to calculate PICA value predictions for all small-scale private forest raster cells (100 m $\times$ 100 m) in the study area (Hansen et al. 2026). In total, we identified 38,085 small-scale private forest cells, amounting to 9.6% of the total forested area (ML 2024). Predicted PICA values ranged from 0.170 to 0.774, with an average of 0.460 (SD = 0.140) and a median of 0.501. Ninety-five percent of the cells scored lower than 0.675.

The top five percent of parcels with the highest PICA values are highlighted in Fig. 4.5. These top PICA raster cells appeared to be rare in large, contiguous forested areas. To determine if this difference was significant, we calculated the area of the surrounding contiguous forest polygon

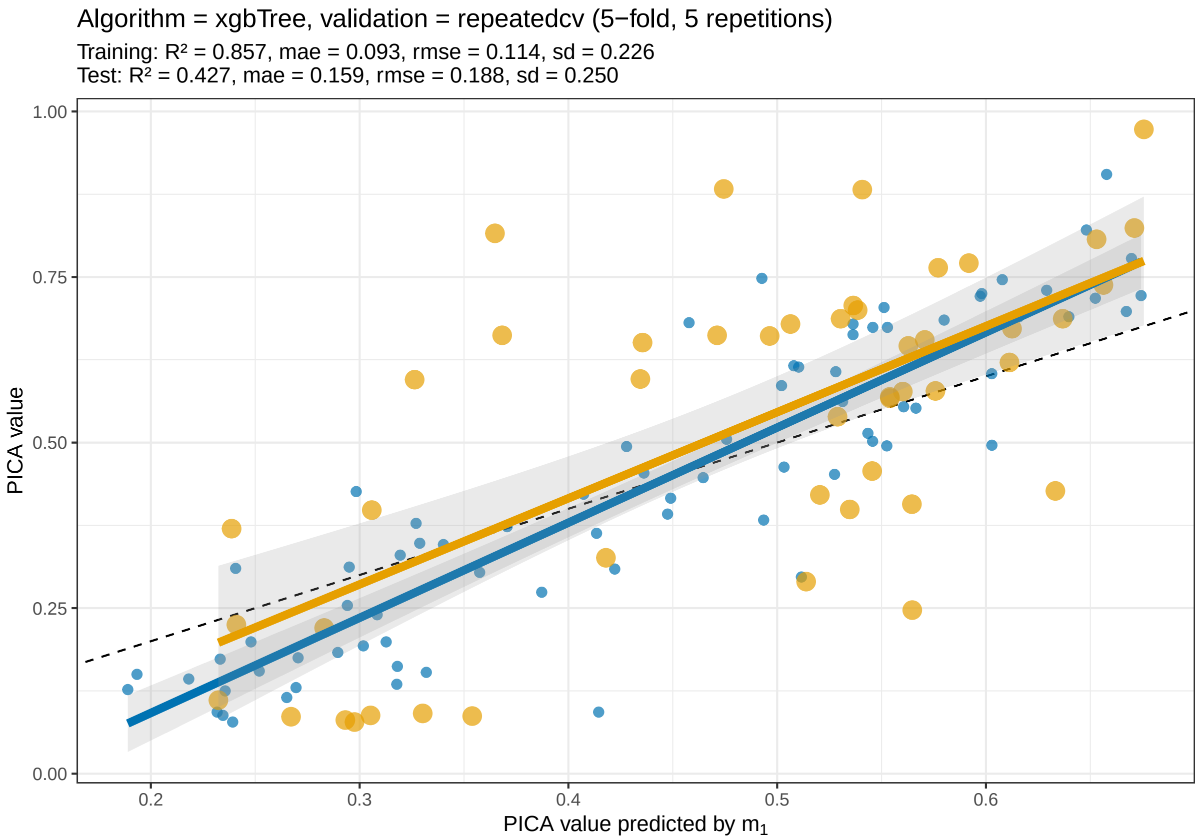

Figure 4.4: Calibration plot for model m_1. Shown are predictions for the training dataset d_{train} (small blue data points, blue regression line), and the result of the external evaluation with the test dataset d_{test} (big orange data points, orange regression line). The dashed line indicates a perfect fit. Confidence intervals are 95%

(OpenStreetMap contributors 2022b) for each raster cell centroid. The mean contiguous forest area around the raster cells with in the top 5% (PICA values larger than 0.675) was 272 ha (SD = 534 ha), with a median area of 84.9 ha. For the remaining 95% of raster cells, the mean contiguous forest area around the cells was 1223 ha (SD = 1979 ha), with a median area of 342 ha. The difference of the means was -951 ha. A Wilcoxon rank sum test confirmed that the top 5% PICA raster cells were significantly different from the remaining 95% of the small-scale private forest raster cells ($p < 0.0001$) when the size of the surrounding contiguous forest area was considered. Given the large number of raster cells, we quantified the effect size of the observed difference using bootstrapped (5000 replicates) 95% confidence intervals for the means. The interval for the mean surrounding forest area of the top 5% raster cells was [248 to 297 ha]. For the remaining 95% of raster cells, it was [1203 to 1243 ha], and [-982 to -920 ha] for the difference of the means.

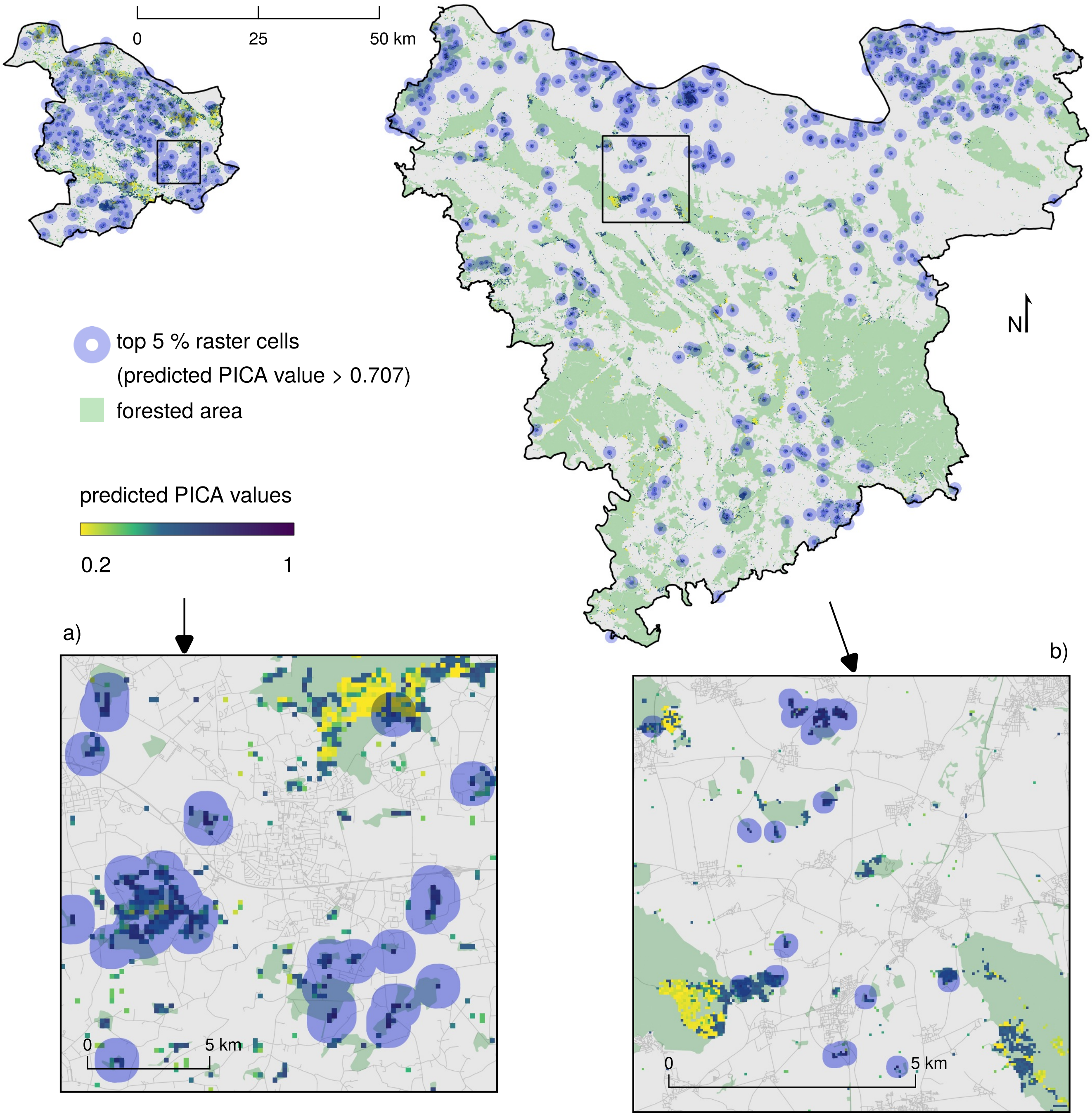

Figure 4.5: Map of the Lower Saxon Hills region showing forest cover in green and PICA values as predicted by model m_2, raster cell size is 100 m $\times$ 100 m. The positions of the top 5% of raster cells with the highest PICA values are highlighted with a blue circle. Detail maps a) and b) enlarge example regions and illustrate rastered PICA predictions

4.4 Discussion

Old-growth structures are vital habitats for a multitude of rare forest species. Their protection often hinges on the availability of precise geographical data, which is lacking in small-scale private forests due to the low organization and difficult reachability of forest owners. Our research was guided by the aims of *(1)* developing an index that represents old-growth structure abundance on small-scale forest parcels; *(2)* investigating the effects of known predictors of such structures on the index; and *(3)* compiling a model that is able to predict stand-specific index values throughout the study area. We proposed a multi-component *Parcel Index of Conservation Attributes*, PICA, that captured main old-growth structures on the land parcel level. Variables that were known to have an influence on these structures, such as slope, broadleaf status, distance to road, and the vicinity of open land, were shown to be valid predictors of PICA index values.

4.4.1 On the response of PICA values to predictor variables

We identified multiple informative relationships between five predictors—*slope*, *broadleaf* (0/1 value given by the CORINE broadleaf status of the parcel), *distance to road*, *openland 200 m* (percentage of open land in a 200 m vicinity of the parcel), *openland 2 km* (dito, for the 2 km vicinity)—and the PICA index value of a parcel.

The slope predictor showed a peculiar hump-shaped influence on PICA values, with medium slopes corresponding to low PICA values, while high and low slopes corresponded to high PICA values. In hilly, densely populated areas, such as the study area in Lower Saxony, larger managed forest areas are often confined to medium-sloped hillsides (Mann et al. 2023). Very steep terrain is not ideally suited for profitable timber production and is often neglected as a result (Bujoczek et al. 2021; Engel 2019). Consequently, small-scale private forest parcels on very steep terrain almost certainly experience a lack of management: Trees can grow to high ages surpassing common harvest maturity and develop high diameters and wood volumes, which increases the PICA components of living broadleaf volume and density of large-diameter trees. Deadwood is often left on these inaccessible parcels due to deficient infrastructure, which directly increases the deadwood PICA component. Conversely, flat terrain often has fertile soil that is used for agriculture. In such landscapes, forest areas often have an insular character and, if managed at all (Engel 2019), are dedicated to producing valuable hardwoods, such as oak, using a long-term selection cutting system, featuring high-diameter broadleaf trees. Forests influenced by groundwater or perched water with azonal natural vegetation such as oaks, hornbeam, and alders, are also confined to flat areas and provide habitats for rare and specialized forest species (Drachenfels 2021). In addition to high wood volumes and diameters, both forest types are recognized as highly valuable in BKompV (2020) and receive high biotope values that further increase PICA values. We found that broadleaf sites (according to the CORINE dataset, Copernicus Land Monitoring Service (2018)) strongly influenced the PICA values, which was to be expected, since two of the index's components (broadleaf living and deadwood volume) depend on broadleaf trees. These findings together suggest that low PICA values correspond to large, conventionally managed regions of conifer forests. This is also supported by the behavior of the distance to road curve (Fig. 4.3). In the study area, higher distances to the next paved road are almost exclusively found in larger hill ranges (OpenStreetMap contributors 2022a), whereas the remaining areas are more densely populated and have a denser road network. Land cover data asserts that these hills are predominantly stocked with conifer species, thus the effects of greater distance from roads and low broadleaf coverage reinforce each other and negatively influence PICA values in these areas.

4.4.2 Old-growth forest structures in mixed cultural landscapes

We found that old-growth structures of high nature conservation value were disproportionately common in isolated and remnant private forest patches within mixed-use landscapes, rather than in parcels embedded within large closed forest areas. Using the surrounding contiguous forest area as our metric, the top 5% of parcels in terms of conservation value (i.e., those with the highest PICA values) occurred, on average, in contiguous forests of barely 300 ha, whereas this metric for the remaining 95% was over 1200 ha. This pattern suggests that small remnant forest patches in a heterogeneous landscape matrix often retain or accumulate old-growth structural features (see Fig. 4.5). Previous research has highlighted the significant conservation value of insular “oases” of old, structure-rich forest patches within agricultural landscapes (Orłowski and Nowak 2007).

While forest interiors typically host a higher proportion of forest specialists (Hofmeister et al. 2016; Wulf and Kolk 2014) and provide more effective heatwave buffering, forest edges exhibit higher total species richness, greater biomass of large-diameter stemwood, more tree-related microhabitats, and higher levels of tree regeneration (Bobiec et al. 2018; Orłowski and Nowak 2007). Therefore, the conservation value of remnant forest patches under private ownership depends heavily on the size, shape, and landscape context of the patches. Maintaining old-growth forest structures in small, highly edge-dominated patches is essential for conserving forest specialist taxa, whereas these patches may also increase overall richness through generalists. Both the interiors and edges of these patches contribute complementary ecosystem services (see Fig. 4.6).

Despite providing essential ecosystem services (Decocq et al. 2016), small forest patches in mixed landscapes often receive little attention from conservation stakeholders (Valdés et al. 2020). Currently, they have no strict conservation status, which makes them vulnerable to the owners' will (Stolz and Riedel 2018). Due to their small size, these forest patches are additionally often considered less important for specialized species (Varela et al. 2018). However, research has shown that they can provide varied habitat conditions that benefit forest specialist species, especially when the parcels are ancient woodlands (Buse 2012; Wulf and Kolk 2014). Mature forest patches serve as vital habitats for forest species and should be prioritized in conservation planning (Buse 2012; Russo et al. 2023; Stolz and Riedel 2018; Valdés et al. 2015; Wulf and Kolk 2014).

4.4.3 Assessment of the model framework and research desiderata

The proposed index PICA, its components, and the predictors we analyzed should be regarded as a flexible framework, open to adaption based on local conditions, data availability, and funding for fieldwork. The described model is calibrated to our datasets, which include low altitude ranges, very small parcel sizes, and a limited set of tree species assemblages. We recommend recalibrating it using a local dataset before deploying it in markedly different regions. In the same spirit, it might be beneficial to adjust the saturation functions that map PICA components to the valid range. They relied on choosing an individual parameter, *h*, for each component to define the threshold at which the saturation function reaches 0.5. The selected *h* values reflected the average values in our survey results and similar thresholds in German nature conservation legislation (see Table 4.2). These thresholds can be modified when transferring the methodology to other regions.

There is strong and ongoing evidence of the correlation between old-growth structures and the occurrence of forest species of particular conservation concern (Storch et al. 2023; Wagenaar et al. 2025; Zeller et al. 2023; Zumr et al. 2023). However, comparing actual and predicted PICA values with specific biodiversity data could further strengthen this connection. Special structures with significant conservation value, such as remnants of former coppice management or forest bogs (Leuschner and Ellenberg 2017), are outside the scope of PICA. Focusing on individual old-growth forest species or groups would require defining specialized indices to capture these species' partic-

Figure 4.6: (a) Borders between forest and agricultural land tend to be clearly defined, with boundary trees of insular forest patches often exempt from wood harvesting. (b) Such boundary trees are prone to developing a multitude of microhabitats. (c) A lack of awareness of valuable structures in private forests can lead to increased logging if the market situation changes. (d) A future-proof protection of old-growth habitats is an ongoing task. Effort to conserve old-growth structures like large-diameter trees at the border as well as in the interior of forest parcels need to be supplemented with measures to ensure the replenishment of old-growth structures

ular habitat preferences (Lachat and Bütler 2009). If a dependency on landscape variables could be established, then extrapolation to the landscape scale would also be possible in these cases.

It could be beneficial to include additional possible predictors of old-growth structures and to examine their impact. Possible candidates include parcel size, stand age, time since the last harvest (if available), soil characteristics, protection status, as well as the variable area of surrounding contiguous forest as developed in Section 4.3.5. On the other hand, it might be possible to reduce the number of open land variables by identifying a single variable that can still explain enough variance in the input data.

Concerning the performance of the models, the calibration plot (Fig. 4.4) shows a slight overestimation of low PICA values and a similarly slight underestimation of high PICA values. This regression toward the mean could result from limited sample coverage at the extremes, or from the fact that the index consists of five different components describing partially disparate aspects of the land parcel. Stratified sampling, as was done for the test data set d_{test}, is advisable for the analysis of future forest parcel pools. Because the forest parcels in our sample were often very small, we sampled only a limited number of plots per parcel. To reduce potential sampling bias, we drew from a relatively large and diverse set of small-scale private forest stands. Nevertheless, predictive performance deteriorates near the extremes of the predictor ranges. For instance, our data has limited representation of very high slope or very large distance to road values. Predictions at the extremes should be treated with caution and validated in the field.

Small forest parcels of high conservation value are heavily influenced by edge effects. Although the negative effects of fragmentation on biodiversity are often overreported (Riva et al. 2024), these effects may actually reflect an influx of generalist species rather than the persistence of old-growth forest specialists (Vanneste et al. 2024). Further, focused research could provide insights into the roles of edges and interiors of small, isolated forest patches, and could further improve predictive modeling.

4.4.4 Practical relevance for conservation management and decision makers

Rare and endangered forest biodiversity depends on structures characteristic of old-growth forests that are scarce in today's production forests. Small remnants of ancient woodlands persist in mixed landscapes, but are often overlooked and underprotected. There is an urgent need to protect such parcels (Valdés et al. 2020), as they provide vital habitat for a multitude of species of conservation concern (Proesmans et al. 2019; Winiger et al. 2023), and can function as biodiversity refugia and stepping stones in an unfavorable background matrix (Buse 2012; Liira and Paal 2013). We have shown that old-growth forest structures can be predicted using freely available landscape data, thus demonstrating a roadmap to minimize the costs and efforts associated with biodiversity surveys and extensive forest structural surveys. We propose conducting low-intensity fieldwork to record forest structures at selected sites and using modeling techniques to gain insights into the landscape-wide distribution of forest parcels of high conservation value. Our findings on the spatial distribution of valuable small forest patches in mixed cultural landscapes align with those of previous studies (Decocq et al. 2016; Proesmans et al. 2019; Valdés et al. 2020). Creating a prediction map of conservation values for a given region allows decision-makers to design targeted actions to ensure the retention and continuous provision of old-growth structures in small, private forests. Recent market incentives and policy decisions support higher management intensities (Eriksson et al. 2024; Lerink et al. 2023), even in small-scale private forests that were shielded from intensive management in the past due to owner inactivity. However, this poses a substantial risk to vulnerable structures of conservation concern that are harder to find in professionally managed forests. Cautious management or even refraining from forest management allows old-growth structures to develop and persist (Larrieu et al. 2026) and is essential for safeguarding rare and endangered forest species.

4.5 Conclusion

Many forest species of high conservation concern depend on special structures related to the old-growth character of forest stands. These structures thrive under low management intensity and are rarely found in intensively managed production forests, except when actively promoted. We developed the *Parcel Index of Conservation Attributes* (PICA) as a tool that allows for a precise quantification of the abundance of old-growth structures in temperate small-scale private forests. Based on findings that the structures captured by this index are influenced by the topography of forest parcels, we developed a model that predicts PICA values on the landscape scale using freely available landscape data. We used a comprehensive model using field data to calculate predictions in the form of a map, highlighting the spatial distribution of valuable old-growth structures in the small-scale private forests of our study area. Landscape planners and decision makers are encouraged to use this tool to pinpoint target areas for conservation efforts in the future. A distribution analysis revealed that the forest stands of highest conservation concern are situated outside larger forested areas, underscoring the importance of forest remnants in agricultural landscapes. These small forest oases have been shown to provide a multitude of ecosystem services at a high intensity per area, to secure carbon retention, and to serve as retreats and stepping stones for forest biodiversity. The continuous conservation and interlinkage of these forest patches should be a high priority for decision makers, and our model can support them by providing reliable spatial information about the location of parcels of high conservation value.

4.6 Appendix

4.6.1 Closing statements

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Authors' contributions P.H.: writing—original draft, visualization, methodology, formal analysis, conceptualization. M.T: writing—review and editing, investigation. T.P.: writing—review and editing, investigation, funding acquisition. A.M.: writing—review and editing, investigation, funding acquisition.

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Data availability All research data used in the scope of this article, as well as the prediction of PICA values across the entire study area, is available at Zenodo (Hansen et al. 2026). DEM data for Lower Saxony are publicly available (GeoBasis-DE/LGLN 2025). A road network was extracted from OpenStreetMap (OpenStreetMap contributors 2022b). Forest type and open land status were taken from CORINE data (Copernicus Land Monitoring Service 2018). We used the following non-free data sources: Cadastral data were provided by NW-FVA, Göttingen, Germany. Data on forest ownership in Lower Saxony were provided by the Chamber of Agriculture in Lower Saxony (LWK). Restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of NW-FVA and LWK, respectively.

Competing interests The authors declare no competing interests.

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Chapter 5

Synthesis

This chapter compiles the results I presented in the previous three chapters, and uses them to illuminate the nature of important interconnections between multiple relevant concepts in the context of small-scale private forests (SPFs). A high-level view of the contributions is provided in Section 5.1. I revisit and compare the hypotheses formulated in Chapter 1 to our results, and use them to focus on valuable forest structures found in SPFs (Section 5.2), on the situation of SPF owners caring for vulnerable ecosystems on a daily basis (Section 5.3), and on the importance of small forest patches for nature conservation (Section 5.4).

5.1 A bird's-eye view on the contributions of this thesis

In Chapter 1, SPFs were presented as a vast field of research with many associated concepts that are tightly interconnected (Figure 1.1). The overarching goal of this thesis is to illustrate some important connections in more detail. I assumed that, for a subgraph of Figure 1.1, the character of these connections could be understood and examined as unidirectional influences rather than as reciprocal interdependencies. For example, I interpreted forest structures as dependent on landscape topography, and not vice versa. This approach enabled me to apply machine learning algorithms capable of searching for influence signals in large, noisy datasets. The subgraph I considered in this work is presented in Figure 5.1. From a practical point of view, I sorted relevant information on SPFs according to the cost (time and resources) of collecting the associate data. While ecologists and environmentalists are most interested in biodiversity data on SPFs, such data, especially when encompassing many different taxon groups, relies on expensive biodiversity monitoring campaigns. Therefore, forest structural data that is more readily available, such as tree-related microhabitats (TreMs) and deadwood quantities, are often used as proxies for biodiversity.

Based on the results of this thesis, I can extend the proxying approach to even more lightweight initial data. In Chapter 2, we presumed an influence of owner goals and attitudes on actual forest structures. Such data can be gathered by surveying the forest owners. While accessing a heterogeneous and weakly organized group, such as SPF owners, can be challenging, leveraging landowner contacts through mass mail questionnaires requires considerably fewer resources than fieldwork in their forests. Data analysis revealed strong additional influences from parcel and landscape topography. Ultimately, it led to the identification of two types of forest structures in SPFs: slowly evolving old-growth structures, such as TreMs, and fast evolving structures, such as deadwood.

The idea of leveraging more lightweight data was also pursued in Chapter 3, where owner management goals and activities were examined for influences from owner sociodemographics, and parcel and landscape topography. The latter two are more easily procurable, sociodemographic data on the forest owners may already be held by relevant institutions. Regarding landscape-related data, we limited our use to free, publicly available geodata, and demonstrated their usefulness by highlighting various influences on more expensive data.

One influence we found was the strong dependence of old-growth structures on parcel and landscape topography. We assumed this influence was strong enough to justify establishing a mathematical prediction model. In Chapter 4, we demonstrate the validity of this approach, providing nature conservation planners with an inexpensive, precise tool to identify regional hotspots of old-growth structures in SPFs with high reliability, using only a small sample of forest survey data.

5.2 Forest structures of high conservation value

My research on forest structures in SPFs was guided by the first hypothesis presented in the introduction (see Section 1.5), where I assumed that the current owner of a forest parcel could change existing structures on their land according to their goals by utilizing management activities of their choice. However, during my research, I was reminded that parcel and landscape topography play major roles, especially when predicting old-growth structures.

Rare species typically benefit from the high structural variability found in SPFs. The varied history and structures of these forests are a valuable asset for nature conservation (Wulf and Kolk 2014). We found that the structures of high conservation value in SPFs fall into two types. We call *Type A* those structures that evolve slowly, such as living wood volume (especially of broadleaf trees) and TreMs. *Type B* structures are fast evolving, such as deadwood quantities on a parcel. Since important structures have different development durations, planners of targeted conservation efforts need to consider this. Understanding the characteristics of both types of structures is beneficial when developing conservation measures in SPFs. However, fostering slowly evolving structures can be difficult. Both deadwood and habitat-bearing trees are important structural elements (Wagenaar et al. 2025) that are in need of protection, and that can benefit greatly from targeted financial compensation for forest owners (Demant et al. 2020). Remnants of traditional management techniques, such as coppicing and coppicing with standards, have survived in SPFs, and provide valuable habitats due to their high structural diversity. Their survival hinges on active conservation measures that will also depend on incentives for forest owners.

Slowly evolving Type A structures Since the development of ecologically important TreMs occurs over very long time spans, conservation efforts should favor large-diameter trees (Kozák et al. 2023). Seeing that trees in primary forests are richer in TreMs, it is desirable to retain existing primary forests wherever they still exist, and to base conservation in secondary forests on protecting old, habitat-bearing trees (Asbeck et al. 2021). Agricultural landscapes usually lack such "champion" trees that offer superior habitat for rare specialist species (Jansone et al. 2025). The presence of champion trees in small forest parcels is the result of historical usage. Recent changes, such as the industrialization of agriculture on consolidated parcels, must be countered by conservation efforts (Orłowski and Nowak 2007). Large, habitat-bearing trees in agricultural landscapes play a pivotal role for specialized species such as bats. These trees are often overlooked in conservation programs, yet their protection should be prioritized because other habitats in open, mixed

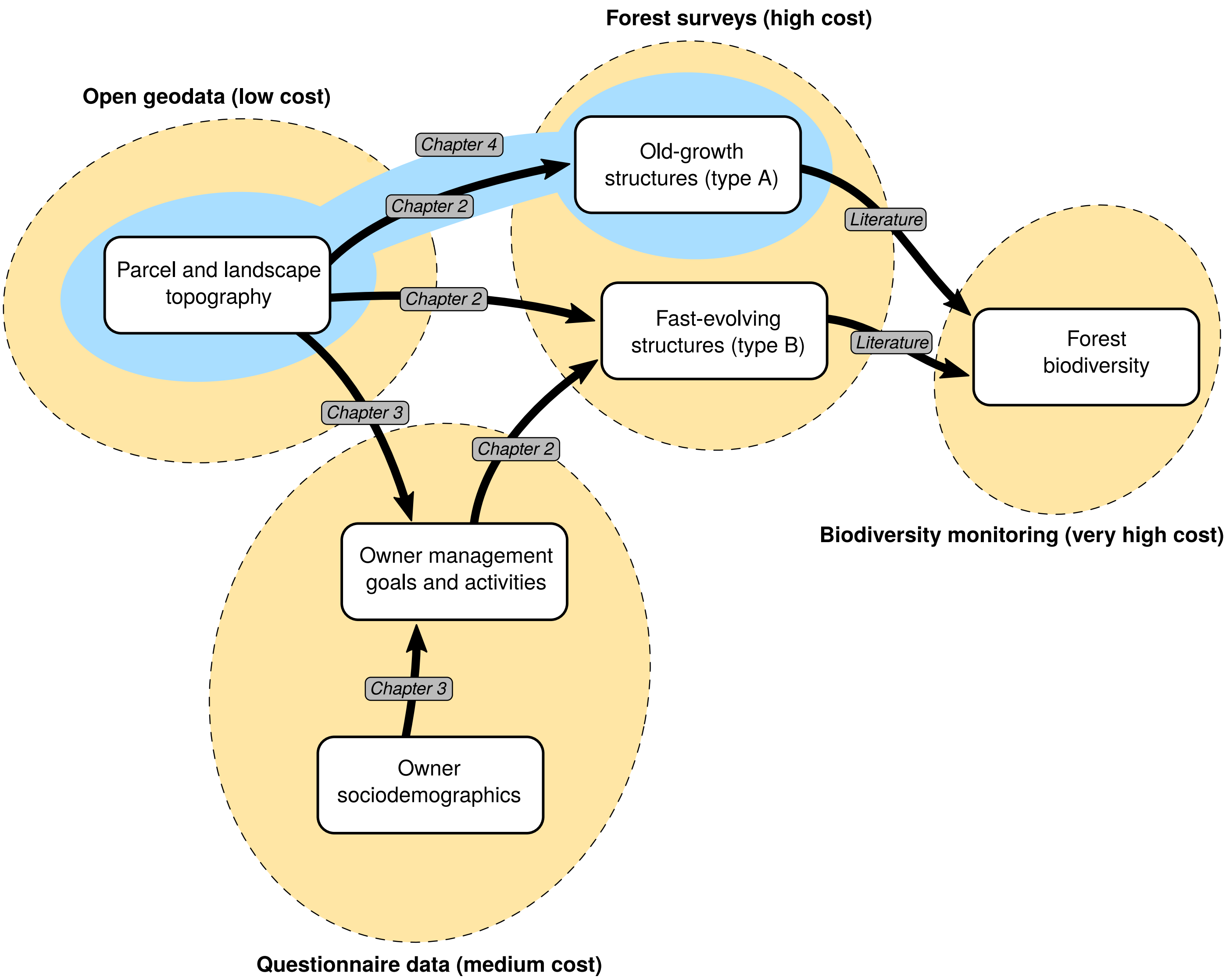

Figure 5.1: Overview of the interconnections between concepts related to small-scale private forests analyzed in this thesis, grouped by cost of data acquisition. In Chapter 2, structures in small-scale private forests are shown to fall into two types (A and B), and are influenced by topography, owner goals, and management activities. Chapter 3 investigates the influence of parcel topography and owner sociodemographics on management goals and activities. In Chapter 4, a prediction model (blue shape) shines a spotlight on old-growth structures and their drivers. The found influences allow for costly information to be proxied by less expensive data. See also Figure 1.1, and refer to Section 5.1 for more details.

landscapes cannot fulfill their function (Froidevaux et al. 2022). Although slowly evolving forest structures can be protected, their regeneration requires considerable and long-lasting commitment and greatly benefits from continuous landowner education. Designating of protection areas ensures ecological continuity, which is important for the genesis of slowly evolving structures. Valuable old-growth structures abound on broadleaf sites with a long history of careful forestry or non-use. Often, these are SPF parcels that constrain industrialized management due to their small size, steepness, or water-influenced terrain. Therefore, low-intensity management and non-use of SPFs are the preferred methods to support endangered old-growth biodiversity, and also to increase biomass levels to combat climate change.

Fast evolving Type B structures Deadwood is an essential habitat for many forest-dwelling species (Wagenaar et al. 2025). Human activities strongly and immediately affect quantities of deadwood, so their regulation should be a primary concern of forest conservation legislation (Kapusta et al. 2020). Deadwood is needed not only as a habitat, but also to balance disturbances, and mitigate climate change by storing carbon over long periods of time (Parisi et al. 2018; Chivulescu et al. 2022). Deadwood quantity is usually higher in old stands with high living volumes (Bujoczek et al. 2021). Careful forest management benefits deadwood, and nature conservation areas and difficult terrain accessibility promote it, additional to their positive effect on Type A structures. Different species of saproxylic beetles benefit from deadwood in different decay classes, and depend on forest management that generates a continuous supply (Lettenmaier et al. 2025). Deadwood also helps in the event of landslides. It increases enzyme activity and microbial biomass, helping to restore the soil (Piaszczyk et al. 2021). Since deadwood quantities depend heavily on management decisions, encouraging owners to increase their deadwood levels can be a quick and effective way to support rare and endangered deadwood-dependent species (Doerfler et al. 2017). SPF owners are rarely dependent on their forests as their only source of income (Tiebel et al. 2024). The lower economic pressure on SPF management can be leveraged to support higher amounts of deadwood and less intense management, which leads to improvements in fast evolving Type B structures. Remnants of historic forest usage forms, such as coppicing and coppicing with standards, can still be found in today's SPFs (Mölder et al. 2021), and contribute to the high structural richness of these forests. Continuing or reintroducing these practices depends on active landowner engagement (Buckley 2020), and can benefit species groups that depend on open forest structures that are rare in contemporary production forests, where clearcutting is often avoided.

When considering the impact of forest management on the carbon storage capacity of SPFs, it is important to remember that many owners primarily use their land to provide firewood for personal use. This aligns with the subsidization of using biomass for heating homes. Although wood burning is sometimes considered emission-free, it actually emits more CO_2 per kWh than coal. Furthermore, regrowth on the land that is used to supply energy wood is slow and not always guaranteed. Given the speed of climate change, we cannot afford to burn wood and wait for it to regrow (Sterman et al. 2022). We urgently need to reduce CO_2 emissions, however, research indicates that burning woody biomass increases atmospheric CO_2 levels for a long time (Norton et al. 2019).

Targeted conservation planning The greater structural diversity of SPFs compared to other ownership classes is threatened by wood mobilization initiatives. With a rising market demand for wood products, forest that are already heavily used in Europe will be subject to further management intensification. Harvest pressure patterns should be analyzed and used to regulate management (Levers et al. 2014). Increased resource use in SPFs in the future will endanger habitats that have enjoyed low-intensity management for periods of time (Eriksson et al. 2024). Since forests of other ownership types are usually already managed at high productivity rates, SPFs are becoming prime targets for wood mobilization initiatives. This poses additional risks when old-growth broadleaf stands are targeted, which are common in SPFs but not used as intensively as conifer plantations (Lerink et al. 2023). To counteract this, incentives need to target SPF landowners. This could consist of financial rewards for biodiversity conservation and ecosystem services. Additionally, SPF owners need information and consulting services related to sustainable forest management (Schaich and Plieninger 2013). High management intensities and accompanying high timber production is in conflict with the provision of other ecosystem services, such as carbon storage, biodiversity conservation, of water regulation. A variety of management strategies will be necessary to meet all requirements (Sing et al. 2018).

Decision makers should be aware of the opportunities and risks posed by the unique yet challenged nature conservation values of SPFs. To assess rare and endangered forest species, a solid body of literature supports using old-growth structures as a proxy (Storch et al. 2023; Zeller et al. 2023; Zumr et al. 2023; Wagenaar et al. 2025). Therefore, any protection effort in SPFs can benefit from precise geographic data on the distribution of valuable structures. According to our results, large-scale, expensive sampling of forest structures to identify parcels of the highest conservation value can be avoided by using modeling techniques based on smaller samples. Such models can then present areas of high conservation value in the form of a landscape-scale map, allowing to direct decision makers' attention toward neglected small forest patches, and enabling them to design targeted protection efforts.

5.3 Small-scale private forest owners

Regarding the relationship between forest owners and their land, my research was guided by the second hypothesis (see Section 1.5), which suggested that owner goals and activities are influenced by sociodemographic factors, and especially gender. Chapter 3 took an in-depth look at the various influences that govern owner actions, shedding light on the (rather marginal) influence of gender and the importance of other sociodemographic and topographic predictors of owner management. Sociodemographic shifts among SPF owners create opportunities to target new owners with more progressive attitudes toward forest management. Thus, the move away from production-oriented management can be promoted (Juutinen et al. 2020). Although the forest sector continues to appear male-dominated, other owners are forming networks to provide alternative spaces and to change the mainstream discourse (Andersson and Lidestav 2016). Female-identifying SPF owners are more likely to express their wish for assistance in their management (Berget and Dwivedi 2024). Non-male identifying SPF owner groups have great potential for unconventional management due to their greater openness to non-economic values (Hamunen et al. 2020). Overall, SPF owners are a highly heterogeneous group and would benefit most from individualized and targeted outreach.

Contrary to the prominence of gendered outreach, but in line with existing literature, our results showed that focusing on female-identifying SPF owners as a target group for specific conservation efforts may forego chances of more goal-oriented and data-driven approaches. We found a solid influence by the size of the owner's land, which is a good predictor of management activities. Targeting owners of larger parcels with conservation-encouraging efforts and guidance may thus be very effective. Intensively managed production sites with large, contiguous parcels, which are often traditionally used for conifer plantations, offer few old-growth structures. These lots can benefit greatly from transition-oriented and climate-informed counseling that also emphasizes the economic viability of such trajectories. On the downside, subsidies that uniformly reward the suspension of management for a certain number of years will produce free-rider effects in landowners who merely wait for the next harvest.

Owners of broadleaf stands, on the other hand, were already more inclined toward conservation goals concerning their forests. This owner group would benefit from further education and professional support for their position. Motivated SPF landowners are more likely to adapt low-intensity management approaches than owners of other forest types. Therefore, their education should be a prime concern of forest conservation. Education could support these owners in their decisions and guard against market-driven influences from peers and forest services. Policy instruments, such as incentives, can stabilize broadleaf forest owners in their non-production oriented management and counterbalance detrimental market influences.

Policymakers and a changing, heterogeneous forest owner group Policies and management strategies must be communicated in a way that is adapted to different owner groups (Tiebel et al. 2024; Westin et al. 2023). Policymakers should consider that SPF owners have different inclinations regarding management changes and attitudes toward climate change. Thus, a variety of policy instruments would be beneficial for approaching heterogeneous owner groups (Husa and Kosenius 2021). Policymakers may perceive SPFs as a less important ownership class, leading to measures that are inauspicious compared to the large heterogeneity among SPF owners' interests (Svensson et al. 2025). Forest owners are affected by changes that are also experienced by society as a whole. Urbanization and the shift toward information societies make owners less dependent on income from wood, and more open to non-traditional management. To achieve policy goals, these owners need to be approached in new ways (Weiss, Lawrence, Lidestav, et al. 2019). Important demographic variables among SPF owners are changing, indicating an urgent need to adopt new outreach efforts (Butler et al. 2016; Sass et al. 2023), but policymakers are not prepared to cater to new, emerging owner types (Weiss, Lawrence, Hujala, et al. 2019).

Landowners' attitudes toward conservation and need for support The willingness of SPF owners to participate in nature conservation programs depends on their perception of such efforts as legitimate and empowering. Their agreement with conservation efforts hinges less on financial arguments, but is often influenced by societal inertia (Dawson et al. 2025), and educating owners should therefore be a prime concern (Paloniemi and Vainio 2011). Owners may adopt close-to-nature forestry, but they need to be approached according to their goals and attitudes (Bieling 2004). They often already perceive regulating and cultural ecosystem services as more important than wood production, and respond increasingly well to targeted compensation programs that emphasize the protection of biodiversity (Ringier et al. 2025). However, they may be hindered by poor conservation communication (Tiebel et al. 2021). SPF owners greatly value support from policymakers, forest owner associations, the local forestry service, and scientific institutions. This support leads to a much higher likelihood of implementing management approaches that are beneficial from a conservation perspective (Fischer et al. 2019). Deadwood quantities in forests are sensitive to differences in ownership and management. Therefore, conservation efforts directed at increasing deadwood need to be specifically targeted for different owner types (Kennedy et al. 2008). The retention of deadwood and forest non-use benefit from SPF owners' perception of their positive influence on biodiversity. Owner education should complement other conservation efforts (Joa and Schraml 2020). Politics and organizations, such as forest owner associations and regional forest services, have an inadequate understanding of SPF owner motivations. Acknowledging and supporting the current paradigm shift toward urban, leisurely managing owners could benefit the implementation of conservation-oriented management approaches (Weiss, Lawrence, Hujala, et al. 2019). Even before the recent changes in SPF owner demographics and attitudes, the owners viewed their forests as more than just economic assets. Political stakeholders would be well-advised to view SPFs as places of identity, family heritage, and responsibility for nature (Joa and Schraml 2020). Voluntary conservation efforts depend on several stakeholders in SPFs. Both forest advisors and owners need to be educated about such efforts, whose effectiveness will be increased by fostering collaboration between the stakeholders (Salomaa et al. 2016).

5.4 The importance of small forest patches for nature conservation

My third hypothesis (see Section 1.5) regarded old-growth structures as being driven by landscape-related variables. The results in Chapter 4 not only support the hypothesis, but also highlight a peculiar distribution pattern: Old-growth structures abound in SPFs on isolated forest patches in mixed landscapes.

Isolated forest patches provide many ecosystem services, including timber supply, habitat for game animals, protection against wind, erosion control, local climate regulation, source of pollinators, and contribute to the water regulation and supply (Decocq et al. 2016). These insular forest patches offer refuges for forest biodiversity and provide multiple services to the adjacent landscape (Valdés et al. 2015; Varela et al. 2018). They can deliver their ecosystem services at high performance levels, yet they are often overlooked by conservation efforts (Valdés et al. 2020). With climate change, threatened species will need to migrate in order to adapt. They require a mosaic landscape with migration corridors (Pörtner et al. 2023). Mobile species can leverage the habitat extension offered by small forest patches (Winiger et al. 2023). Thus, the protection of SPFs is needed to increase the structural diversity on the landscape scale (Johann and Schaich 2016). Old-growth structures present on SPF parcels, such as broadleaf trees with cavities, provide indispensable habitat for a multitude of species such as birds and bats in an otherwise adverse agricultural landscape (Russo et al. 2023). Also, the importance of structure-rich forest edges is often overlooked in conservation planning. Forest edges provide special habitats for biodiversity, and are often equipped with exceptional tree individuals (Vanneste et al. 2024).

Protecting small, structure-rich forest patches It is easier for policymakers to realize protection efforts in landscapes of homogeneous, consolidated ownership, while mixed landscapes with agricultural use and dispersed forest parcels require special attention. Despite providing a variety of ecosystem services, small forest patches are rarely considered by conservation planners (Decocq et al. 2016). Supporting collaboration with SPF owners and nonprofit organizations that work with them is crucial (Loeb and D'Amato 2020). Information about the variety of ecosystem services that isolated forest patches provide needs to be disseminated to promote their protection (Decocq et al. 2016). The retention and care for large broadleaf trees in mixed landscapes has been motivated by their high utility in preindustrial societies. The continuity of such stands depends on the appreciation of their value, which must be thought broader than in the economic sense (Orłowski and Nowak 2007). Isolated forest patches are often centuries old. Their removal, even when substituted by newly planted forests, should be avoided at all costs because biodiversity depends on the ecological continuity of the parcel (Liira and Paal 2013). We confirmed the high conservation value of insular forest patches in a mixed landscapes. Their function as refuges and stepping stones for forest biodiversity is crucial, and protecting them should be a high priority.

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Appendix

Declaration on AI use

A preliminary translation of the Abstract into German was produced using a translation service (deepl.com). This was then proofread manually to create the final version.

The Introduction and Synthesis were checked for spelling and grammar errors using deepl.com. The same process was followed for the initial drafts of the three papers before they were submitted to the relevant journals.