Assessment of forest functionality and the effectiveness of forest management and certification

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1. Summary

Forest ecosystems are complex systems that develop inherent structures and processes relevant for their functioning and the provisioning of ecosystem services that contribute to human wellbeing. So far, forest management focused on timber production while other services were less rewarded. With increasing climate change impacts, especially regulating ecosystem services such as microclimate regulation are ever more relevant to maintain forest functions and services. A key question is how forest management supports or undermines the ecosystems' capacity to maintain those functions and services. Forest management implies silvicultural interventions such as thinning and timber harvesting and ranges from single tree extraction to large clearcuts as well as forest reserves without active forest operations and shape the character of forest ecosystems (e.g. natural versus planted forests). Artificial plantings, monocultures and management for economic timber production simplify forest structures and impair ecosystem resilience, resistance and the existence of forests but also the services essential for the prosperity and health of humanity. Efforts to reduce the negative impacts and attempts to safeguard forest functions are manifold and include compulsory national and international guidelines and regulations for forest management, conventions, but also voluntary mechanisms such as certification systems.

The main objective of this thesis was the development of a concept to assess the functionality of forests and to evaluate the effectiveness of forest ecosystem management including certification. An ecosystem-based and participatory methodology, named ECOSEFFECT, was developed. The method comprises a theoretical and an empirical plausibility analysis. It was applied to the Russian National FSC Standard in the Arkhangelsk Region of the Russian Federation – where boreal forests are exploited to meet Europe's demand for timber. In addition, the influence of forestry interventions on temperature regulation in Scots pine and European beech forests in Germany was assessed during two extreme hot and dry years in 2018 and 2019.

Microclimate regulation is a suitable proxy for forest functionality and can be applied easily to evaluate the effectiveness of forest management in safeguarding regulating forest functions relevant under climate change. Microclimate represents the most decisive factor differentiating clearcuts and primary forests. Thus, the assessment of forest microclimate regulation serves as convenient tool to illustrate forest functionality. In the boreal and temperate forests studied in the frame of this thesis, timber harvesting reduced the capacity to self-regulate forests' microclimate and thus impair a crucial part of ecosystem functionality. Changes in structural forest characteristics influenced by forest management and silviculture significantly affect microclimatic conditions and therefore forest ecosystems' vulnerability to climate change. Canopy coverage and the number of cut trees were most relevant for cooling maximum summer temperature in pine and beech forests in northern Germany. Maximum temperature measured at ground level increased by 0.21 – 0.34 K when 100 trees were cut. Opening the forest canopy by 10 % caused an increase of maximum temperature at ground-level by 0.53 K (including pine and beech stands). Relative temperature cooling capacity decreased with increasing wood harvest activities and dropped below average values when more than 656 trees per hectare (in 2018; and 867 trees in 2019) were felled. In pine stands with a canopy cover below 82 % the relative temperature buffering capacity was lower than the average. Mean maximum temperature measured

at ground-level and in 1.3 m was highest in a pine-dominated sample plots with relatively low stand volume (177 m^3 ha^{-1}) and 9 K lower in a sample plot with relatively high stock volumes of *F. sylvatica* (> 565 m^3 ha^{-1}). During the hottest day in 2019, the difference in temperature peaks was more than 13 K for pine-dominated sample plots with relatively dense (72 %) and low (46 %) canopy cover.

The Russian FSC standard has the potential to improve forest management and ecological outcomes, but there are shortcomings in the precision of targeting actual problems and ecological commitment. In theory, FSC would transform forest management practices and induce positive changes and effective outcomes by addressing 75 % of the identified contributing factors including highly relevant factors and threats including large-scale (temporary) tree cover loss, which contributes to reducing about half of the identified stresses in the ecosystem. It is theoretically plausible that FSC prevents logging in high conservation value forests and intact forest landscapes, reduces the size and number of clearcuts, and prevents hydrological changes in the landscape. However, the standard was not sufficiently explicit and compulsory to generate a strong and positive influence on the identified problems and their drivers. Moreover, spatial data revealed, that the typical regular clearcut patterns of conventional timber harvesting continue to progress into the FSC-certified boreal forests, also if declared as ‘Intact Forest Landscape’. This results in the need to verify the assumptions and postulates on the ground as it remains unclear and questionable if functions and services of boreal forests are maintained when FSC-certified clearcutting continues. On the clearcuts, maximum temperature exceeded 36 °C and stayed below 30 °C in the closed primary forest. The number of days with temperatures above 25 °C at least doubled on clearcuts. Temperature cooling capacity was reduced by up to 14 % and temperature buffering capacity up to 60 %. The main reason why FSC-certified clearcuts do not differ from conventional clearcuts is that about 97 % of trees within equally large clearcut sites of up to 50 ha were removed. The spatial design of clearcuts, their size and the intensity of clearing as well as the density of skidding trails for timber extraction was not positively influenced by FSC-certification. Annual tree cover loss was lowest in non-certified areas. This means, that FSC may even contribute to an increased biomass removal within the clearcuts, which compromises the ecosystems’ capacity to recover and maintain ecological functions and services. The analysis of satellite-based data on tree cover loss showed that clearcutting causes secondary dieback in the surrounding of the cleared area. FSC-certification does not prevent the various negative impacts of clearcutting and thus fails to safeguard ecosystem functions. The postulated success in reducing identified environmental threats and stresses, e. g. through a smaller size of clearcuts, could not be verified on site. The empirical assessment does not support the hypothesis of effective improvements in the ecosystem. In practice, FSC-certification did not contribute to change clearcutting practices sufficiently to effectively improve the ecological performance. Sustainability standards that are unable to translate principles into effective outcomes fail in meeting the intended objectives of safeguarding ecosystem functioning. Clearcuts that carry sustainability labels are ecologically problematic and ineffective for the intended purpose of ecological sustainability.

The overexploitation of provisioning services, i.e. timber extraction, diminishes the ecosystems’ capacity to maintain other services of global significance. It also impairs ecosystem functions relevant to cope with and adapt to other stresses and disturbances that are rapidly increasing under climate change.

Forest management under climate change needs to apply precautionary principles and reduce further ecological risks such as secondary dieback and deterioration of regulating services that are relevant for the functioning of forests. Forest managers have to avoid ecological disimprovements by applying strict ecological principles with effective outcomes in order to maintain functional forests that regulate their own microclimate also as a basis for sustainable economic benefits.

2. Zusammenfassung

Wälder sind komplexe Ökosysteme, die mit zunehmendem Wachstum und Entwicklung diverse inhärente Strukturen und Prozesse ausprägen, die für ihre Funktionstüchtigkeit und die Bereitstellung von Ökosystemleistungen relevant sind und auch zum menschlichen Wohlergehen beitragen. Bislang war die Waldbewirtschaftung hauptsächlich auf die Maximierung der Holzproduktion ausgerichtet, wobei andere ökosystemare Leistungen weniger honoriert wurden. Mit zunehmendem Klimawandel werden insbesondere regulierende Ökosystemleistungen, wie z. B. die Regulation des Mikroklimas immer relevanter, um die Funktionen und Leistungen des Waldes dauerhaft zu gewährleisten. Eine zentrale Frage dabei ist, wie Waldbewirtschaftung die Fähigkeit der Ökosysteme diese Funktionen und Leistungen aufrecht zu erhalten, unterstützt oder untergräbt. Das Management von Wäldern umfasst waldbauliche Eingriffe wie Durchforstung, Auflichtung und Holzernte und reicht von der Entnahme einzelner Bäume bis hin zu mehr oder weniger großen Kahlschlägen, bedeutet aber auch Waldreservate ohne aktive Waldbewirtschaftung. Die Waldbewirtschaftung, aber auch die Art der Bestandesbegründung beeinflusst die Strukturen und damit die Eigenschaften von Waldökosystemen. Künstliche Anpflanzungen, Monokulturen und waldbauliche Bewirtschaftung simplifizieren die Waldstrukturen und beeinträchtigen damit die Resistenz, Resilienz und Existenz von Wäldern, aber auch die Bereitstellung der für die Menschheit überlebenswichtigen Ökosystemleistungen. Bemühungen, die negativen Auswirkungen zu reduzieren und die Waldfunktionen längerfristig zu sichern, sind vielfältiger Natur und umfassen verbindliche nationale und internationale Richtlinien sowie Regelwerke zur Waldbewirtschaftung, Konventionen, aber auch freiwillige Mechanismen wie Zertifizierungssysteme.

Das Hauptziel dieser Arbeit ist die Entwicklung eines Konzepts zur Beurteilung der Funktionstüchtigkeit von Wäldern und zur Bewertung der Wirksamkeit von Waldökosystemmanagement und Zertifizierung. In diesem Zusammenhang wurde eine ökosystembasierte und partizipative Methodik entwickelt, die den Namen ECOSEFFECT trägt. Diese Methode umfasst eine theoretische und eine empirische Plausibilitätsanalyse, die zur Beurteilung und Bewertung des russischen FSC-Standards in der Region Archangelsk der Russischen Föderation eingesetzt wurde - dort wo boreale Wälder großflächig kahlgeschlagen werden, um die europäische Nachfrage nach Holz zu decken. Zusätzlich wurde der Einfluss von forstwirtschaftlichen Eingriffen auf die Temperaturregulation von Kiefern- und Rotbuchenwäldern in Deutschland während zweier extrem heißer und trockener Sommer in den Jahren 2018 und 2019 untersucht.

Die Regulation des Mikroklimas ist ein geeigneter Proxy für die Funktionstüchtigkeit von Wälder und kann zur Bewertung der Effektivität von Waldbewirtschaftung angewendet werden. Mikroklima stellt den entscheidenden Indikator dar, der Kahlschläge von Primärwäldern unterscheidet. Damit ist die Bewertung der Mikroklimaregulation von Wäldern ein geeignetes Instrument zur Darstellung der Waldfunktionalität. In den borealen und gemäßigten Wäldern, die im Rahmen dieser Arbeit untersucht wurden, hat die Holzernte die Fähigkeit zur Selbstregulierung des Waldmikroklimas reduziert und damit die Funktionstüchtigkeit des Ökosystems beeinträchtigt. Waldstrukturen die durch die Waldbewirtschaftung und den Waldbau beeinflusst werden, wirken sich erheblich auf die mikroklimatischen Bedingungen und damit auf die Anfälligkeit des Ökosystems gegenüber dem Klimawandel aus. Der Kronenschlussgrad und die Anzahl der gefällten Bäume zeigten sich als die

relevantesten Indikatoren, die Temperaturspitzen beeinflussen. Die in Bodennähe gemessene Maximaltemperatur stieg um 0,21 - 0,34 K wenn 100 Bäume gefällt wurden. Das Öffnen des Konendaches um 10 % verursachte einen Anstieg der Maximaltemperatur in Bodennähe um 0,53 K (gemessen in Kiefern- und Buchenbestände). Die relative Temperaturkühlkapazität nahm mit zunehmender Holzernteaktivität ab und fiel unter den Durchschnittswert, wenn mehr als 656 Bäume pro Hektar (im Jahr 2018; und 867 Bäume im Jahr 2019) gefällt wurden. In Kiefernbeständen mit einem Kronenschluss von weniger als 82 % war die relative Temperaturpufferkapazität geringer als der Durchschnitt. Die in Bodennähe und in 1,3 m gemessene mittlere Maximaltemperatur war in einer kieferdominierten Untersuchungsfläche mit relativ geringem Bestandsvolumen (177 m^3 ha^{-1}) am höchsten und in einer Buchenfläche mit relativ hohem Bestandsvolumen (> 565 m^3 ha^{-1}) um 9 K niedriger. Während des heißesten Tages im Jahr 2019 waren die Temperaturspitzen in einem Kiefernbestand mit relativ dichtem (72 %) Kronendach mehr als 13 K höher als in einem Kiefernbestand mit offenem (46 %) Kronendach.

Der russische FSC-Standard hat das Potenzial, die Waldbewirtschaftung in Archangelsk zu verbessern, aber es gibt zahlreiche Ungenauigkeiten bei der Adressierung der tatsächlich identifizierten Probleme und bei der ökologischen Verbindlichkeit. Theoretisch könnte FSC die Waldbewirtschaftungspraktiken positive verändern und effektive Ergebnisse bewirken, indem 75 % der identifizierten Faktoren adressiert werden, darunter sehr relevante Faktoren und Bedrohungen für das Ökosystem, einschließlich der großflächigen Kahlschläge, was dazu beiträgt, etwa die Hälfte der identifizierten Probleme im Ökosystem zu reduzieren. Es ist theoretisch plausibel, dass FSC den Holzeinschlag in Wäldern mit hohem Schutzwert und intakten Wäldern (*Intact Forest Landscapes*) verhindert, die Größe und Anzahl der Kahlschläge reduziert und negative hydrologische Veränderungen in der Landschaft verhindert. Allerdings ist der russische FSC-Standard nicht explizit und verpflichtend genug, um einen starken und positiven Einfluss auf die identifizierten Probleme und deren Treiber zu erzeugen. Darüber hinaus haben die räumlichen Analysen gezeigt, dass die typischen regelmäßigen Kahlschlagsmuster der konventionellen Holzernte auch in den FSC-zertifizierten borealen Wäldern fortbestehen, auch wenn sie als "intakte Wälder" deklariert sind. Daraus ergibt sich die Notwendigkeit, die theoretischen Annahmen und Postulate vor Ort zu überprüfen, da es unklar und fraglich bleibt, ob die Funktionen und Leistungen der borealen Wälder erhalten bleiben, wenn der FSC-zertifizierte Kahlschlag weitergeht. Die empirische Untersuchung zeigt, dass auf den Kahlschlägen die Maximaltemperatur über 36 °C lag, während sie im geschlossenen Primärwald unter 30 °C blieb. Die Anzahl der Tage mit Temperaturen über 25 °C war Kahlschlägen mindestens doppelt so hoch. Die Temperaturkühlungskapazität wurde um bis zu 14 % und die Temperaturpufferkapazität um bis zu 60 % reduziert. FSC-zertifizierte Kahlschläge unterscheiden sich vor allem deshalb nicht von konventionellen Kahlschlägen, weil auf genauso auf Kahlschlagflächen von bis zu 50 ha Größe etwa 97 % der Bäume geerntet wurden. Die räumliche Gestaltung der Kahlschläge, ihre Größe und die Intensität der Rodung sowie die Dichte der Holz-Rückegassen wurden durch die FSC-Zertifizierung nicht reduziert. Die jährliche Abholzung war in nicht-zertifizierten Gebieten am geringsten. Das bedeutet, dass FSC möglicherweise sogar zu einem erhöhten Holzbiomasseverlust innerhalb der Kahlschläge beiträgt, was die Fähigkeit der Ökosysteme, sich zu erholen und ökologische Funktionen und Leistungen zu aufrecht zu erhalten, beeinträchtigt. Die satellitenbildbasierte Analyse zum Verlust der Baumbedeckung zeigte, dass Kahlschläge ein sekundäres Absterben in der Umgebung der gerodeten Fläche verursachen. Eine FSC-Zertifizierung verhindert die verschiedenen negativen Auswirkungen des Kahlschlags nicht und versagt somit bei der Sicherung der Ökosystemfunktionen. Der postulierte Erfolg bei der Reduktion von ökosystemaren Bedrohungen, z. B. durch eine geringere Größe von Kahlschlägen, konnte vor Ort nicht verifiziert werden. Die empirische Untersuchung widerlegt die Hypothese einer effektiven Verbesserung im Ökosystems. In der Praxis hat die FSC-Zertifizierung nicht dazu beigetragen, die Kahlschlagpraktiken ausreichend zu verändern, um die ökologischen Indikatoren wirkungsvoll zu verbessern. Nachhaltigkeitsstandards, die nicht in der Lage sind, Prinzipien in wirksame Maßnahmen mit messbaren positiven Ergebnissen umzusetzen, scheitern darin, die Funktionsfähigkeit des Ökosystems zu sichern. Zertifizierte Kahlschläge, die ein Nachhaltigkeitssiegel tragen, sind ökologisch problematisch und für den beabsichtigten Zweck Ökosystemfunktionen zu schützen, unwirksam.

Die vorwiegende Nutzung von Wäldern primär zur Holzgewinnung vermindert die Fähigkeit der Ökosysteme, andere (v. a. regulierende) Leistungen, von globaler Bedeutung aufrechtzuerhalten. Sie beeinträchtigt die Ökosystemfunktionen, die für die Bewältigung und Anpassung an andere Belastungen und Störungen relevant sind, die im Zuge des Klimawandels häufiger und extremer werden.

Eine Waldbewirtschaftung unter Einfluss des Klimawandels muss Vorsorgeprinzipien einhalten und entsprechende ökologische Risiken, wie z. B. sekundäre Absterbeerscheinungen und die Verschlechterung von Regulationsleistungen, die für die Funktion des Waldes relevant sind, reduzieren und vermeiden. Waldbewirtschafter und Waldbesitzer müssen strenge ökologische Prinzipien anwenden, um funktionsfähige Wälder mit einer ausgeprägten mikroklimatische Regulationsfähigkeit zu erhalten und zu befördern, um Zustandsverschlechterungen entgegenzuwirken, auch als Grundlage für eine nachhaltige wirtschaftliche Nutzung.

3. General introduction

3.1 Introduction and Background

3.1.1 Forest ecosystems

Forest ecosystems are complex systems comprising trees and many other biotic and abiotic components that interact and generate diverse structures and functional pathways. Over time, forests grow and their inherent structures and processes develop. They accumulate biomass, develop networks and gather information constituting a multi-layered tree canopy of different tree species and ages in complex interaction with other organisms including fungi and microorganisms (Fath et al. 2004). Forests dissipate, transform and store solar energy and are permanently in exchange within their surrounding environment (Wagendorp et al. 2006). With ecosystem development and continuity, the systems' available energy and functional pathways enhance and contribute to a higher thermodynamic efficiency and ecosystem resilience (Mausolf et al. 2018a; Mausolf et al. 2018b; Norris et al. 2012). Mature ecosystems exhibit a higher degree of self-organisation and self-regulation and develop more dissipative structures that increase their thermodynamic efficiency and therefore their ecological functionality and capacity to cope with perturbations (Jørgensen & Fath 2004).

Ecosystem functionality was mapped on a global scale using proxy indicators with vegetation density, topographical heterogeneity and carbon storage being the most determining characteristics (Freudenberger et al. 2012). Key ecological attributes relevant for the functioning of ecosystems are energy input, atmosphere, hydrosphere, lithosphere, matter cycle-related processes, biomass, information (including genes, morphology, ecological traits, and habitats), network (including connectivity of habitats, communities, and species interactions), species-specific key attributes, energy efficiency, resilience and resistance (Schick et al. 2019). Ecosystem functions are the fundamentals for the provision of ecosystem services and comprise the inherent structures and processes in ecosystems (Gómez-Baggethun et al. 2010). Ecosystem services represent the ecological processes and resulting products and services that are – knowingly or unknowingly, consciously or unconsciously – consumed by humans and comprise provisioning, regulating and cultural services (Brockerhoff et al. 2017; CICES 2013). Thus, functional forest ecosystems provide diverse ecosystem services that contribute human wellbeing (Miura et al. 2015; Mori et al. 2017).

Humankind always used ecosystems and therefore depended on their services, but as industrialisation progressed, these relationships became less obvious and the belief in technical and mechanical solutions for the production of goods to meet the increasing resource and energy demand prevailed. Certainly, economic growth and production are coupled with the exploitation of natural resources for the production of raw materials and thus depend on the existence and functioning of ecosystems.

3.1.2 Forest climate and climate change

Global climate change impairs the provision of ecosystem services in addition to anthropogenic ecosystem degradation (Weiskopf et al. 2020). Recent climate extremes amplified pests and diseases and caused large-scale tree dieback in Central Europe (Seidl et al. 2017; Schuldt et al. 2020). The most recent drought impacts induced a decline of tree vitality and productivity (Rohner et al. 2021; Senf et al. 2020). This hydroclimatic anomaly (Büntgen et al. 2021) will not remain an exceptional case but might be considered as normal in the near future (Hari et al., 2020; Scharnweber et al., 2020).

With ongoing climate change impacts, increasing heat, and drought stress, microclimate regulation becomes a key process relevant for the maintenance of forest functions and services and it is increasingly important to assess the resilience to weather extremes in relation to ecosystem structure (Wiesner et al. 2021).

A critical challenge for forest management is to support the ecosystems' capacity for microclimate regulation, especially in times of frequently recurring dry and hot years, when precipitation is absent during longer periods of drought. It is, therefore, of high interest, which forest management interventions have the potential to amplify or attenuate the consequences of heat waves within forest stands.

3.1.3 Forest management

Forest management comprises diverse silvicultural practices but also non-intervention approaches which vary in their objectives (Duncker et al. 2012). Typically, forests are exploited for timber (Noble & Dirzo 1997; Sheppard et al. 2020; Eggers et al. 2019). But the commercial forest use for timber production impacts on forest ecosystems by deteriorating functional processes with negative consequences for the provision of other ecosystem services (Thompson et al. 2011; Miura et al. 2015). More recently, forest resistance and resilience became a relevant target in order to conserve forest functions under increasing climate change impacts whereby resilience will be even more important to recover from unpreventable disturbances and increase resistance in the long-term (DeRose & Long 2014).

Especially boreal forests are important for timber supply and the production of coniferous roundwood required by the construction industry. Boreal forest ecosystems consist mainly of pine and spruce forests and are systematically logged, often in regular clearcutting patterns. These patterns are most evident in the forests of the Russian Federation in general and the Arkhangelsk region in particular, which are part of the largest forest ecosystem complex in the world. On the one hand, boreal forests store and sequester large amounts of carbon and comprise a high share of the global *Intact Forest Landscapes*, and on the other hand, Russia is one of the leading timber exporting countries (Potapov et al., 2008, Furukawa et al., 2015 – see Chapter 4 and Chapter 5 for more information). Clearcutting for timber harvest and sanitary cuttings or salvage logging imply the complete removal of trees within a certain area with or without retaining residual trees. Salvage logging has negative impacts on regulating ecosystem services and biodiversity (Leverkus et al. 2020; Thorn et al. 2020).

Simultaneous replanting of forest stands after clearcutting comes at the cost of structural complexity and is ecologically not comparable to stand development after natural stand-replacing disturbances (Kuuluvainen 2009). Resulting even-aged monocultures, especially coniferous timber plantations, imply simple forest structures with negative impacts on forest microclimate (Ehbrecht et al. 2017).

Artificially forest stands are planted in order to optimize timber production and are in contrast to naturally developing and self-organising forest ecosystems with passive management. Planted forests are typically thinned in regular intervals to selectively remove trees in order to increase access to resources for the remaining trees. Mostly, thinning is a mechanised process including the use of harvesters and skidders, which caused the expansion of infrastructure throughout forests.

In Europe, and especially in Germany, permanent forest cover used to be maintained by single-tree harvesting, but recently sanitary clearcutting and salvage logging has been expanding rapidly due to increasing calamities. Coniferous species (e.g. *Pinus sylvestris, Picea abies*) were planted after extensive forest clearances for reparation payments after the Second World War, but also in the following decades, and form the foundation of efficient, plantation-like, mechanised forestry. They displaced many of the naturally grown deciduous forests in Germany, especially in the north-eastern lowlands and in the low mountain ranges of Germany, and promised to generate sustained economic profits and to meet the growing timber demands.

3.1.4 Forest certification

Forest certification was invented as a market-driven mechanism to improve forest management, label sustainably produced woody products for consumers and generate higher prices and better market access for timber sales (Rametsteiner and Simula 2003; Auld et al. 2008). Globally, 3 % of forests and about 10 % of commercial forests, mainly located in the Northern Hemisphere, are under certification (Siry et al. 2005; Kraxner et al. 2017).

Certification aims at inducing sustainable forest management with ecological, economic and social benefits. Ecological effectiveness of forest management and certification describes the success of changing and mitigating primarily negative environmental but also socio-economic forestry impacts (Gulbrandsen 2005). The crucial question is to what extent certification has actually improved ecological impacts in forest ecosystems and therefore contributes to maintain forest functions and services in the long term.

3.2 Objectives and approach

Forests and the services they provide were and are of utmost importance for human existence and well-being, but the utilisation of forest resources, fragmentation, degradation and deforestation impair forest functions. This does not only compromise the resilience, resistance and existence of forests but also the services essential for the survival of humanity. Efforts to reduce the negative impacts and attempts to safeguard forest functions are manifold and include compulsory national and international guidelines and regulations for forest management, conventions, but also voluntary mechanisms such as certification systems. The crucial question to answer is, how can we evaluate objectively the success of the attempts that try to conserve the functions and services of forest ecosystems, especially those relevant under climate change.

The main objective of this thesis was to assess the functionality of forests, especially focussing on microclimate, and to evaluate the effectiveness of forest ecosystem management including certification. In this context, an ecosystem-based and participatory methodology, named ECOSEFFECT, was developed. The method comprises a theoretical and an empirical plausibility analysis that were applied to assess and evaluate the principles, criteria and indicators (PCI) of the Russian National FSC Standard. In the first and theoretical phase, the potential for reducing recognized environmental threats to biodiversity that result from conventional forest management practices in the Arkhangelsk Region in the Russian Federation was assessed during expert workshops (**Chapter 4**). In a second and empirical phase, a selection of ecological indicators was measured on the ground to investigate whether FSC-certified clearcuts are different from non-FSC-certified clearcuts (**Chapter 5**). Microclimatic indicators were tested for their relevance in classifying the differently treated forest stands. In addition, also the effectives of changes induced by FSC were assessed on a spatial scale (**Chapter 6**). Furthermore, this thesis aims to quantify the effects of structural changes caused by forestry interventions on the temperature regulation of forests. In a case study in Scots pine and European beech forests in Germany, forest interior summer temperatures were analysed during two extreme hot and dry years in 2018 and 2019 (**Chapter 7**).

3.3 Research questions

A systematic approach was developed and applied in the frame of two research projects' case studies in order to find answers to the following research questions:

I. What are the actual drivers of forest management and the impacts on forest functions in a case study in the Arkhangelsk Region, Russian Federation and how can FSC-certification potentially contribute to mitigate threats and stresses to the ecosystem in order to safeguard forest functions and services? (**Chapter 4**)
II. Which indicators adequately describe the differences in forest management as they result from FSC certification, and how effective is FSC certification in reducing negative impacts of forest management in the Arkhangelsk region, Russian Federation? What role does microclimate regulation play in quantifying the loss of forest functions resulting from clearcutting or management with and without certification? (**Chapter 5**)
III. Does FSC-certification change clearcutting practices on a spatial scale as contributions to preserve forest functions? (**Chapter 6**)
IV. How does forest management and silviculture influence the regulating forest functions and the capacity to attenuate and buffer extreme summer temperatures in the forest interior? (**Chapter 7**)

The main body of this cumulative dissertation comprises four peer-reviewed international publications (Chapter 4-7), which can be read independently but are thematically related and provide answers to the above-mentioned research questions. The author of this thesis is the first author of the four co-authored papers. This thesis was developed and conducted in the frame of two research projects at the Centre for Econics and Ecosystem Management at the Eberswalde University for Sustainable Development. **Chapter 4 – 6** based on a project that was implemented together with WWF Germany, WWF Russia and the Northern (Arctic) Federal University named after M.V. Lomonosov in Arkhangelsk. *Gläserner Forstbetrieb* (Ecological and economic assessment of integrated nature conservation measures in forest management to ensure ecosystem services and forest ecosystem functioning (Gläserner Forst) - Subproject 3: Ecological assessment and ecosystem services' by the German Federal

Ministry for Education and Research (BMBF) via the German Aerospace Center (DLR), grant number 01LC1603C) presents the foundation for **Chapter 7**.

3.4 References of the general introduction

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4. Towards the Evaluation of the Ecological Effectiveness of the Principles, Criteria and Indicators (PCI) of the Forest Stewardship Council (FSC): Case study in the Arkhangelsk Region in the Russian Federation

Blumröder, J.S., P.R. Hobson, U.F. Gräbener, J.-A. Krüger, D. Dobrynin, N. Burova, I. Amosova, S. Winter & P.L. Ibisch (2018): Towards the Evaluation of the Ecological Effectiveness of the Principles, Criteria and Indicators (PCI) of the Forest Stewardship Council (FSC): Case study in the Arkhangelsk Region in the Russian Federation. Challenges in Sustainability 6(1): 20-51.

4.1 Abstract

The Forest Stewardship Council (FSC) is a voluntary sustainability standard with global reach that has been developed to encourage responsible and sustainable forest management. Despite its broad appeal, there is little scientific assessment to substantiate the effectiveness of FSC in the boreal zone. In this study, an ecosystem-based and participatory approach was applied to a case study in the Arkhangelsk Region of the Russia Federation to assess the potential influence of the principles, criteria and indicators of the Russian FSC standard. An ECOSEFFECT theoretical plausibility analysis was conducted to evaluate the potential effectiveness of FSC in safeguarding the ecological integrity of the ecosystem. Besides spatial analysis and a field visitation, core elements of the methodological procedure were workshops with experts and stakeholders who directly contributed to knowledge mapping and analysis. The results of the study suggest FSC can potentially influence and improve forest management including monitoring and evaluation, foster the institutional capacity, and enhance knowledge on the impacts of forest management. Theoretically, FSC has a certain potential to reduce a range of anthropogenic threats to the ecosystem, such as large-scale deforestation and forest degradation, logging of High Conservation Value Forests, large size of clear-cuts, excessive annual allowable cuts, damage to trees during forest operations, and hydrological changes. However, human-induced fire is the only ecological stress that was assumed to be effectively tackled through a strong and positive influence of FSC. The results of the theoretical analysis with a semi-quantitative evaluation revealed the potential for FSC to generate much more effective outcomes for biodiversity by prudently targeting key ecological problems. The biggest problem is the large-scale clear-cutting practice, especially within IFL. These devastating practices are not promoted by, but are compliant with the current Russian FSC standard. This feeds doubts about the consistency of FSC practice and its credibility.

4.2 Keywords

Arkhangelsk; boreal forest; ecological effectiveness; FSC-certification; sustainability.

4.3 Introduction

The Forest Stewardship Council (FSC) is a voluntary sustainability standard developed to promote responsible management of the world's forests that is environmentally appropriate, socially beneficial, and economically viable [1]. Based on a generic certification system with a given set of general principles and criteria, 46 national standards for 38 different countries have been formulated and approved, each with their own specific indicators, verifiers, norms, and guidance [2]. FSC is a market-based tool that has been prepared by a multi-stakeholder group and is the most widely adopted forest standard, already covering 196 million hectares of the forest across 83 different countries worldwide [3]. Motivated by ethical concerns for the environment and underpinned by the Sustainable Development Goals as well as international directives to safeguard biodiversity, FSC is regarded as a powerful instrument to achieve Sustainable Forest Management (SFM) [4]. SFM aims to commercially use forests without compromising biodiversity, biomass productivity, the capacity for natural regeneration, vitality, and the functionality to provide ecosystem services in the long-term and without threatening other ecological systems [5]. The concept of SFM seems to be in accordance with the requirements of the ecosystem approach [6]; at least both pursue the same ultimate goals [7]. The ecosystem approach promotes the conservation of biodiversity and sustainable use of natural resources taking into account the inherent dynamics and complexity of ecological systems [8]. It acknowledges the close interrelation and interdependency of ecological and anthropogenic systems as well as the need for protecting biodiversity when utilizing natural resources [9]. The reduction of present and future anthropogenic threats to biodiversity fosters ecosystem resilience by supporting ecosystem functionality in the long-term, and in doing so, increasing the ability of ecosystems to cope with perturbations and environmental changes [10,11]. Growing scientific evidence indicates that forest certification probably decreases social and environmental shortcomings [12]. FSC members are convinced that FSC certification generates social benefits such as improved communication processes and the resolution of conflicts [13]. For instance, FSC certification induced beneficial social outcomes in terms of living conditions of forest workers and benefit-sharing in the Congo basin [14]. In Tanzania, FSC-certified community forests showed improved forest structure and forest regeneration as well as a less fire incidents [15]. Nevertheless, the effects of FSC certification on the management of community forests are often limited and do not necessarily refer to certification itself, but to the emphasis of public policy and positive institutional influence [16]. Regarding short-term environmental impacts, FSC certification led to a slight reduction in logging damage, impacts from skidding trails and roads, and loss of above-ground biomass in Gabon [17]. In Indonesia, FSC certification decreased deforestation and air pollution and was associated with benefits to local communities including health issues, but still, forest management for timber harvesting causes ecosystem disturbance [18]. Amongst three different commercial forest reserves in Malaysia, mammal species richness including threatened species and aboveground biomass were highest in a FSC-certified area [19]. In Mediterranean oak woodlands, FSC had a positive effect on stream quality after five years by enhancing riparian vegetation [20]. In a global panel analysis it was concluded that forest certification can reduce deforestation directly and indirectly [21]. However, logging activities under FSC cannot always be associated with lower carbon emissions [22]. More than one fifth of the world's FSC-certified area is located within the Russian Federation [3]. The increasing demand for certified timber together with an active promotion from international organisations, especially from environmental NGOs, has been the main driving force behind FSC certification in the Russian Federation [23]. However, evidence for the environmental benefits of FSC is to be found mainly in the tropical and subtropical biomes. In contrast, there have been very few studies published on FSC practices in boreal forests, and those that have are restricted to EU-countries such as Sweden or Finland, and to North America. A study conducted in 12 stands in the USA concluded that FSC-certified harvesting showed no significant differences at stand level in comparison to noncertified forestry, except for an increase in woody residues [24]. In the boreal forests of the Russian Federation less evidence about the impacts of FSC certification was produced. Maintaining the functionality of the Russian forests is highly relevant, as forest cover in the Russian Federation is the most extensive of all the larger countries [25]. In 2010, forest was estimated to cover almost 800 million hectares of the Russian territory [26]. The taiga represents a boreal forest ecosystem encompassing the largest terrestrial biome on the globe, but much of the natural structures and dynamics have been heavily impacted by anthropogenic exploitation [27]. In the production forests of the Russian Federation clear-cuts of up to 50 ha are allowed in accordance with the forest code [28]. In more recent times, the predominantly high intensity timber logging, clear-cuttings, and human-induced fires have caused substantial tree cover losses and ecosystem degradation [29]. The transformation from intact forest landscapes (IFL) to forests that are deeply fragmented, especially in European Russia, changed the ecology of the region and threatens to reduce ecosystem functionality in the long-term [30]. At present, within the Arkhangelsk Region and the Komi Republic, large tracts of IFL remain [31], but at the same time these areas continue to suffer from substantive tree cover loss [29,32]. The FSC promotes the preservation of IFL as part of high conservation value forests (HCVF) [33]. The reduction of logging in primary forests and the identification of HCVF were encountered as positive environmental impacts of FSC that contribute to biodiversity conservation in the Russian Federation [23]. Specifically, in tracts of forest managed as clear-cut, those areas spared from felling are important landscape elements for biodiversity and are promoted by FSC certification [34]. Nevertheless, most studies about the impacts of FSC in the Russian Federation focus on issues relating to governance and society [35–38], and much less on ecological effects. In this study, an ecosystem-based and participatory methodology, named ECOSEFFECT, is applied to systemically assess and evaluate the principles, criteria and indicators (PCI) of FSC and their potential for reducing recognized environmental threats to biodiversity that result from conventional forest management practices. ECOSEFFECT has been developed specifically to assess the performance of certification systems for the sustainable management of natural resources with a focus on maintaining ecosystem functionality. The Arkhangelsk Region was the chosen study site because of its relevance for timber supply in Europe and Russia, and also because it supports large tracts of intact forest, but most crucial is the recent expansion of FSC across the forest leaseholders. The main aim of the study was to estimate the potential benefits derived from implementing the PCI of FSC in the Arkhangelsk Region, and to identify eventual challenges and shortcomings of the standard.

4.4 Method

4.4.1 Geographical Scope

The Arkhangelsk Region is located in the north-west of the Russian Federation, bordered to the north by the White Sea and Nenetskiy, to the east by the Komi Republic, the Karelia Republic to the west, and the Vologda Region and Kirov Region to the south. The subarctic climate of the boreal moist forest biome is characterised by cold and long winters, and short summers, which sets limits on the growing season for plants. The mean annual temperature is 1.5 ◦C and annual precipitation around 670 mm [39]. Forest covers the largest part of the land surface with a share of about 39%, of which approximately one third is classified as IFL [40]. The coniferous spruce forests are adapted to the harsh growing conditions. With about two persons per square kilometre on average, the Arkhangelsk Region is quite sparsely populated [41]. The economy is based predominantly on timber extraction and processing, and by the beginning of the 20th century, Archangelsk was already one of the largest sawmilling regions in the world [42]. After a dip in productivity after the collapse of the Soviet Union [43], the region again has become a centre of Russian forestry [44].

4.4.2 Conceptual Scope and General Methodological Approach

The methodological framework ECOSEFFECT (*ECOsystem-based assessment of Sustainability standards and their EFFECTiveness*), used in this study is based on MARISCO, an adaptive and proactive conservation management tool [45,46]. The applied method is grounded in an ecosystem approach which includes the principle that humans and their economic activities are an integral part of the global ecosystem and depend on the full functioning of ecosystems. In the case of forests and their management it becomes especially apparent that both economic and social sustainability entirely depend on the functioning of the ecosystem. For this reason, we postulate a clear 'hierarchy of sustainabilities' reflecting that the sustainable existence and functioning of the ecosystem is a *conditio sine qua non* for any dependent subsystem. To justify the development and use of a sustainability standard for ecosystem management such as FSC requires proof of its effectiveness in safeguarding the ecology and the integrity of the service-provisioning system. Beneficial influences of FSC on the social and economic sphere can be important achievements, which are very much appreciated, but if short-term benefits for human well-being do not translate into potential ecological outcomes then they are irrelevant to our study (e.g., safety requirements that lead to reduced injuries of forest workers does not induce any positive impacts in the forest ecosystem [47]). Nevertheless, we fully recognize the complexity inherent in nature and its relationship with society. The evaluation of the benefits and gains made by applying certification cannot focus solely on changes in forests and forest management operations, but also requires an analytical framework that carefully considers the causal origin of outcomes [48]. ECOSEFFECT scrutinizes the human-induced threats to ecosystems and the ability of sustainability standards to reduce the resulting ecological stresses by abating the underlying drivers of negative environmental change. The human dimension, including social and economic aspects, appears in the analysis as the drivers of environmental change on the one hand and on the other hand, human well-being is directly affected by the consequences of deteriorated ecosystems. The approach taken deliberately applies a systemic framework with as much of the complex situation and prevailing conditions represented as possible. It pools information from experts and stakeholders, and is an open-source, transparent knowledge sharing platform with the purpose of understanding different view-points and angles of interpretation.

4.4.3 Theoretical Plausibility Analysis

A theoretical plausibility analysis was conducted according to a series of procedural steps making up the ECOSEFFECT method (Table 1) [49].

Table 1. Methodological steps of the ECOSEFFECT method that were conducted in this study.

ECOS EFFECT	Details and content of the ECOSEFFECT methodological steps	Output
1. Ecosystem Diagnostics Analysis (EDA)	• Examination of available spatial data on land cover and land-use change • Meetings with forest managers and visitation of forest sites that have been logged recently and a longer time ago, with and without FSC-certification • Obtaining further information from local experts and stakeholders • Verification of spatial data	Maps and impression about the landscape, the distribution of forests, natural and anthropogenic land-use change in the Arkhangelsk Region and tree cover loss in particular
2. Ecosystem-based Situation Analysis	• Participatory workshop for systematical analysis of the situation in the Arkhangelsk Region using the knowledge of experts and stakeholders in the context of forest ecosystems • Visualization of the situation in Arkhangelsk by creating a conceptual model presenting the comprehensive systemic web of identified and causally interlinked system elements • Semi-quantitative evaluation of contributing factors, threats and stresses: Strategic relevance = Current criticality: Importance for the vulnerability of biodiversity object • Scope (geographic extent) • Severity (intensity of negative impact on biodiversity within the next 10 years) • Irreversibility (degree of permanency or impermanency) + Past criticality: The status of criticality 20 years ago + Current trend of change: Tendency that the current criticality is changing + Future criticality: Future scenario to estimate the change of criticality in 20 years + Systemic activity: • Level of activity (number of outgoing influences in relation to number of incoming influences) • Number of influenced elements Manageability: Potential to be influenced and changed by actors with available resources Knowledge: Available information and quality of information	Conceptual model presenting the situation in the Arkhangelsk Region which allows for prioritising most relevant elements
3. Strategic inter-pretation	• Translation of FSC principles into strategic complexes, FSC criteria into strategies and FSC indicators into activities • Coherency: determination of interrelations between the strategic components within FSC PCI. Expected interplay and dependencies between strategies	Synopsis of strategic measures stipulated by the Russian National FSC Standard

4. Leverage points	• Participatory workshop with experts on forests and FSC-certification in Arkhangelsk • Mapping of sustainability-strategies into the conceptual model	Identification of the locations in the conceptual model where FSC-Criteria exert influence
5. Theory of change and secondary risk analysis	• Determining the direction (positive or negative) and intensity (low or high) of the influence (semi-quantitative assessment by experts) $m^3\ ha^{-1}$ • Reformulation of addressed elements into expected outcomes (direct and indirect results) along postulated results-webs through logically linked assumptions • Comparing influence of FSC against values of strategic relevance of contributing factors, threats and stresses	Quantification of influence and postulation of theoretical results
6. Gap analysis	• Identifying elements in the conceptual model which have not been addressed by FSC but were in reach of FSC objectives and rated to be strategically relevant as well as elements that are influenced in a negative way (intensified in their potential to induce threats and stresses to biodiversity)	Identification of strategic gaps

4.4.4 Ecosystem Diagnostics Analysis

Ecosystem Diagnostics Analysis (EDA) is the first step in ECOSEFFECT and comprises a desktop assessment of available spatial data combined with quick field visitations of a designated project site or landscape. In the spatial analysis, forest cover and evidence of land cover change were examined as preparation for both the conceptualisation of the situation analysis and a field inspection. Data on annual tree cover loss between 2001 and 2014 [50] was used to look at logging patterns and to calculate tree cover loss before and during FSC certification, as well as in the forest landscape outside of FSC-certified concessions. Maps on the spatial distribution of FSC-certified forest management units (FMU) as of May 2016 [51] were processed, the issue date for each certificate holder was revised according to available certificates [52], and the dataset was clipped with annual tree cover loss [50] using the software ArcGIS [53]. In the spatial analysis, the relative year in relation to the implementation of FSC was computed. In particular, tree cover loss that occurred within a logging concession before it was FSC-certified was classified as “before FSC”. Tree cover loss classified as “during FSC” implies that the tree cover was lost while an FSC-certificate was valid. Tree cover loss in the initial and final year of certification as well as tree cover loss after FSC certification (altogether accounting for 12% of the dataset within FSC concessions) was excluded from the analysis to reduce uncertainty, as it was unclear if that particular moment of tree cover loss was recorded just before or after certification. In addition to the spatial analysis, a visitation to a forest management unit in the Vinogradovskiy district, east of Bereznik (Vaengskiy Lespromhoz LLC, Coordinates: NL 63◦05’, EL 43◦29’), was carried out on recently and formerly logged forest areas to verify the available spatial data and to discuss changes to forest structure, hydrology, and soil conditions brought about by harvesting practices with experts in the field.

4.4.5 Ecosystem-Based Situation Analysis of Arkhangelsk

A situation analysis describes the process of systemically collecting available knowledge to assess the conditions within a region of interest, including the vulnerability of biodiversity, and the complex interaction of the main drivers of change. A three-day workshop was launched in June 2014 close to the city of Arkhangelsk to conduct a situation analysis of the Arkhangelsk Region together with 16 experts affiliated to NGOs, FSC, academic research institutions, and timber companies (Table 2). Together with the findings of the previously conducted EDA, the results of the situation analysis were visualised in a conceptual model presenting a systemic knowledge map depicting causally interlinked factors that are responsible for shaping the actual situation within the scope (Figure 1). The systemic analysis began with the identification of the main ecosystem types and the fundamentals necessary to maintain full ecological function, the so-called key ecological attributes (KEA). Other information imported into the conceptual model include a list of aspects relating to human well-being, which is supported by ecosystem services provided by functional ecosystems on the one side, and by social services generated by social systems on the other side. Observable and also speculated environmental stresses that represent negative impacts on biodiversity were compiled as well as the contribution and interaction of the different pressures or threats that cause environmental stresses. The respective drivers of threats, called contributing factors, were also incorporated into the conceptual model. After cumulating and arranging all elements comprising the conceptual model (Table 3), the various systemic components were interlinked according to the most logical cause-effect relationships known or assumed by experts participating in the workshop in order to generate a complex and complete picture of the forests and the impacts of human interventions. The key question for this 'backwardmoving' procedure detecting potential causality was "Where does this come from? What are the direct drivers?". The method described for this form of conceptual modeling relies on repeated revision and refining of the analysis by the stakeholders participating in the process based on their knowledge and assumptions, until the best possible representation of the situation is achieved. In order to determine those elements in the system that contribute most to the overall vulnerability of biodiversity, the *strategic relevance* of contributing factors, threats, and stresses was semi-quantitatively evaluated by the workshop participants. It presents a cumulative measure comprising *criticality* (including *geographical scope, severity of impact, and irreversibility), dynamics (e.g., trend of change, expected future criticality)*, and *systemic activity (in- and outgoing influence)* (Table 3) applying the MARISCO rating scheme [45]. Elements rated as being highly relevant are those that should be prioritized by FSC to initiate targeted mitigation strategies and action to restore and safeguard the function of the forest environment in the long-term. The situation analysis provides the fundament for the further analysis and represents the situation of forests without FSC certification. *2.6. Strategic Interpretation of FSC* The PCI of the Forest Stewardship Council Standard for the Russian Federation (FSC code: FSC-STD-RUS-V6- 1-2012 Russia Natural and Plantations EN, Version 6- 01, 2012—FSC in the following) were strategically interpreted by classifying the 10 principles of FSC as *strategic complexes* that encompass a group of strategies related to a distinct thematic realm. The 56 FSC criteria were understood as *strategies* that are a set of activities or measures designed to deliver desirable goals and objectives. Indicators of each criterion were interpreted as *activities* describing specific actions or series of decisions related to a certain strategy. *2.7. Leverage Points* In complex systems, such as ecosystems or societies, leverage points represent those locations where small interventions can induce crucial changes [54]. In this study they present points in the conceptual model where FSC criteria apply. At this point, at least one activity of a strategy addresses a specific factor and influences it in such a way as to generate one or more outcomes. The leverage points of FSC were determined by seven experts made up of representatives of WWF Russia, FSC Russia and FSC International, the Northern (Arctic)

Federal University of Arkhangelsk as well as one timber company working on the conceptual model during a three-day workshop organized in April 2015 (Table 2, Figure 2).

Table 2. Number of experts and affiliated institutions that participated in the two ECOSEFFECT-workshops.

Institution	Number of Participants	
	Workshop 2014	Workshop 2015
WWF Russia	3	2
Researcher		1
• Northern Arctic Federal University named after M.V. Lomonosov	2	
• Institute of Zoology, Russian Academy of Science	1	
• Saint Petersburg Research Institute of Forestry	1	
Forest company (2)	3	1
FSC Russia		2
• Russian National Office	1	
• Technical Committee of FSC National working group	1	
FSC International	1	1
Arkhangelsk conservation initiative	1	
Certification body	2	

Table 3. Definition of elements comprising the conceptual model determined during the situation analysis.

Element	Explanation
Social system	Governmental and non-governmental institutions, business, religious groups, private organisations and any other group of organized individuals as well as their interaction.
Social services	Provided by social systems and can relate to directly applied social benefits as well as the organization and administration of ecosystem services.
Human well-being	Several human dimensions including subjective and objective factors such as human health, quality of life, life satisfaction and freedom of opportunity. Depending on ecosystem and social services.
Ecosystem services	Beneficial (provisioning, regulating, cultural) services people obtain by functional biodiversity including food, fiber and water, flood and disease control and recreation
Biodiversity objects	Ecosystems (forests, rivers, lakes, etc.) within the scope and their interrelated components, such as populations and species that make up the local biodiversity.
KEA: Key ecological attributes	Fundamental properties or integral elements for the functioning of biodiversity objects. Key requirements that maintain ecosystem functions and provide necessary adaptation and resilience to cope with perturbations. KEAs relate to abiotic master factors including energy input, moisture, temperature and nutrients as well as to biomass, information and network.
Stresses	Results of ecosystem degradation and the subsequent critical and negative change of Key Ecological Attributes. Eco-systemic stresses are consequences of threats and reduce the viability and integrity of the biodiversity, which then negatively affect resilience and adaptive capacity and can drive the system to collapse.
Threats	Negative environmental impacts that degrade the natural structure and dynamics of ecosystems and result in stresses to biodiversity.
Contributing factors	Human interventions or activities that directly or indirect drivers result in anthropogenic threats. Assignable to various sectors: spatial factors, governmental and institutional factors, economy and culture.

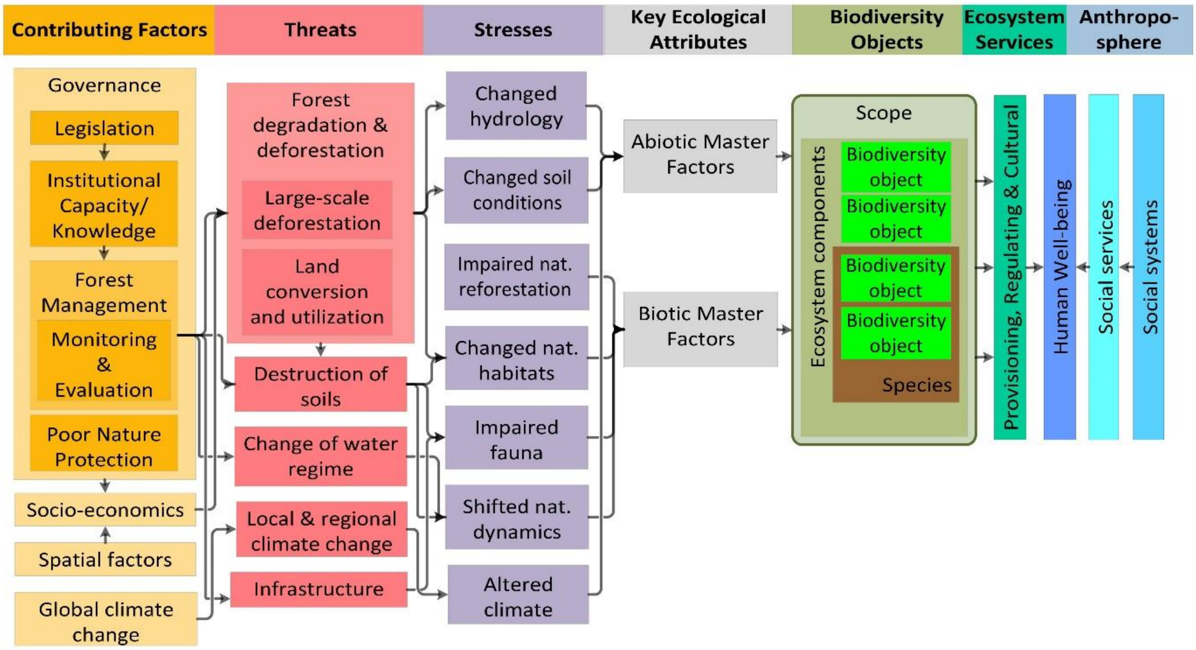

Figure 1. Generalized conceptual model with causally interlinked elements (definitions given in Table 3): Contributing factors are the drivers of threats, which in turn provoke environmental stresses that degrade the key functional requirements of the ecosystems and the provision of ecosystem services essential to human well-being (left to right). Social systems provide social services that contribute to human well-being (right to left).

4.4.6 Strategic Interpretation of FSC

The PCI of the Forest Stewardship Council Standard for the Russian Federation (FSC code: FSC-STD-RUS-V6-1-2012 Russia Natural and Plantations EN, Version 6-01, 2012—FSC in the following) were strategically interpreted by classifying the 10 principles of FSC as strategic complexes that encompass a group of strategies related to a distinct thematic realm. The 56 FSC criteria were understood as strategies that are a set of activities or measures designed to deliver desirable goals and objectives. Indicators of each criterion were interpreted as activities describing specific actions or series of decisions related to a certain strategy.

4.4.7 Leverage Points

In complex systems, such as ecosystems or societies, leverage points represent those locations where small interventions can induce crucial changes [54]. In this study they present points in the conceptual model where FSC criteria apply. At this point, at least one activity of a strategy addresses a specific factor and influences it in such a way as to generate one or more outcomes. The leverage points of FSC were determined by seven experts made up of representatives of WWF Russia, FSC Russia and FSC International, the Northern (Arctic) Federal University of Arkhangelsk as well as one timber company working on the conceptual model during a three-day workshop organized in April 2015 (Table 2, Figure 2).

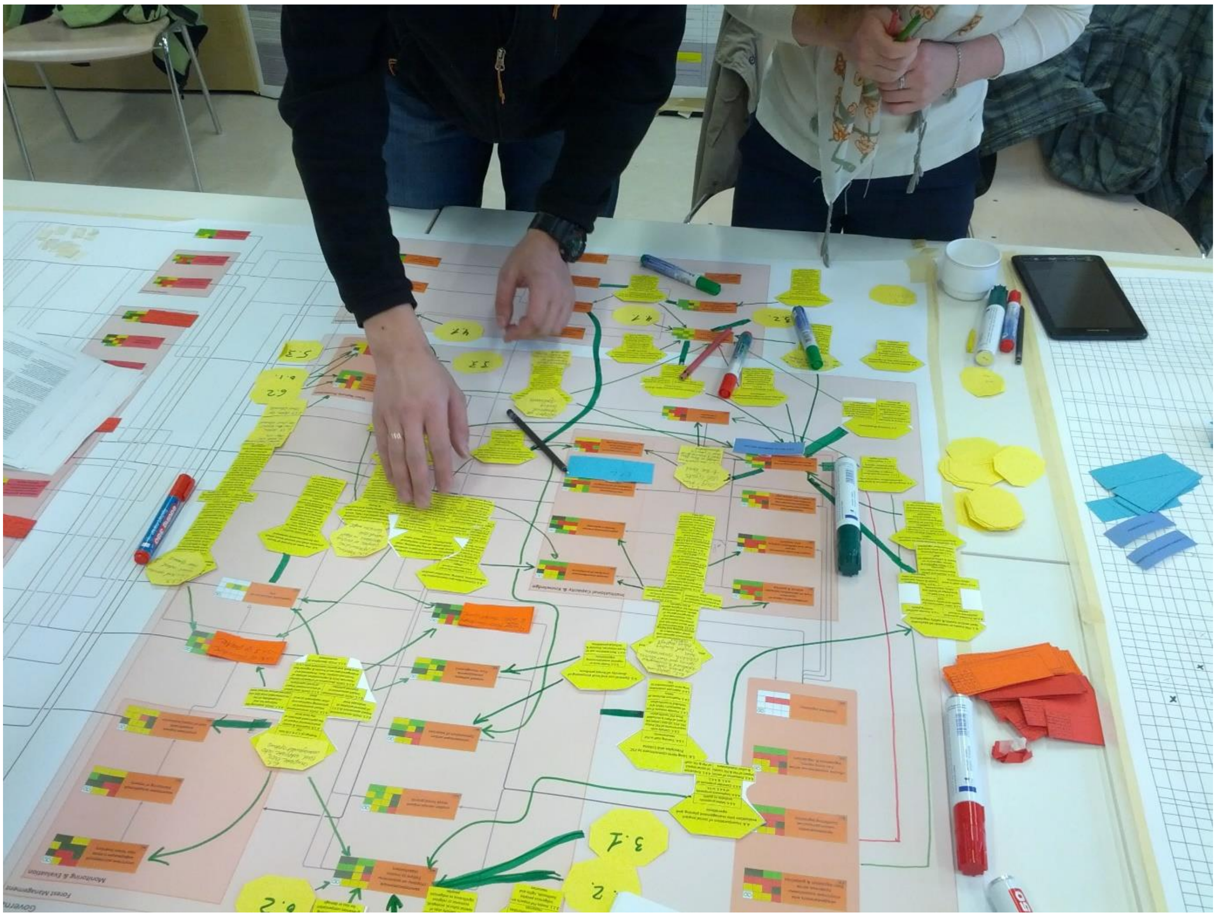

Figure 2. Experts identify the leverage points and influence (green and red arrows) of the Russian National FSC standard (yellow hexagons) and map it against contributing factors (orange boxes) in the conceptual model that illustrates the causally interlinked elements responsible for the situation in Arkhangelsk.

In the same workshop experts postulated and semiquantitatively evaluated the *influence* of FSC. The nature of influence of a particular strategy depends on the sufficiency, adequacy, and accuracy of activities in addressing the targeted problem or contributing factor. Whilst FSC is expected to induce positive outcomes in the environment, there remains the risk of exacerbating factors, threats, and stresses if associated strategies are found to be detrimental. Four possible scores were disseminated representing the *direction* and *intensity* of influence and ranging from one (strong and negative influence) to four (strong and positive influence) (Table 4).

Table 4. The four possible scores for influence refer to the direction and intensity of a strategy: positive influence creates opportunities; negative influence intensifies the negativity of a factor or impairs existing opportunities; strong influence results from targeting factors precisely; weak influence refers to addressing factors only partially.

Influence		**Intensity**	
		Strong	Weak
Direction	Positive	4 = Strong and positive	3 = Weak and positive
	Negative	1 = Stong and negative	2 = Weak and negative

4.4.8 Theory of Change

The theory of change describes a process of predetermining the outcomes derived from the influence of FSC on the causally interlinked elements collected in the conceptual model. The direct influence and positive transformation of factors induced by FSC can potentially trigger a cascade of responses leading to a mitigation of anthropogenic threats and the alleviation of environmental stresses. The reformulation of contributing factors, threats and stresses was conducted in the second workshop by participating experts according to their best knowledge, by experience, and logical assumptions.

4.4.9 Gap Analysis

In a gap analysis, those elements in the conceptual model that remain unaddressed by FSC as well as PCI, that do not apply to the situation in the Arkhangelsk Region, were identified. Any contributing factor, threat, and environmental stress unaddressed or intensified by a strategy could potentially jeopardize the effectiveness of the certification system in achieving its ecological objectives. Potential limitations of FSC have been identified and recommendations for improving the certification system and its effectiveness were developed. This step takes into account the scope of FSC in the Arkhangelsk Region that was delineated by discussing the effective range of influence of the standard with focus on forest ecosystem management with experts.

4.5 Results

4.5.1 Ecosystem Diagnostics Analysis

The Arkhangelsk Region comprises an area of around 31 million hectares of which almost half is classified as forest (as of 2000) [50]. The complex ecosystem mosaic of forests, rivers and mires is fragmented by roads. Large tracts of managed forest are under FSC certification (Figure 3).

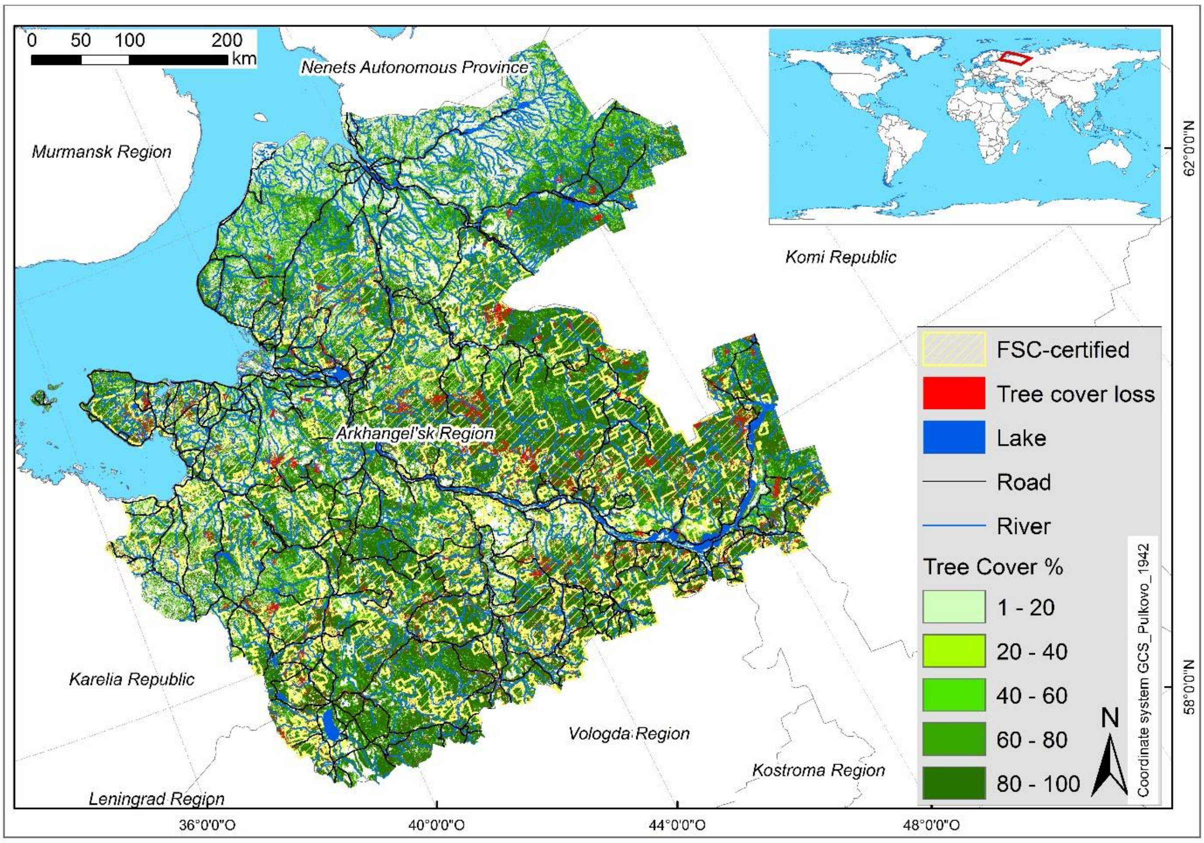

Figure 3. Map showing the Arkhangelsk Region and tree cover as of 2000 and tree cover loss between 2000 and 2014 [50], FSC-certified areas [51], and the network of lakes, rivers, and roads [55].

The implementation of FSC in the Arkhangelsk Region first started in 2004 with the certification of two companies encompassing around 235 thousand hectares. FSC-certified areas have been increasing up to more than 9 million hectares, leased under 41 different companies in 2016 (Figure 4).

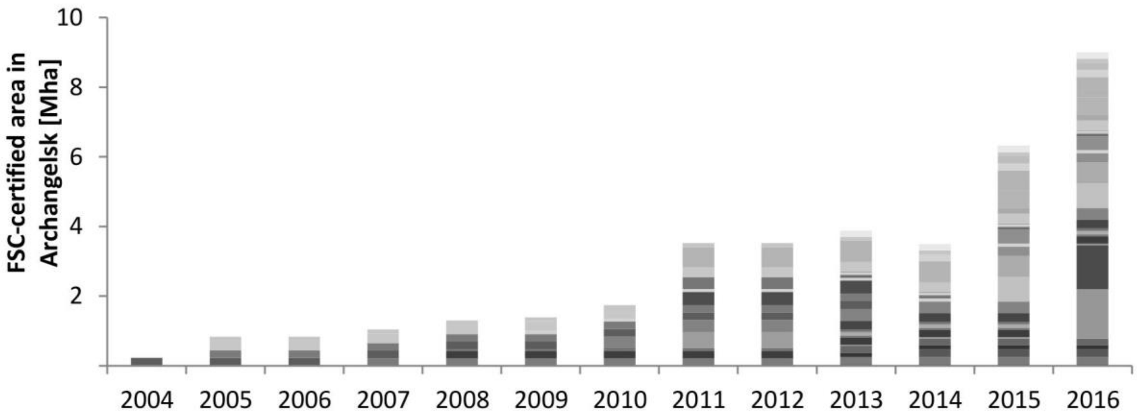

Figure 4. Spatial coverage of FSC-certified timber companies in the Arkhangelsk Region between the beginning of its implementation in 2004 until 2016 [52]. Different levels of grey represent each of the 41 FSC-certified companies.

Over the years commercial logging has reshaped the natural boreal forest ecosystem into a patchwork of checkerboard-like patterns created by systematic geometric clear-cutting (Figure 5a). The clear-cuts appear as geometrical rectangles, and forest roads become visible as straight lines of tree cover loss, whereas larger irregular patches of tree cover loss are most likely burnt sites, but could also be the results of deforestation for mining activities. Due to the inaccessibility of remote forest areas and the absence of local population, the small and diffuse patches of tree cover loss were not referred to logging but classified as forest die-back. Examples of die-back, particularly in spruce forest, were noticed in unmanaged stands during field-trips in the neighborhood of clear-cuts. Across most of the study area, the systematic harvesting of timber brought about a distinctive ‘checkerboard’-pattern that has been steadily increasing both within and outside FSC-certified areas. The consecutive, year-by-year clear-cuts add up to larger continuous clear-cuts without any substantial remaining tree cover that can be several square kilometers across (Figure 5b). Legal logging activities, also in FSC-certified logging concessions, have contributed to a considerable decrease in the extent of IFL in 2013 in comparison to 2000 and logging patterns in the example area show how the remaining IFL has been shrinking in recent years and how formerly continuous tracts of forest are now fragmented and can be prone to tree dieback (Figure 5c).

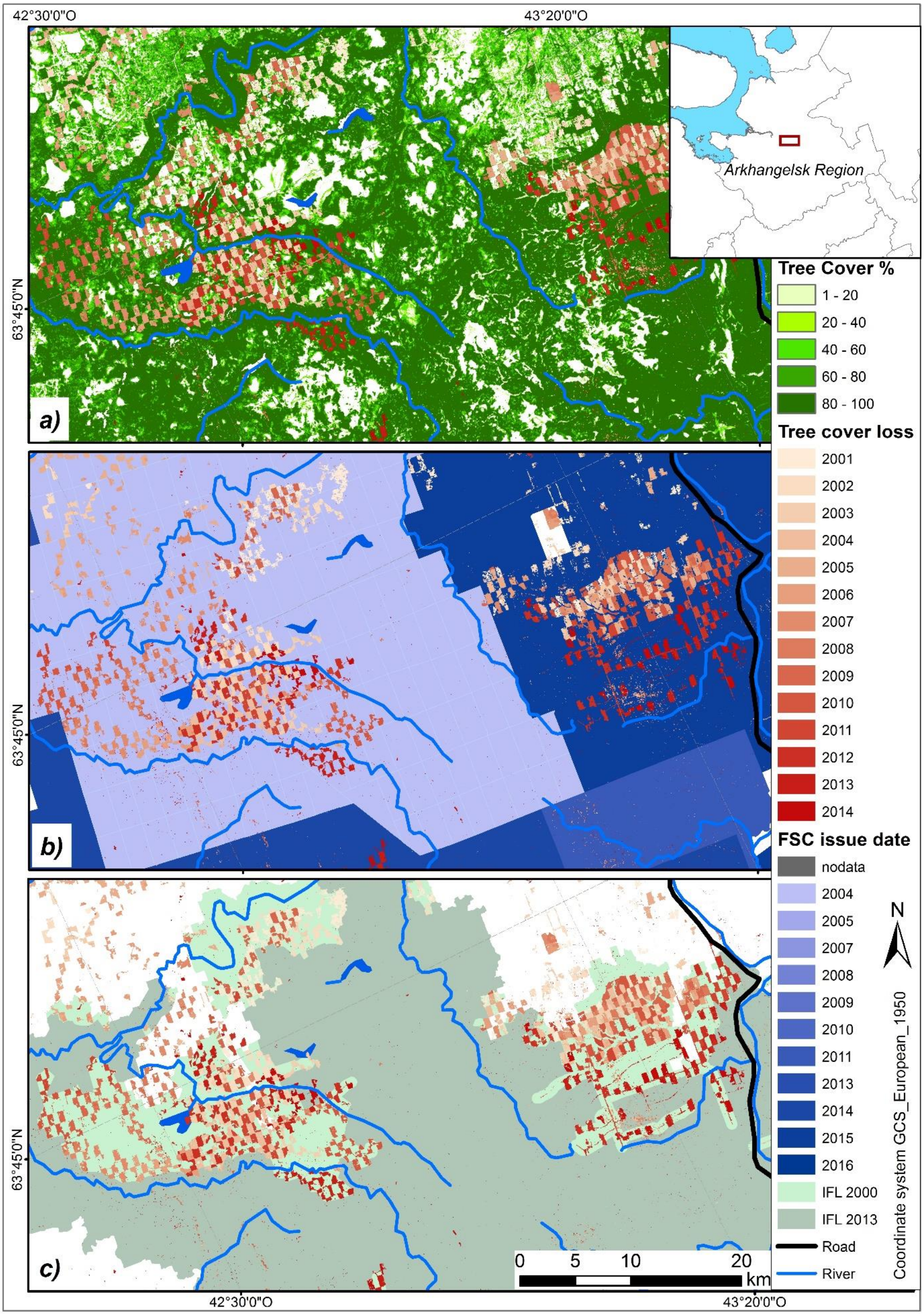

Figure 5. Forest, forestry and FSC certification within an example area in the centre of the Arkhangelsk Region: a) tree cover (light to dark green) is being reduced by consecutive geometric clear-cuts(light to dark red) [50]; b) tree cover loss patterns before and during valid FSC certification (colours from light to dark blue indicates the issue date of FSC certification) [50,51]; c) annual tree cover loss has reduced the extent of intact forest landscapes (IFL) [32]. Other visible data includes roads and rivers [55].

Between 2000 and 2014, almost one million hectares of forest in the Arkhangelsk Region were affected by tree cover loss, of which more than half was recorded within the concessions that were already FSC-certified or had acquired certification during this period (Figure 6).

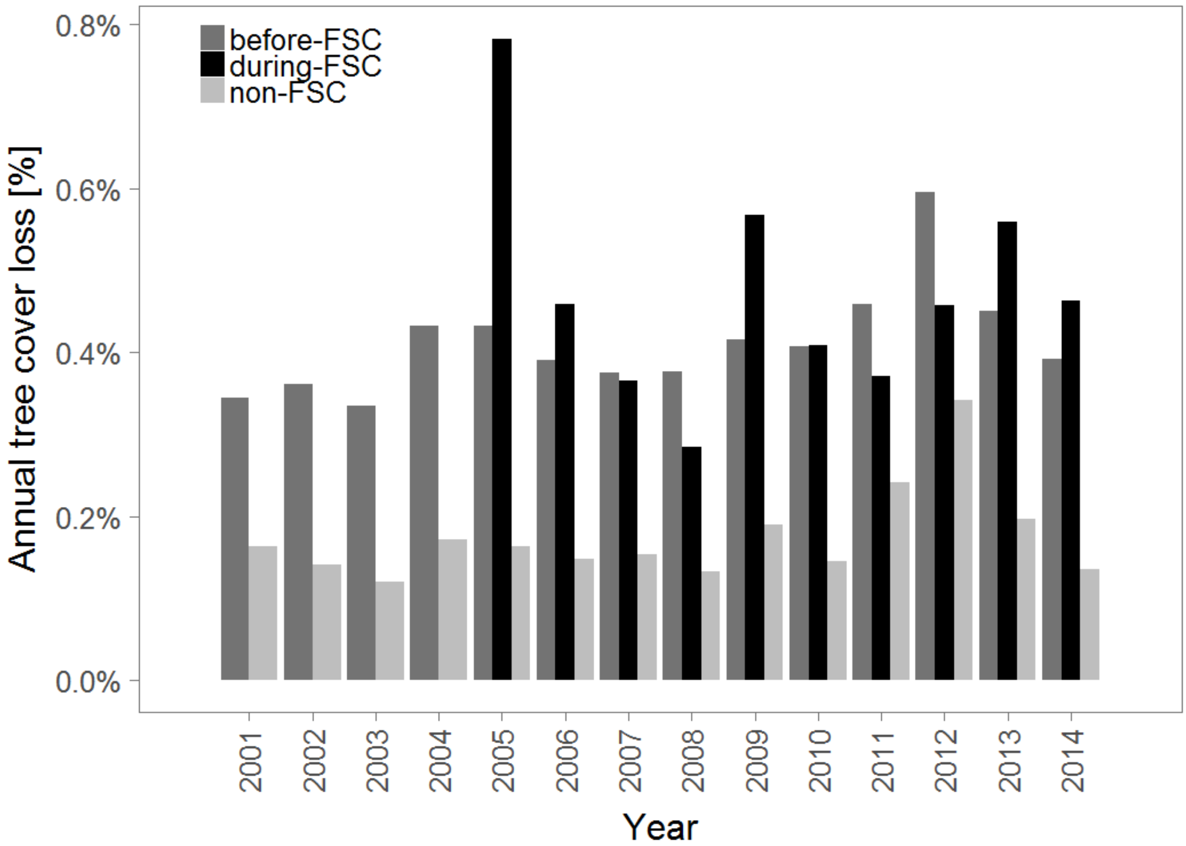

Figure 6. Annual tree cover loss between 2001 and 2014 [50] within and outside of FSC-certified areas in the Arkhangelsk Region. 'Before-FSC' refers to concessions where tree cover loss occurred before FSC-certificates were issued; 'duringFSC' indicates tree cover loss that happened while FSC-certificates were valid; non-FSC covers areas for which no FSC-certificates were available throughout this period.

Tree cover loss was detected in 5.35 % of the total area held by companies that have been or are in the process of certification compared with 2.44 % of forest that has never been under FSC-certification (Table 5).

Table 5. Tree cover loss inside (before-FSC: before FSC certification was issued; during-FSC: while FSC certification was valid) and outside (non-FSC) of FSC-certified logging concessions.

	Mean	Standard deviation	Median	Sum	Max	N	Coverage [ha]
before-FSC	1.20	9.18	0.10	431883	2701	361083	9358863
during-FSC	1.28	8.62	0.07	68353	1131	53554	
non-FSC	0.75	9.80	0.07	483649	4554	645889	19790859

4.5.2 Ecosystem-Based Situation Analysis with Experts

The set of causally interrelated elements representing the situation in the Arkhangelsk Region were identified during the expert workshops and illustrated in a conceptual model (Annex 1). The ecosystem complex '*taiga of Arkhangelsk*' is determined to be an umbrella **biodiversity object** encompassing 27 nested biodiversity objects. The nested objects include key species of flora and fauna within the three interacting sub-ecosystems forests, mires (ombrotrophic and mineralotrophic), and aquatic ecosystems. The diverse mosaic of forest ecosystems comprises spruce forest, aspen forest, broad-leafed forest, karst forest, dune forest, herbrich forests and riparian forests, and supports important fauna, including soil biota as well as aquatic and semiaquatic organisms. The workshop participants described 21 regulating, provisioning, and cultural **ecosystem services** that contribute to 11 objects of **human well-being** classified under: health, security, materials for living, and social relationships. The **Key Ecological Attributes** (KEA) consist of 11 abiotic factors relating to energy, humidity, lithosphere, wind, and temperature together with 23 biotic factors classified broadly under three categories: biomass (living and dead), information (genetic information), and networks (structures and interrelations). Biotic and abiotic factors, but particularly those attributes relating to networks and information, are found to be affected by human-induced disturbances. The lithosphere and the hydrological regime would also be impacted, but in general, abiotic KEA are considered to be less affected by the identified stresses than biotic ones. A total of 38 **contributing factors** (Annex 2) cause 20 **threats** (Annex 3) and are believed to be responsible for inducing 32 **stresses** (Annex 4) in the Arkhangelsk Region.

4.5.3 Rating of Stresses, Threats, and Contributing Factors

The semi-quantitative evaluation of stresses, threats, and contributing factors by experts and stakeholders suggests that all identified and rated contributing factors are important or extremely important in increasing the overall vulnerability of the conservation objects, which is represented by high values of *'criticality'*. **Contributing factors** relating to governance and socio-economics, forest management, institutional capacity and knowledge as well as nature protection are assumed to be the major and persistent drivers of negative changes in the taiga of the Arkhangelsk Region. The **threats** that are rated highest for criticality are linked to problems of *"Deforestation and forest degradation", "Infrastructure within the forest"*, the *"Construction of non-forest roads"*, and *"Extreme weather events"*. The problem of large-scale clear-cuts (*"Too big size of clear-cut"*), which in turn links up to *"Harvesting in HCVF, including intact forests"*, and *"Forest infrastructure"* is recorded as highly critical to the long-term security of biodiversity. One third of all identified **stresses** are considered to be very critical symptoms of negative impacts. In particular, *"Contamination of surface and underground water", "Decrease of natural forest regeneration", "Dissociation of populations - gene flow", "Change of forest age distribution - less very old trees", "More homogenous and contrast spatial structure", "Diversity of forest ecosystem is reduced", "Number of habitat is reduced", "Vulnerable species extinction", "Change of wood species - changed cycles"*, and *"Changed routes of animal migration"* are rated as extremely important stresses. Most of the rated elements are estimated to be moderately relevant. Apart from three contributing factors, none of the other factors, threats or stresses is rated as being highly relevant. Almost one fourth of all the contributing factors and less than one third of threats are recorded as being highly relevant (Figure 7).

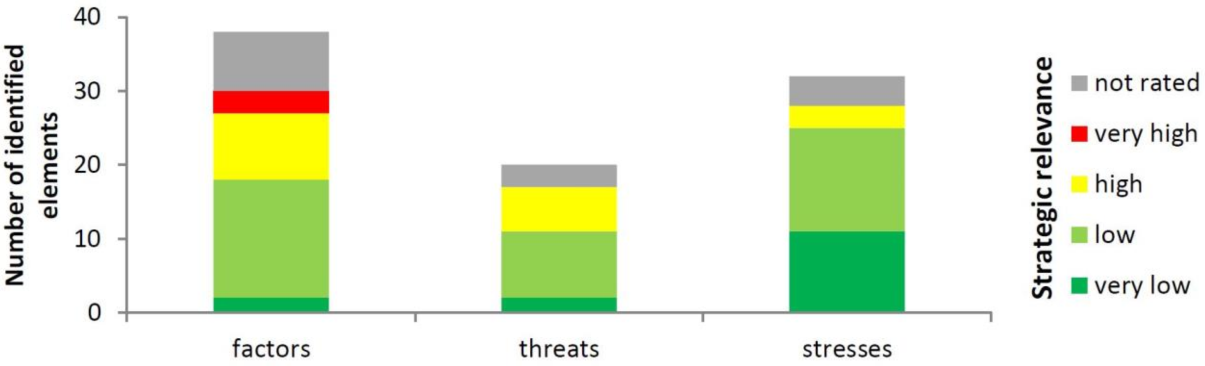

Figure 7. Distribution of values of strategic relevance rated for identified contributing factors, threats, and stresses.

The three most strategically relevant contributing factors identified in the workshop are linked to governance and include *"Too many norms, legislations & regulations", "Poor legislation & guidelines"* as well as the institutional factor *"Lack of long-term multipurpose planning"*. This suggests ambiguous and contradictory legal instruments and governance, together with insufficient specifications, hamper the effective implementation of ecologically relevant legislations. The strategically most relevant threats refer to large-scale forest degradation, infrastructure, landform configuration, and climate change. Changes to the natural structure and character of habitats are considered to be the most strategically relevant stresses including *"More homogenous and contrast spatial structure", "Diversity of forest ecosystem is reduced"*, and *"Number of habitat is reduced"*. The stated causes of natural habitat destruction given by the participants are manifold; the most important ones relate to forest management practices and the need for accessibility by roads.

4.5.4 Systemic Analysis of FSC Strategies

According to the experts and stakeholders, FSC strategies target more than 75 % of all identified contributing factors directly. Most of the contributing factors are addressed only once, but several strategies refer to the same contributing factor several times (Figure 8).

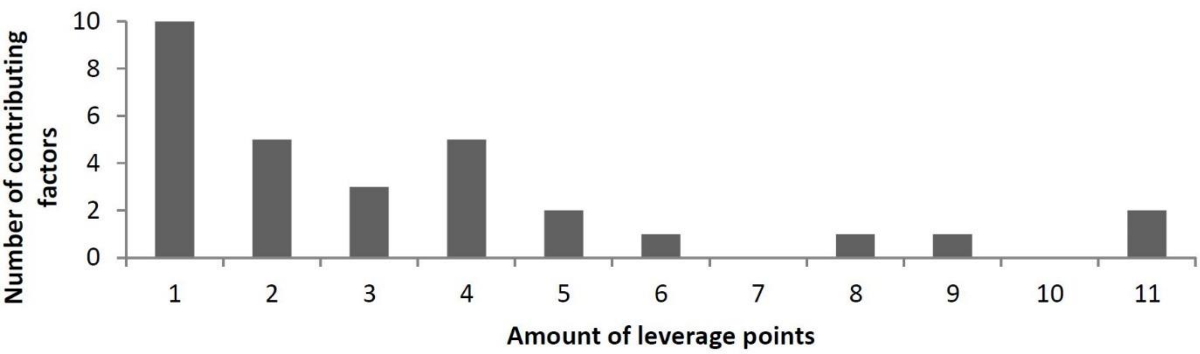

Figure 8. Frequency of leverage points: Number of counts contributing factors targeted by FSC strategies.

In total, 104 points in the conceptual model are leveraged on 29 different contributing factors by 39 different strategies. Two contributing factors, namely *"Poor law enforcement"* and *"Failure to involve stakeholders"*, are targeted most often and addressed by 11 different strategies. The estimated influence of the strategies ranges from weak and negative to strong and positive, whilst most strategies appear to influence contributing factors in a weak and positive way (Figure 9).

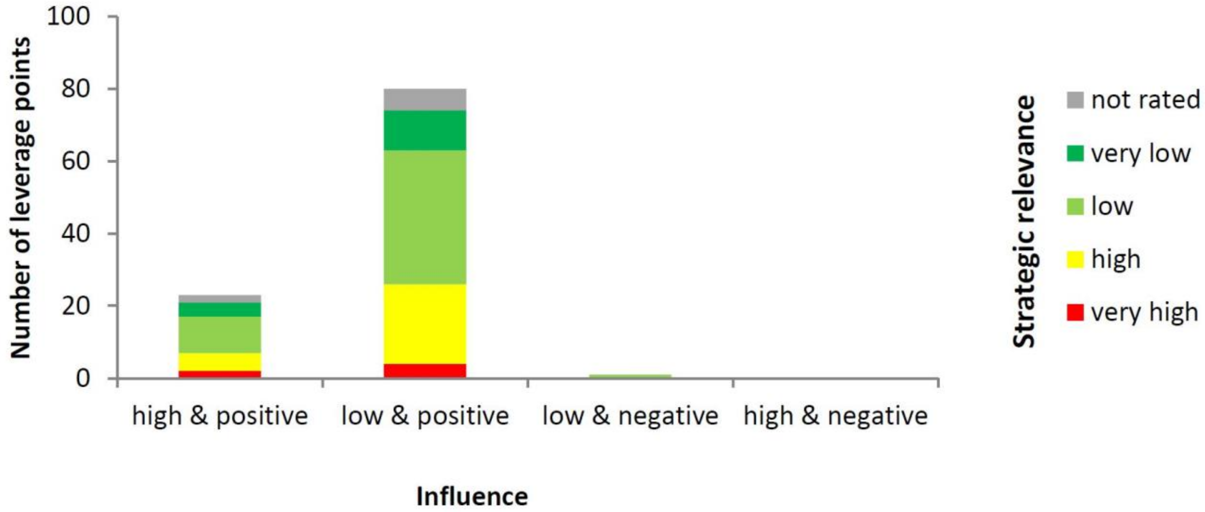

Figure 9. Distribution of strategic relevance of factors that are influenced by FSC strategies.

All contributing factors that are rated as being highly and very highly strategically relevant are addressed by FSC, whereas the two strategically relevant contributing factors *"Inadequate government control (of nature use)"* and *"Mining"*, as well as the two strategically less relevant factors *"Wish to make quick money"* and *"Violations of technological regulations"*, are understandably not covered by FSC (Figure 10).

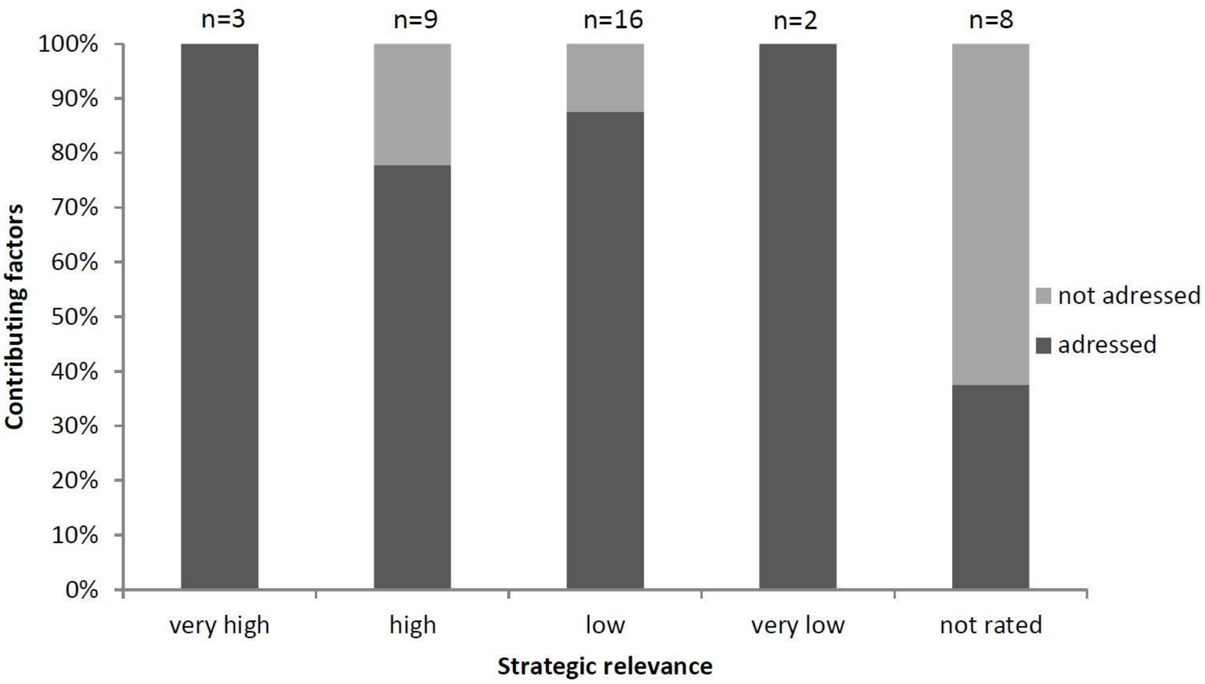

Figure 10. Contributing factors addressed directly by FSC and categorized according to their strategic relevance (1 = low, 4 = high).

Most of the strategies derived from the FSC criteria are assumed to target one or several of the contributing factors. A total of 17 strategies (including nine based on criteria describing principle 10: "Plantations") do not target any of the threats or contributing factors in the conceptual model. Some of the strategies are seen to relate more often to certain contributing factors than others. For example, criterion 1.6 ("Long-term commitment to FSC Principles and Criteria") is mapped most frequently and leveraged 11 factors. Three criteria, criterion 1.1 ("Respect all national & local laws and administrative requirements"), criterion 6.1 ("Complete Environmental Impact Assessment and integrate into management"), and criterion 6.2 ("Safeguards to protect rare, threatened and endangered species and their habitats; establish conservation zones and protection areas; control inappropriate hunting, fishing, trapping and collecting"), are referred to seven different contributing factors (Figure 11).

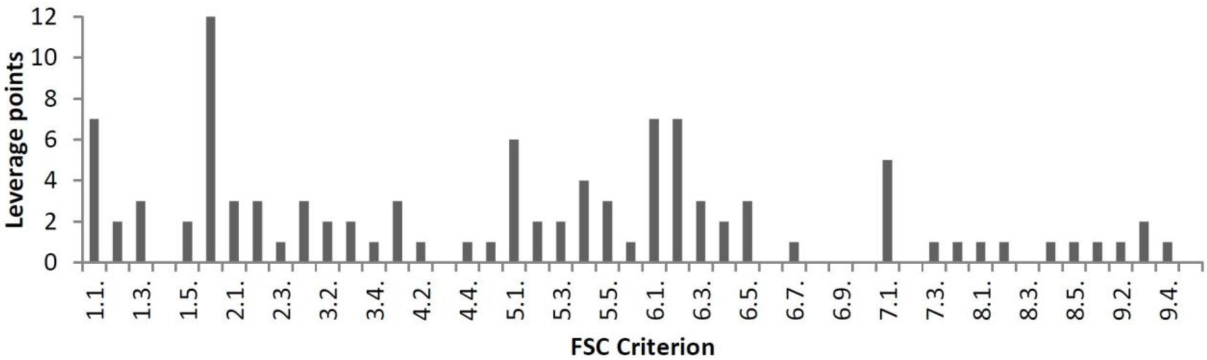

Figure 11. Histogram showing each of the FSC criteria and the frequency being referred to different contributing factors that were identified during the situation analysis.

4.5.5 Theory of Change

The following paragraphs present the results for the assessment of the potential outcomes of action triggered by FSC certification according to the postulated theory change (Annex 5). The scope of certification embraces the total leased area rather than including just selected sites. Consequently, all potential outcomes would have to apply to all FSC-certified logging concessions. Within the group of **contributing factors** linked to governance, FSC criterion 1.1 targets each of the contributing factors relating to legislation in a positive but weak way. In theory, the negative influence attributed to strategically relevant ineffective norms and the current legislation relating to forests and forestry are supposed to be reduced. The strategically relevant factor *"Corruption"* is considered to be reduced by the weak but positive influence of three different FSC criteria designed to enhance the documentation of legislative requirements and long-term land-use rights. Theoretically, FSC would lead to the provision of effective and clear legislation for responsible forest management, based on the given guidelines for road and bridge construction, and the contribution to a more stringent enforcement of administrative regulations. Illegal activities, including illegal logging, are assumed to be prevented under FSC. The rights, as well as all health and safety requirements of workers are believed to be respected. All kinds of applicable payments are supposed to be documented and promptly paid. The attendance by staff on training in the proper implementation of FSC and on forest management planning would, hypothetically enhance their level of knowledge, expertise, and proficiency. The expectation would be for clear and obvious compliance with laws and international treaties ratified by the Russian Federation. According to the experts, all factors relating to forest management would be directly influenced by various FSC criteria. As a possible outcome, the management objectives of a certified company would be defined in the long-term, at least for a minimum of five years. Poor forest management is expected to improve in certified forest companies by amending the forest management plans according to the findings of an Environmental Impact Assessment (EIA). In theory, the EIA would be conducted and a forest monitoring system would be established according to the guidelines anchored in the FSC standard. Moreover, it is assumed an economic analysis would be conducted and the findings incorporated into the forest management plan. A monitoring program is supposed to be established, being clearly documented, consistent, replicable, and regularly revised by the FSC-certified forest companies. Deviations from the management plan and discrepancies between actual and expected results would be assessed and considered in the revision of the management plan. It is presumed that transparency would be enhanced through the publication of management documents and monitoring results for certified companies, except in cases where confidentiality is required. Consequently, the quality of available information would be enhanced, including environmental, economic, and social aspects of forestry as well as improved access to information on natural resources for planning purposes. In addition, FSC is expected to deliver improvements in the availability of data on yields, growth rates, forest composition, regeneration, and changes in the composition of flora and fauna. The analysis concludes that FSC would lead to a reduction of logging in primary or old-growth forests. In theory, FSC requires HCVF areas to be identified and considered in the planning and the implementation process of forest management operations. Stakeholders, such as local people, authorities, administrations, and forest managers would be technically consulted, especially in the frame of a social impact analysis. Land-use rights for indigenous people and their access to natural resources are requirements for companies operating under FSC. The interests of local communities extend to unrestricted access to timber and non-timber forest resources. In principle, the FSC PCI are designed to reduce the risk of disputes and grievances between local communities and commercial companies, and in part, this is achieved through an anticipated enhancement in environmental and social awareness amongst forest workers and staff by providing training, and by employing predominantly local people with strong concerns for the forest and its natural resources. In theory, the planning and implementation of forest management under FSC takes into account international treaties as well as conventions on biodiversity conservation and protected areas. For example, the identification, monitoring, and protection of rare, threatened and endangered species, key habitats, and HCVF would be developed by researchers and in consultation with specialists and other stakeholders, and then implemented by the certified company. Thus, in theory, it is assumed that HCVF and undisturbed areas would be protected from forestry activities and buffer zones would be established around sensitive sites. Under FSC, water protection zones would be maintained and riparian areas that have been degraded by forest operations would be restored. Moreover, a network of representative examples of existing ecosystems is supposed to be established and management restrictions observed. The effectiveness of conservation measures on HCVF would be assessed annually by the certified company. Participants assume that under FSC, the annual allowable cut (AAC) is calculated sustainably. Forest operations would take account of economically inaccessible regions and areas where logging is restricted, such as in HCVF. The rationale for the calculation of AAC and planned harvesting level is expected to be provided in the management plan of FSC-certified logging companies. The financial resources needed to implement the forest management plan would be available at certified companies. As a potential result, it is postulated that forest management would be conducted according to the management plan and any negative environmental impacts due to forest operations described as “cut-and-go practice” are reduced. FSC promotes the use of all merchantable woody resources and the diversification of utilized and processed forest products. Thus, it is assumed that a FSC-certified forest company would optimize their expenses by an effective economic analysis being incorporated into the management plan. Data on costs, productivity, and efficiency of the forest management are supposed to be collected and analyzed by FSC-certified forest companies. This is expected to result in high profitability and economic sustainability that would also contribute to stabilizing the local economy. As a theoretical result, income opportunities for the local population are enhanced by getting the chance of an employment in the forestry sector and the possibility to increase incomes of forest workers by negotiating with their employers. The illegal use of natural resources would be banned under FSC. The changes to contributing factors by FSC are assumed to initiate a strong and positive influence on 45 %, and a weak and positive influence on 30 %, of the identified threats. All of the strategically least relevant threats are anticipated to have a strong influence in a positive way (Figure 12).

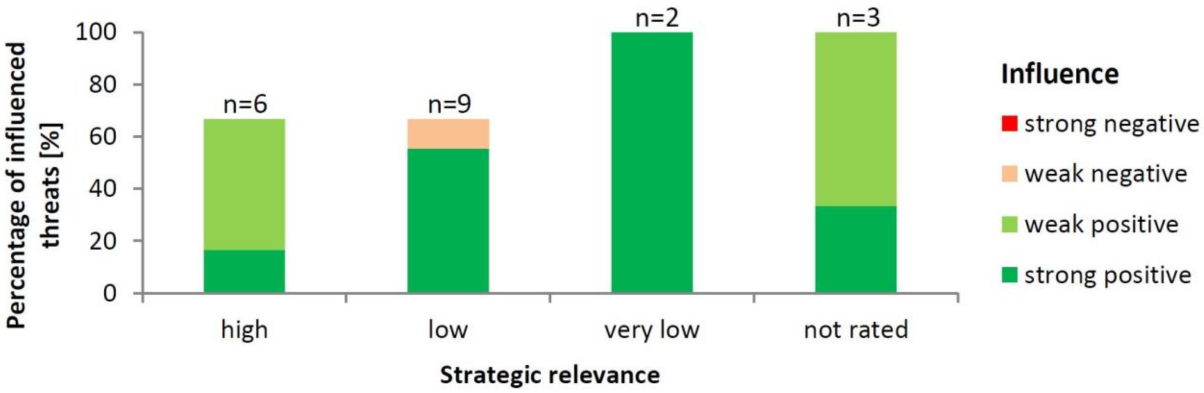

Figure 12. Influence of FSC strategies on described threats categorized according to their strategic relevance.

Half of the threats believed by the participants to be strategically relevant, in theory, are, likely to be influenced by FSC in a weak and positive way, whilst 17 % are considered to be effected in a strong and positive way. For each of the targeted threats, threat-reduction-results are formulated (Annex 6). Only one of the threats, namely *"Gathering of forest litter"*, is assumed to be negatively influenced due to the diversification and optimal use of forest that increases the collection of forest residues. A strong and positive influence is postulated for 60 % of the identified threats. The strong and positive influence of FSC is assumed to mitigate all identified threats leading to large-scale tree cover loss. In theory, the strong positive influence of FSC would reduce the size of clear-cut patches and also decrease the percentage of clear-cuttings, prevent logging in HCVF, reduce the deterioration of soil quality, avert the change of soil composition and hydro melioration, lower the excess of allowed cut during selective logging, induce selective logging without damaging trees, and foster a more sustainable use of nontimber forest products. Potentially, the identified negative impacts of infrastructure on the forest ecosystem induced by the construction of new roads and bridges would be slightly reduced. Moreover, the weak and positive influence of FSC requirements would reduce the overexploitation of timber resources and encourage negotiations as well as agreements between the certified forest company and communities about the location of pastures. Moreover, changes in the hydrological regime are supposed to be avoided, and water quality would be maintained. The anticipated reduction of perceived threats to the forest environment is estimated to reduce almost half of all identified stresses (Annex 7). Most of the stresses are anticipated to be moderately reduced. The three most relevant stresses are expected to be influenced in a weak and positive way (Figure 13).

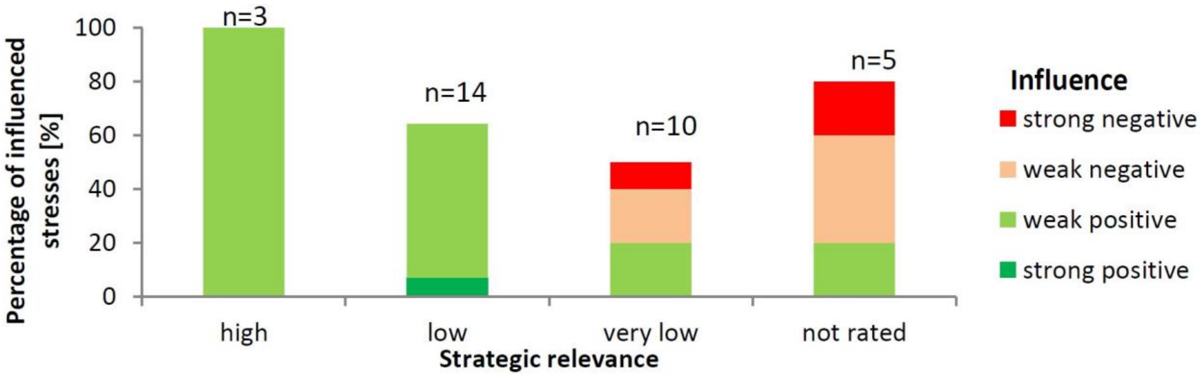

Figure 13. Influence of FSC strategies on stresses of different strategic relevance.

One single potential stress-reduction result, namely *"Reduced anthropogenic forest fires"*, being rated as less strategically relevant, is transformed through a strong positive influence of FSC. The presumed reduction of tree cover loss in HCVF, key habitats, and representative samples of ecosystems would contribute to a loss of habitat for forest-dwelling species in general, but forest operations and habitat degradation would continue elsewhere within the concession. FSC certification does not specifically require the restoration of degraded forests. The homogeneity and loss of forest diversity are assumed to be reduced by the promotion of smaller and fewer clear-cuts, and retaining mature and old trees in primary forests under the FSC regime. The potential for regeneration in logged forests is supposed to be improved by supporting natural rejuvenation and retention of seed-trees. The extinction of vulnerable species and the disturbance of forest fauna would be possibly reduced where rare, threatened and endangered species and their habitats are identified and where protection or restoration measures are implemented. The intensity of flooding is supposed to be reduced by retaining or restoring riparian vegetation. The quality of water would improve thanks to reduced pollution after FSC-certification.

4.5.6 Gap Analysis

Four of the identified contributing factors are assumed to be out of the scope of FSC. In particular, *"Mining", "Agricultural activities", "Global human population growth"*, and *"Increasing global resource demand"* are neither directly nor indirectly related to forest management. Those contributing factors are not directly manageable by applying forest management strategies and are not addressed by the PCI. All identified threats, apart from the climate change related threat *"Extreme weather events"*, are supposed to be impacted by forest management operations and could potentially be strategically influenced by forest certification. The gap analysis revealed that *"Inadequate government control (of nature use)"* and the introduction of exotic fauna, together with the disruptions they can cause to forest ecosystems, as well as *"Overhunting"* of animals (except for those species identified as rare, threatened or endangered) would remain unaddressed by FSC. FSC targets the negative impacts of infrastructure construction and the reduction of negative impacts of existing infrastructure on biodiversity, but only inside designated IFL. FSC does not address forest fragmentation and isolation outside IFL and HCVF, including areas that are voluntarily spared from felling, inaccessible or unprofitable for timber extraction. According to the Russian FSC standard, timber logging companies are not required to alter the systematic and extensive felling of trees according to the prevailing 'checkerboard system'. Large-scale forest degradation is likely to continue unless there is active conservation planning to establish wildlife corridors at a scale appropriate for the needs of large mammals such as elk, bear, wolf and wild reindeer. Continuing with current practices in forest management, even under FSC certification, is predicted to disadvantage large mammal populations and to contribute further to ecosystem degradation. Changes in the migration routes of the larger mammals are addressed indirectly by FSC through the specifications for HCVF, representative ecosystems, and through ecological networks. All criteria and indicators associated with principle 10 (*"Plantations"*) do not apply to the situation analysis, as all forestry in Arkhangelsk Oblast is carried out in primary and secondary forest landscapes. In the situation analysis, the conventional forest management scenario is described with no reference to potential conflicts between FSC PCI and national legislation. As a result, criterion 1.4 (*"Conflicts between laws, regulations and the FSC Principles and Criteria shall be evaluated for the purposes of certification, on a case by case basis, by the certifiers and the involved or affected parties"*) does not apply. The matter relating to forest employees is not recognized by the workshop participants as an issue likely to affect the ecology of the forest, and this is reflected in the analysis. The specific FSC criterion 4.3 (*"The rights of workers to organize and voluntarily negotiate with their employers shall be guaranteed as outlined in Conventions 87 and 98 of the International Labor Organization (ILO)"*) does not address any of the threats and contributing factors in the conceptual model. Another example of non-coverage by FSC standards relates to the use of pesticides. In the case of Arkhangelsk, there is no pest management. For this reason, criterion 6.6 (*"Management systems shall promote the development and adoption of environmentally friendly nonchemical methods of pest management and strive to avoid the use of chemical pesticides. World Health Organization Type 1A and 1B and chlorinated hydrocarbon pesticides; pesticides that are persistent, toxic or whose derivatives remain biologically active and accumulate in the food chain beyond their intended use; as well as any pesticides banned by international agreement, shall be prohibited. If chemicals are used, proper equipment and training shall be provided"*) and criterion 6.8. (*"Use of biological control agents shall be documented, minimized, monitored and strictly controlled in accordance with national laws and internationally accepted scientific protocols. Use of genetically modified organisms shall be prohibited"*) do not relate to any of the threats and contributing factors recorded by the participants. Similarly, exotic species are not addressed by forest management operations in Arkhangelsk, and so, criterion 6.9. (*"The use of exotic species shall be carefully controlled and actively monitored to avoid adverse ecological impacts"*) is not mapped into the conceptual model. Criterion 6.10 (*"Forest conversion to plantations or non-forest land uses shall not occur, except in circumstances where conversion: a) entails a very limited portion of the forest management unit; and b) does not occur on high conservation value forest areas; and c) will enable clear, substantial, additional, secure, long term conservation benefits across the forest management unit"*) does not apply because forest in Arkhangelsk is logged exclusively for timber harvesting. The operational guidelines in the conventional forest management that influence the logging operations are not described in a way that allowed to map criterion 7.2. (*"The management plan shall be periodically revised to incorporate the results of monitoring or new scientific and technical information, as well as to respond to changing environmental, social and economic circumstances"*). Concerning matters relating to forest economics, the criterion 8.3 (*"Documentation shall be provided by the forest manager to enable monitoring and certifying organizations to trace each forest product* *from its origin, a process known as the "chain of custody"*) does not apply to the identified elements that ecologically influence the forest ecosystem.

4.6 Discussion

The findings of this study are broadly in line with the outcomes of previous research carried out on the effectiveness of FSC in that compliance with FSC standards has the potential to influence substantially most activities associated with commercial forestry [56]. Previous assessments on the effectiveness of FSC using interviews and questionnaires concluded there was a positive ecological benefit to forest biodiversity and ecosystem integrity from FSC [57]. In our conceptual model of the Arkhangelsk Region, a considerable proportion of contributing factors relating to forest management, including monitoring and evaluation but also the institutions' capacity and knowledge, were assumed to be transformed towards the better by FSC. Consequently, following the theory of change, FSC has the potential to reduce a range of anthropogenic threats such as large-scale deforestation, logging in HCVF and intact forests, large clear-cuts, excessive AAC, tree damage, and hydrological changes. However, the reduction of human-induced forest fires was assumed to be the only stress abated effectively. The semi-quantitative evaluation of the FSC-induced influence, as estimated during the theoretical plausibility analysis, suggests that FSC could produce even more effective outcomes for biodiversity by targeting identified problems more specifically and precisely in order to generate a strong and positive influence on relevant drivers of negative environmental impacts. Quite a few FSC-induced measures seem to induce rather minor improvements. For instance, the concept of safeguarding biodiversity by adopting a 'setaside' area such as HCVF is in contrast to more contemporary thinking that advocates the ecosystem-based approach targeting functional landscape ecosystems rather than small even though representative patches. The protection of parts of commercially used forests with high conservation values and key biotopes by FSC is important for biodiversity conservation in Russia [58]. However, the size and quality of HCVF were found to be much more related to the scale and type of tenure but were also regarded as a means of demonstrating compliance with existing legislation for designated protected species, and not for maintaining or promoting ecosystem function [59]. A more in-depth analysis and evidence-based study is recommended to determine the effectiveness of current HCVF in reducing biodiversity loss and maintaining ecosystem functionality, especially in the boreal zone. More specific guidance for forest managers on the control and restoration of habitats, including riparian vegetation and wildlife corridors is strongly recommended. A key finding is that the participatory situation analysis does not entirely match with findings gathered from the spatial analyses and field visitations. According to the conceptual model developed by the workshop participants, large-scale clear-cuts present a key problem of unsustainable forestry practices in the region. Apart from fragmenting habitats and reducing populations of organisms, this creates massive impacts on soil and hydrology, leads to largescale land cover change and is likely to change micro- and mesoclimate. The clear-cuts do not resemble large-scale natural disturbance such as forest fires. Fires do not lead to almost complete loss of biomass and nutrients, and do not mechanically change the soils – as industrialized timber mining does. FSC PCI would encourage small-scale, close to nature practices of harvesting that would mimic natural gap dynamics in boreal forests. This is not supported by the spatial analysis and site visits, which indicated substantial clear-cuts of 50 hectares or more, after a few years covering much larger areas of consecutively cleared forest. The conventional 'checkerboard' clear-cutting continues even after certification, and clearly progresses into IFL as shown for the example area. The loss of tree cover under certification appears to increase over time in response to a greater up-take of certification by commercial companies operating in the field. Our analysis does not suggest that FSC certification promotes large-scale clear-cutting in primary forests, but equally, there is no evidence for either a decrease or avoidance of large-scale degradation of forest cover in certified areas. Theoretically, deviations observed from expected outcomes can also be related to an incomplete implementation of FSC criteria and indicators. This would be corrected during the audits. Indeed, more than half of the so called corrective action requests (CAR) that were raised during FSC audits were related to environmental issues [60]. However, the key problem of large-scale clear-cuts in primary forests seems to be compliant with the Russian standard which gives reasons for serious concerns. The continued practice of large-scale clear-cuts has far reaching consequences for the forest environment. In particular, it causes long-term degradation to soils and the hydrological regime, and also affects local climatic conditions. The complex ecosystem with its mosaic of mires, peats, and water systems contributes substantially to the resilience of the planet, specifically, they contribute to the global temperature balance [61] and store huge amounts of carbon [62]. However, the boreal is also a deeply vulnerable ecosystem, responding rapidly to human disturbance. Most of the fires in recent times can be attributed to human activity, and also the change in fire frequency and intensity that threatens the survival and resilience capability of the boreal zone. Regarding climate change, FSC refers to the United Nations Framework Convention on Climate Change and whilst certain criteria target climate change mitigation by restricting forest conversion (6.10), reducing erosion (6.5), and supporting forest regeneration (6.3 and 8.2), a more specific guidance on developing and adopting climate change adaptation measures is urgently needed to foster sustainable development and to ensure the provision of ecosystem services by the boreal forest of the Arkhangelsk Region in the long-term. The findings of our spatial analysis are in line with recent studies from other continents that found no or very limited effects of certification on halting tree cover loss [18,48,63,64]. Especially in the case of poor forest governance, forest certification alone cannot limit deforestation [65]. The disparity between theory and reality revealed in this study underpins the need for generating measurable indicators along the postulated cause-effect chains following the theory of change induced by FSC certification. By employing a definitive set of indicators as part of a complementary empirical assessment of FSC practice in the field, it should be possible to effectively assess the benefits and drawbacks of the certification scheme.

4.7 Conclusions

The theoretical plausibility analysis revealed that FSC is able to address various elements critical for the effective functioning of forest ecosystems in the Arkhangelsk Region. However, any perceived benefits on forest management were, according to the theoretical assessment, deemed to be weak and likely to result in ineffective outcomes for safeguarding biodiversity and ecosystem services in the long-term. An ecosystem-based forest management, which is specially tailored to the present situation, is highly recommended, under certification or not. The postulated success in reducing identified environmental threats and stresses through a smaller size of clear-cuts, more selective logging, and harvesting in secondary forests needs further investigation and evidence on the ground, including additional spatial analysis. Sustainability standards that are unable to translate principles into effective action with measurable outputs will fail in meeting intended objectives of safeguarding the environment and securing human well-being. The discrepancy between the guidance provided by the PCI and its interpretation by certification bodies and the implementation on the ground are noted even within the FSC itself [13]. Inevitably, the setup of certification systems reflects the philosophy and expertise of its designers [66]. In the case of FSC, the three chamber system was designed to balance ecological, economic and social impacts of certification. Actually, this is not compatible with an ecosystem approach that accepts that humans and their activities are dependent components of the ecosystem, which therefore must be kept functional by all means. Recent FSC decisions on rejecting ‘Motions’ such as the “Landscape Approach to Protect Intact Forest Landscapes at the Landscape Level” (Motion GA2017/17, FSC 2017) at the general assembly 2017 in Vancouver, Canada, give the impression that the development of relevant ecological issues can easily be outvoted by one of the other chambers [67]. The modus operandi of FSC based on the development of national interpretations of the global principles and criteria seems to provide a solid fundament for creating an effective, regionally adequate sustainability standard. But there is no evidence that beyond the audits of certified companies or concessions, FSC systematically compiles overarching assessments on certification effectiveness for further development of the various national standards. The franchising-like approach, where a good part of the responsibility for the national standards is delegated to national experts influenced by the corresponding conceptual and legal frameworks, does not allow for consistency and credibility of the standard. The simple fact that, according to the Russian FSC standard (and legislation), it seems to be acceptable to exploit primeval forests by creating large-scale clear-cuts, seriously undermines the credibility of FSC.

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5. Ecological effects of clearcutting practices in a boreal forest (Arkhangelsk Region, Russian Federation) both with and without FSC certification

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5.1 Abstract

The Forest Stewardship Council (FSC) is widely recognized as certification standard for responsible forest management across all major forest biomes. Still, only few field studies assessed if FSC certification generates measurable positive impacts in a managed forest ecosystem. Consequently, unequivocal evidence on ecological effectiveness of FSC is scarce. Especially the Russian boreal forests, where FSC has shown a rapid growth of certified areas, have hardly been studied regarding ecologically positive achievements delivered by certification compared to conventional practices. In this case study, systematic research was carried out to assess the ecological effectiveness of FSC in the boreal forests of the Arkhangelsk Region, Russian Federation. At harvested sites belonging to two companies, managed with and without FSC-certification respectively, and at a primary reference forest, 95 variables related to five indicators (living tree biomass, deadwood, rejuvenation, vegetation, and microclimate regulation) were empirically assessed. With regard to the most ecologically relevant parameters chosen for this study, there were very few substantial differences of FSC-certified forestry operations to conventional ones. This can be explained with the equally high amounts of harvested timber (ca. 97 % extracted) as well as the practice of large-scale clearcutting (up to > 50 ha), generating significant structural and functional ecological changes in the forest ecosystem. The findings suggest that there is no real change in forest operations towards an ecologically responsible harvesting. Rather, FSC-certified forestry contributes to the ongoing loss of primary forests in the remaining Intact Forest Landscapes, and FSC does not seem to slow down the loss of ecosystem functionality. Actually, the large-scale clearcuts do not resemble any comparable natural disturbance regime and produce risky ecological changes related to micro- and mesoclimate. Our data show substantial heating of the large clearcuts and the loss of ecosystemic buffering capacity, being highly relevant in the context of vulnerability to climate change.

5.2 Keywords

FSC; effectiveness; Arkhangelsk; clearcut; microclimate; forestry

5.3 Introduction

Functional forest ecosystems and the manifold services they provide are a key resource for human wellbeing (Aerts and Honnay, 2011; MEA, 2005; Miura et al., 2015; Mori et al., 2017). Predominantly, forests have been utilized to mobilize timber resources for firewood, construction, pulp and paper, and are increasingly seen as source for new types of biofuel (Curtis et al., 2018; Hosonuma et al., 2012). The world's forests are under anthropogenic pressure driven by an ever increasing demand for timber resources, urbanisation, fragmentation, and impacts of climate change (Kissinger et al., 2012). Deforestation and forest degradation are associated with biodiversity loss and greenhouse gas emissions (Baccini et al., 2012; Foley et al., 2005; Giam, 2017; Harris et al., 2012; Thompson et al., 2013; van der Werf et al., 2009). Environmental concerns regarding the importance of maintaining functional forest ecosystems and promoting sustainable use are permanently growing (Auld et al., 2008; Kraxner et al., 2008). Especially, European markets are increasingly demanding sustainably produced products (Golden et al., 2010; Henry and Tysiachniouk, 2018; Rametsteiner and Simula, 2003). Market-based instruments such as voluntary certification schemes have emerged and globally gained importance in terms of trade volumes as well as certified areas and companies (Kraxner et al., 2017; MacDicken et al., 2015).

About 25 years after creation as the first forest certification standard, the Forest Stewardship Council (FSC) has become a well-known tool for labelling timber and wood products as responsibly produced by managing forests sustainably. Assumed to be credible and effective, FSC was approved as a measure for accomplishing at least 11 goals and 35 targets within the framework of the Sustainable Development Goals (SDG) (FSC, 2016; Ugarte et al., 2017). However, there have been few studies carried out to assess the on-site impacts of FSC and even less show a more or less clear and positive impact of FSC-certification on the ecosystem (Blackman and Rivera, 2010; Burivalova et al., 2016; Romero et al., 2017). To ascertain the effects of a certification scheme on the ground, a comparison with a non-certified conventional management systems as well as a non-managed system is a logical approach. Such assessments have been demanded for quite a while (Elbakidze et al., 2011). Still, corresponding empirical studies and environmental indicators as well as standardized methodological approaches to measure the ecological effectiveness, including the improved maintenance of ecosystem functionality by certification schemes, were missing. To close this gap, we have developed a methodological framework (ECOSEFFECT) to assess sustainability standards and their effectiveness (Blumroeder et al., 2018).

Amongst the forest biomes, the taiga stands out as the largest forest ecosystem complex, representing a giant carbon pool and climate regulator of global relevance. Boreal forests constitute more than 40% of the global Intact Forest Landscapes (IFL) being confined to mainly two countries, the Russian Federation and Canada (Potapov et al., 2008). According to the forest harvest index, the Russian Federation was the country with the second-largest timber exports worldwide (Furukawa et al., 2015). The European boreal forests have been called a timber frontier, where exploitation started with extensive wood-mining of primary forests (Angelstam et al., 2018, 2017, 1997; Naumov et al., 2016; Nordberg et al., 2013; Pennanen and Kuuluvainen, 2002). A primary forest is characterised as a "forest that has never been logged and has developed following natural disturbances and under natural processes, regardless of its age" (Secretariat of the Convention on Biological Diversity, 2002).

After the collapse of the Soviet Union, the European market had become ever more relevant to Russian timber companies and it was inevitable that mounting public and political pressure within consumer countries for stronger environmental regulation was going to drive demands for certified forest products. Currently, the Russian Federation is the country with the most FSC certificate holders, covering an area of more than 45 million hectares, as of June 2018 (FSC, 2018). Especially the Arkhangelsk Region, located in the Northwest of the country, has a relatively long history and an extensive coverage with FSC certificates (Blumroeder et al., 2018).

Given the rapid growth in FSC-certification in this region as well as the lack of quantitative research that provides evidence for the effectiveness of FSC, we carried out a systematic and comprehensive study looking at the potential and actual impact of the standard in mitigating ecological problems created by conventional logging, which is represented by clearcutting in the case of the Arkhangelsk Region. Our investigation embraced a theoretical plausibility analysis (Blumroeder et al., 2018), spatial analyses, and an empirical study comparing certified areas with uncertified sites and with unmanaged primary forests. The theoretical plausibility analysis revealed that FSC-certification does not seem to stimulate a sufficient change in conventional forestry practices such as moving away from large-scale clearcuts to safeguard the forest ecosystem functionality (Blumroeder et al., 2018). The biggest problems clearly represent large-scale clearcuts of up to 50 ha, which are acceptable under the Russian forest legislation, as well as the fact that certified timber is harvested in primary forests, which decreases the last remaining IFL (Blumroeder et al., 2018; Potapov et al., 2017, 2009).

In this paper we present the results of the empirical analysis, concluding the cycle of the ECOSEFFECT methodology that was developed to assess the ecological effectiveness of sustainability standards (Blumroeder et al., 2018, 2017). The aim of this study is to assess and quantify selected ecological impacts of clearcutting-based forestry in a boreal forest of the Arkhangelsk Region, both with and without FSC certification. Focussing on a case study of two selected companies we also suggest a new methodological design and a variety of indicators for measuring the impacts that harvesting practices have on the forest ecosystem.

5.4 Materials and Methods

All data analyses were performed with R (versions 3.4.3, 3.4.4, and 3.5.0) (R Development Core Team, 2008). Microsoft Excel (2010) was used for the random selection of plots, and ESRI ArcMap (10.2.2) for study site demarcation and the determination of study plot locations as well as for the preparation of spatial data and maps.

5.4.1 Study location and research design

The study region is located in the European taiga, in the north-western Russian Federation, eastern Arkhangelsk Region (Figure 1).

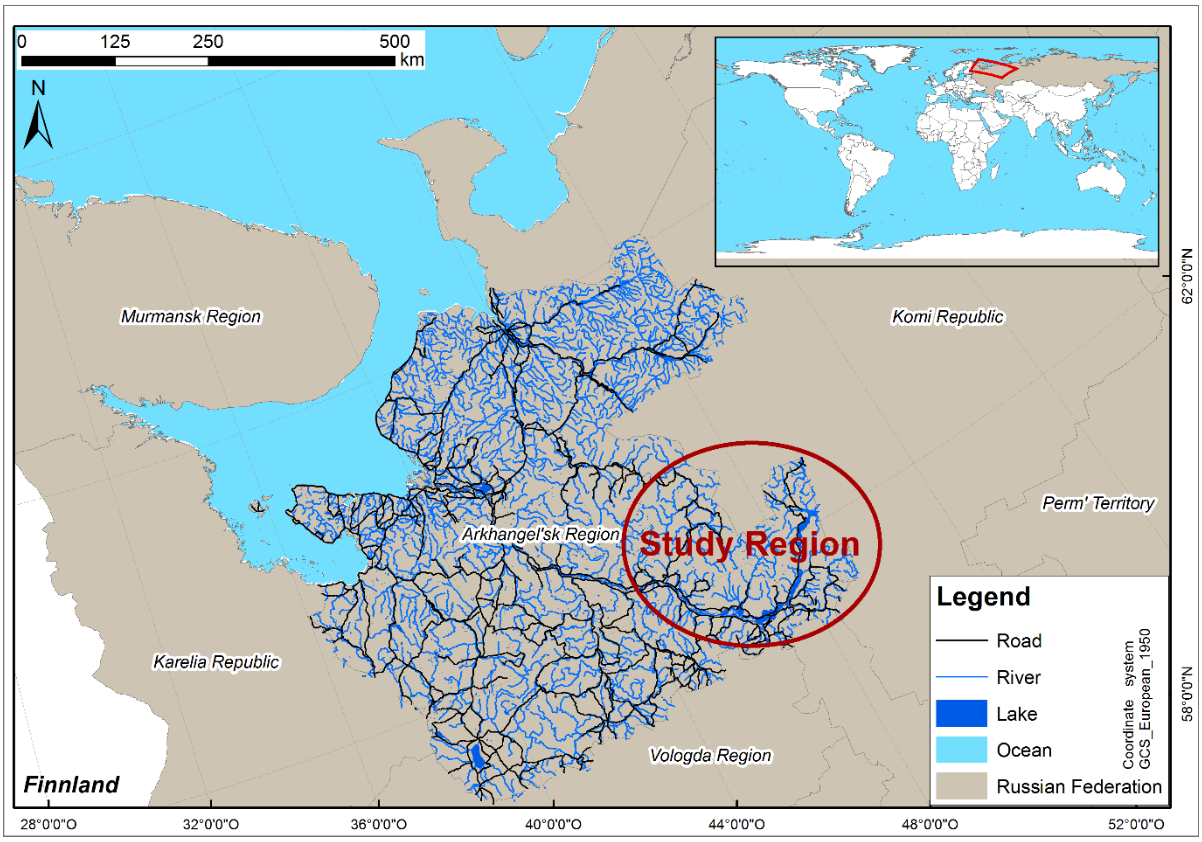

Figure 1: Study region in the east of the Arkhangelsk Region, Russian Federation.

The scope of the study encompasses forest management units of two forest companies that agreed to support the research if they remained anonymous. The two companies were similar regarding the time of logging, forest and soil type, and logging techniques. Accessibility and relative proximity of logging sites to ensure similar climatic and comparable local environmental conditions were also considered when selecting the sites. Based on a preliminary analysis of the study area using spatial data, local consultation with foresters, and in-field inspections, the study sites selected deemed to be representative of typical Arkhangelsk forestry operations (compare Blumroeder et al., 2018; Greenpeace International, 2017, 2014; Karvinen et al., 2011, 2006). Logging was completed between 2009 and 2011 using a clearcut system of harvesting. The area of forest representing the FSC site was harvested by a company that had received FSC certification status in 2006 (referring to 'FSC' in the following). The second company by now is FSC-certified as well, but the investigated sites were logged several years before the company became certified and certainly before the company intended to strive for certification in 2013, correspondingly, it served as the non-certified counterpart ('non-FSC' in the following). Within each of the two companies' forest management units, five clearcuts were randomly selected as study sites and a 50m wide grid was generated within each clearcut of which four points were randomly selected as study plot locations. Primary spruce forest in direct vicinity served as an ecological reference area ('reference' in the following), and was sampled using the same plot design (Figure 2).

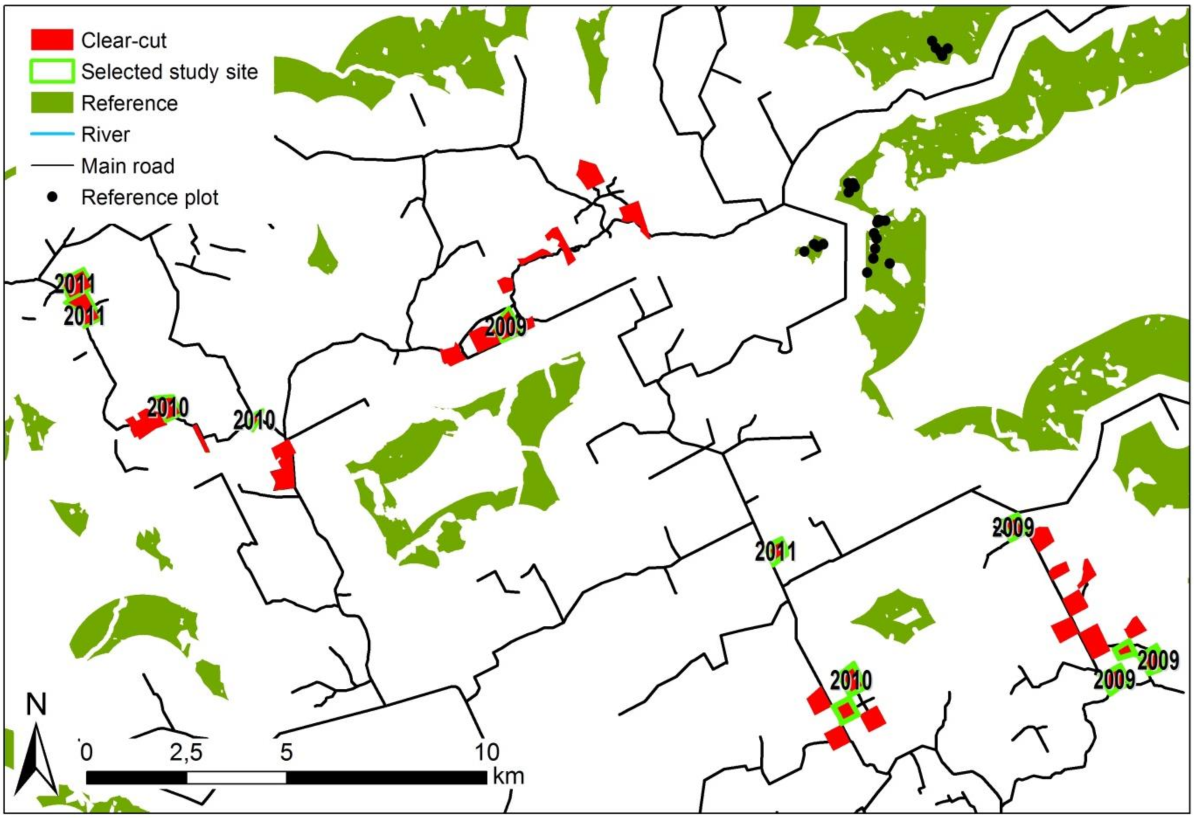

Figure 2: Distribution of investigated study sites, within which study plot locations were randomly determined, and reference plots. Numbers displayed represent the surveyed clearcuts and the year of logging.

Within each of the three areas, on 10 out of the 20 determined plots, data-loggers were installed to record microclimate. All other indicators were assessed in a circle around the centre of the plot. In the remaining plots, all indicators except for microclimate were surveyed.

5.4.2 Indicators

The determination of indicators was based on the previous theoretical plausibility analysis generated from stakeholder and expert consultations, and corresponding findings on potential ecological effects of FSC-certification (Blumroeder et al., 2018). The selected indicators also directly refer to the principles, criteria and indicators (PCI) of the Russian National FSC Standard (FSC, 2012) assumed to be the most relevant in inducing effective positive changes in the forest ecosystem. In this context, the most important FSC criterion was 6.3, which comprises several ecologically relevant standard indicators and lays the foundation for the selection of indicators measured in the field (Table 1).

Table 1: Principle, criterion and indicators of the Russian National FSC Standard that were particularly relevant for the selection of field indicators assessed in the study.

FSC criterion	Relevant FSC indicators	Field indicators
6.3. **Ecological functions and values shall be maintained intact**	6.3.4. The organization shall implement measures (reforestation and reclamation) to restore forest areas degraded as a result of management activities	Rejuvenation (25 variables)
	6.3.5. Silvicultural operations shall mimic natural dynamics of a particular forest. Guidance: Mimicking natural processes in varying degrees may cut the costs of forest regeneration and conservation of biological diversity and may reduce environmental risks related to peculiarities of the natural forest succession. Harvesting, regeneration and	Living trees (3 variables), rejuvenation,

	tending techniques shall consider typical disturbances (death of individual trees or their groups, susceptibility to windfall and fire), forest succession (e.g. natural replacement of dominating species during succession), composition and spatial stand structure. For forests heavily disturbed by man (frequent grass fires, heavy erosion and waterlogging of cutovers, simplified stand composition etc.), the silvicultural system shall focus on maintaining and/or regenerating elements of the natural dynamics. Harvesting shall not mimic catastrophic disturbances of low frequency (e.g. large-scale fires killing almost all stand).	vegetation (25 variables)
	6.3.8. The following windthrow resistant key stand elements (residual trees and their groups) shall be completely or partially left during timber harvesting: old trees of non-target species; large trees with holes; trees with large bird nests; veteran trees whose age noticeably exceeds the average age of the main canopy; and tree species considered to be rare in this area.	Living trees
	6.3.9. For survival of species dependent on deadwood, during harvesting (including salvage cuts) the following key stand elements that do not threaten forest health and future forest regeneration shall be retained: windthrow resistant dying trees and snags located far from roads, landings and other similar sites, such trees left within clumps and groups; hanging and dying trees and snags more than 30-40 cm in diameter which are a hazard shall be cut down and left as deadwood; high stumps of natural origin; large down deadwood, especially more than 30-40 cm in diameter; and big logging residues.	Deadwood (16 variables)
	6.3.10. In case of clearcuts (and final cut in multi- stage systems), the organization shall ensure regeneration of target tree species while preserving other tree species occurring in the natural forest.	Rejuvenation
	→ **Ecological functions and values shall be maintained intact, enhanced, or restored**	Microclimate (26 variables), Vegetation, rejuvenation
Principle 6: ENVIRONMENTAL IMPACT. Forest management shall conserve **biological diversity** and its **associated values**, water resources, soils, and unique and fragile ecosystems and landscapes and, by so doing, maintain the **ecological functions** and the integrity of the forest		

5.4.2.1 Microclimate

Forest ecosystems are complex and open systems in permanent exchange with the environment, capturing incoming solar radiation and transforming it into eco-exergy (Jørgensen, 2006; Kay et al., 2001; Schneider and Kay, 1994a; Wagendorp et al., 2006). More mature, self-organized and self-regulated ecosystems develop more dissipative structures, increasing both their thermodynamic efficiency as well as their capacity to cope with perturbations, thus becoming more resistant and resilient (Fath et al., 2004; Ibisch et al., 2010; Jørgensen, 2008). Empirical research shows that mature and complex ecosystems are better able than younger or more disturbed ones to moderate temperature extremes and stabilize temperature fluctuations (Norris et al., 2012; Schneider and Kay, 1994b). Many ecological processes are directly impacted by microclimate as the microclimate reflects subtle changes in ecosystem functionality across scales (Chen et al., 1999). In this study, indicators of microclimatic regulation, based on surface temperature and relative humidity measurements, were recorded as proxies for ecosystem functionality. The hypothesis behind this was that harvesting under FSC-certification would retain more structures needed for maintaining regulative microclimatic functions compared to conventional logging practices. Based on this premise, the assumption was that those sites managed under FSC would indicate a microclimatic signature relatively similar to the reference forest but different from the non-certified harvesting sites.

Two sets of data-loggers were installed within each of the 10 clearcuts and another 10 sets on randomly selected locations within the reference area. At the centre of each of the 30 plot locations, one set of data-loggers was mounted on the north-facing side of the nearest small tree. All branches were removed from the tree except for the apex. One set of data-loggers consisted of two devices: one, measuring temperature (Onset HOBO UA-001-64 Pendant), was placed at 1.3m above ground (level a) and the second, measuring temperature and relative humidity (Onset HOBO U23-001 Pro V2; technical details can be found at http://www.onsetcomp.com/), directly at ground-level (level b) (Figure 3).

Figure 3: Microclimatic data-loggers installed at a small tree in the centre of a study plot. Top: Data-logger measuring temperature at 1.3 m. Bottom: Data-logger measuring temperature and relative humidity at ground-level. Pictures were taken by JSB.

The data-loggers were initially left for 12 hours minimum to acclimatize to conditions before readings were taken at 30 minute intervals between 4th June 2017, 8:00 am, and 18th September 2017, 11:30 pm. The following microclimatic variables were computed: T_{max20} (maximum temperatures per plot for days with a daily mean > 20 °C); $T_{max1520}$ (maximum temperatures per plot for days with daily mean temperatures of 15-20 °C); $T_{\#days20;25;30;35;40}$ (number of days with maximum temperature > 20 °C; 25 °C; 30 °C; 35 °C; and 40 °C respectively); RTC (relative temperature cooling capacity: difference of mean temperature per plot to mean of all plots); RTB (relative temperature buffering capacity: difference of standard deviation per plot to mean of standard deviation of all plots), RHM (relative humidity maintenance capacity: difference of mean per plot to mean of all plots), RHB (relative humidity buffering capacity: difference of standard deviation per plot to mean of standard deviation of all plots).

5.4.2.2 Tree biomass

Forest structure was assessed within a 17.84 m radius plot by recording the number of living trees for each species observed at each forest layer and by measuring the diameter at breast height of four (if present) representative trees. An estimation of mean height for each species was also recorded, and a visual assessment of the vitality of each tree made (1 = not weakened; 2 = weakened; 3 = severely weakened; 4 = dying). The volume of biomass was determined (Voinov et al., 2012).

All cut and broken tree stumps within the plot were recorded as well as their height and diameter. The volume of biomass that had been cut and extracted during harvesting was determined by extrapolating height and diameter using forest mensuration data (Voinov et al., 2012). Finally, the absolute volume of living biomass and the amount of stems, as well as the relative volume and number of stems not extracted in relation to the reconstructed volume of the initial stand, was calculated.

5.4.2.3 Deadwood

Length and diameter of lying deadwood with a minimum diameter of at least six cm and of at least 1.5 m length was measured within the borders of the plot. Height and diameter at breast height of standing dead wood higher than 1.5 m and thicker than six cm was also recorded. The stage of decay was visually estimated and by manually testing the hardness of wood. The decay stage for logs and snags was recorded using a standard classification system (Table 2) (Federal Agency of Forestry, 2011).

Table 2: Criteria to determine the decay level of deadwood.

Decomposition stage	Description
1: none	Fresh and solid dead wood with no signs of decay
2: light	Surface rotten and core solid
3: moderate	Surface solid and core rotten
4: severe	Completely decomposed, but trunk still visible

In the further analysis, the volume of lying deadwood was calculated using Huber's formula (Patterson et al., 1993):

$$V = \pi / 4 d^2{}_{0.5l} l \qquad (1),$$

where V= Volume, d=diameter, l=length.

The volume of standing deadwood was calculated using formula 2 (Grundner and Schwappach, 1952):

$$V = \pi / 4 d_{1.3h}^2 h F \qquad (2),$$

where V= Volume, d=diameter, h=height, F=expansion factor (tree species and diameter specific factor).

5.4.2.4 Rejuvenation

All trees smaller than 6cm in diameter at breast height that potentially regrow the forest stands were recorded as rejuvenating trees within a 5 m x 20 m rectangle located directly next to the centre of the plot. The species and height of each individual were recorded and the vitality estimated and assigned according to five different categories (Table 3) (Melekhov, 1980).

Table 3: Criteria to determine the damage class of rejuvenating trees.

Category	Description
1: No damage	No visible signs of damage
2: Little damage	No damage of apex, but (at least 5-10 % of) leafs dry or side branches broken
3: Indeterminate	Recently damaged, but consequences for further development unclear
4: High damage	Apex broken at least once
5: Dead	Completely dried

The tree *species Sorbus aucuparia, Alnus incana* and *Salix caprea* were not included in the list of rejuvenating tree species, but recorded as part of the shrub-layer because under the present growing conditions of the region, they show a shrub-like life-form.

5.4.2.5 Vegetation

The cover-abundance of ground-covering and epiphytic species was estimated within a 10m circle positioned at the centre of each plot according to Braun-Blanquet (1964) and then converted to percentage coverage based on Tüxen and Ellenberg (1937).

The tree species *Sorbus aucuparia, Alnus incana* and *Salix caprea* and other shrubs such *as Juniperus communis, Lonicera xylosteum, Rosa acicularis, Rubus idaeus* as well as lianas (*Atragene sibirica*) were assigned to the herbal layer. Bryophyte and lichen species were distinguished into ground-dwelling and epiphytic species. Epiphyte coverage was estimated as shown in Table 4.

Table 4: Criteria to determine the abundance of epiphytic species.

Abundance class	Criteria	Coverage [%]
3	Species covers 50-75 % of the trunks and branches	62.5
2	Species covers 25-50 % of the trunks and branches	37.5
1	Species covers 5-25 % of the trunks and branches	15
+	Species covers less than 5 % of the trunks and branches	2.5

Further analyses of the vegetation were carried out using the vegan package (Oksanen, 2018) including species richness (number of species) and the Simpson Diversity Index (Simpson, 1949), as variable for differentiating sites (Morris et al., 2014):

$$D = 1 - \sum_{i=1}^{S} p_i^2 \qquad (3),$$

where D= Simpson Diversity Index; i=Species; pi = proportion of coverage of species i.

Indicator species for old growth forests and disturbance were identified and applied to the vegetation data (Andersson et al., 2009) (Table 5).

Table 5: Register of species indicating old-growth or disturbed conditions in the forest ecosystem.

Old-growth indicator species	Disturbance indicator species
Atragene sibirica	*Calamagrostis epigejos*

Galium triflorum	*Pohlia nutans*
Goodyera repens	*Trifolium repens*
Hypogymnia vittata	
Listera cordata	
Microcalicium disseminatum	
Nephroma bellum	
Nephroma parile	
Ptilium crista-castrensis	
Ramalina thrausta	

Ellenberg indicator values were determined to indicate prevailing environmental conditions (Ellenberg, 1978) (Table 6).

Table 6: Categories and interpretation of Ellenberg indicator values.

Environmental factor	Symbol	Indicator value and ecological range
Light value	L	1=deep shade, 5=semi-shade, 9=full light
Temperature value	T	1=alpine-subnival, 5=submontane-temperate, 9=Mediterranean
Continentality value	K	1=euoceanic, 5=intermediate, 9=eucontinental
Moisture value	F	1=strong soil dryness, 5=moist, 9=wet, 10=aquatic, 12=underwater
Reaction of soil value (pH)	R	1=extremely acidic, 5=mildly acidic, 9=alkaline
Nitrogen value	N	1=least, 5=average, 9=excessive supply
Salinity value	S	0=no, 1=weak, 5=average, 9=extreme salinity

Ecological functional traits of herbaceous species and rejuvenation were considered by applying the CSR-classification system (Grime, 1977) (Table 7).

Table 7: Categories and definition of CSR values indicating ecological functional traits (Grime, 1977).

Environmental factor	Symbol	Explanation
Competiveness	C	low intensity stress and low disturbance with abundant resources
Stress-tolerance	S	scarce resources and severe conditions but low disturbance
Ruderality	R	High and frequent disturbances with abundant resources and moderate conditions (not extreme)

5.4.3 Data analysis

Exploratory data analysis was carried out using 95 explanatory variables linked to the five indicators: tree biomass, deadwood, rejuvenation, vegetation, and microclimate recorded in the three sample areas FSC, non-FSC, and reference. The dataset was divided into two parts, depending on the availability of observations and variables. The first one was based on data consisting of all 60 study plots, excluding the variables containing missing values, i.e. temperature and humidity data (model 1), in result with 67 explanatory variables. The second dataset (model 2) consisted of all 95 explanatory variables, but only available data was included covering 30 plots.

5.4.3.1 Principle Component Analyses

After standardizing all variables, a principal component analysis (PCA) was conducted to determine the highly correlated variables, to combine them into principal components, and to visualise the structure of the dataset. Determining the principal components (PCs), especially the first two, which have the greatest strength to explain variability in the data set, helps to designate most important variables. These would be those variables which are most correlated with the extracted PCs.

5.4.3.2 Random Forest

Random forest analysis (RF), a machine learning (ML) algorithm, was employed to determine the explanatory variables that influence and allow for distinction of the three sampled areas to the greatest extent (Breiman, 2001). This multivariate approach is usually applied in classification and regression problems. Its main advantages over other ML methods are high accuracy, ability to deal with highly correlated data, and the ability to identify the most relevant variables (referred to as predictors or features). Random forests are recently gaining more attention in ecological analyses (Cutler et al., 2007; Ryo et al., 2018). The main idea of RF is to use the ensemble approach that generates many decision tree models and averages their results. Here, the analysis aimed less at predicting the area of the plot, but at determining variables, which are most predictive of the area. Therefore, the whole dataset was used as model training set, without distinguishing the validation set. The methodology was used to distinguish relevant from irrelevant predictors (Hapfelmeier and Ulm, 2013). In the first step, an importance measure using the original data was computed. Each variable was permuted separately many times in order to assess the empirical distribution of its importance measure under the null-hypothesis of independence between this particular variable, the response variable, and the remaining predictors. For each variable, the p-value was calculated for each variable, and variables with p-values not exceeding a certain threshold (0.05) were selected with use of the Bonferroni adjustment for multiple comparisons. In the second stage, the final RF model was built, based only on the predictors selected in the first step as being potentially important. After this procedure, the final importance of the selected variables was determined.

The computation of unbiased RF was done with use of the cforest() function, which is included in the party package (Hothorn et al., 2018; Strobl et al., 2009). Conditional inference trees that are used to construct the classification trees via this function, are unbiased in variable selection (Strobl et al., 2007). The number of preselected variables was set to the square root of the number of predictors (initially mtry = 8 for model 1 and mtry = 10 for model 2). Each random forest consisted of ntree=5000 trees in order to produce stable variable splits, in contrast to 500 and 1000 in preliminary analysis. Importance measures of variables were calculated with use of the varimp() function, which follows the permutation principle of the mean decrease in accuracy (MDA). The number of permutations in the first stage of the procedure was set to 1000 for both models.

5.4.3.3 ANOVA

In order to determine whether there are statistically significant differences between central tendency measures of particular explanatory variables in different areas, one-way analysis of variance (ANOVA) was conducted for each variable, with the parametric ANOVA's assumptions pre-checked (normality of distributions with use of the Shapiro-Wilk's test and equality of variances with the Levene's test, in particular). In cases when the assumptions were not satisfied, the Kruskall-Wallis H tests (one-way ANOVAs on ranks) were carried out. In case of rejection of the null hypothesis, the post-hoc test was applied using pairwise t-Student's tests with Bonferroni adjustment or pairwise Wilcoxon rank sum tests with Bonferroni adjustment, respectively. Along with the respective p-values for the one-way analysis of variance, we calculated effect sizes ($R2$ which corresponds to $\eta 2$, and the relatively unbiased estimator $\omega 2$ in case of parametric ANOVA, and $\eta 2H$, which was calculated according to Tomczak and Tomczak (2014).

5.4.3.4 Effectiveness

For each of the 95 variables, the results of the ANOVA were interpreted and rated in relation to the actual impact of FSC-certification. To each of the eight possible combinations of ANOVA results indicating significant differences between the three sampled areas, a certain effectiveness category was assigned (Table 8).

Table 8: Impact: Conversion of statistical outcomes (ANOVA) of indicators and interpretation regarding the ecological effectiveness of FSC in changing forest management operations.

FSC ≠ Non-FSC = ≠ Reference	Unambiguous	Impact	Positive	A
FSC = Non-FSC = ≠ Reference	Ambiguous	Impact	Likely to be positive	B
FSC = Non-FSC ≠ ≠ Reference	Unambiguous	No Impact		C
FSC = Non-FSC = = Reference	Unambiguous	No Impact		C
FSC = Non-FSC ≠ = Reference	Ambiguous	Impact	Likely to be negative	D
FSC ≠ Non-FSC ≠ = Reference	Unambiguous	Impact	Negative	E
FSC ≠ Non-FSC = = Reference	Ambiguous	Impact	To be determined	NA
FSC ≠ Non-FSC ≠ ≠ Reference	Ambiguous	Impact	To be determined	NA

5.5 Results

5.5.1 Principal component analysis

In model 1, all 60 plots, but only 67 out of 95 variables were considered by excluding variables related to temperature and humidity, since values were not available for all of the plots. As a result of the PCA, 17 principal components were extracted based on the eigenvalue criterion (Figure 4, left). Together they explained 86.53 % of the variance contained in the whole data set (respective values for each PC can be found in Table A.1). The first principal component was most correlated with the remaining tree biomass, variables describing CSR-values for rejuvenation, CS-values for the herb layer, variables explaining the composition, such as percentage of rejuvenating tree species (Abies sibirica, Betula pendula and B. pubescens), deadwood biomass, and species richness of epiphytes. The second principal component was highly correlated with the number of rejuvenating trees lower than 50cm height and Ellenberg indicator values (reactivity and nutrient), while the third one was highly correlated with lying deadwood biomass of decomposition stage 2, Ellenberg indicator value of moisture, and R-value for the herb layer (more details can be found in the correlation matrix of Table A.2).

Model 2 concerned all variables, including temperature and humidity data, but only 30 plots were considered (Figure 4, right). The PCA results indicated that according to the eigenvalue criterion, 17 principal components explained almost 94.5 % of the whole data variance (respective values for each PC can be found in Table A.3). The first component was most correlated with the temperature and humidity variables, and also with the remaining tree biomass, similar to model 1. The same variables as in model 1 contributed to the first PC: CSR-values for rejuvenation, percentage of rejuvenating tree species (Abies sibirica, Betula pendula and B. pubescens), CS-values for the herb layer, and species richness of epiphytes. However, when including the microclimatic variables, they superseded other variables. The second principal component was strongly correlated with deadwood biomass (lying, standing and lying, decomposition stage 4), Ellenberg indicator values (reactivity and nutrient), the share and number of rejuvenating *Picea abies* (more details can be found in the correlation matrix of Table A.4).

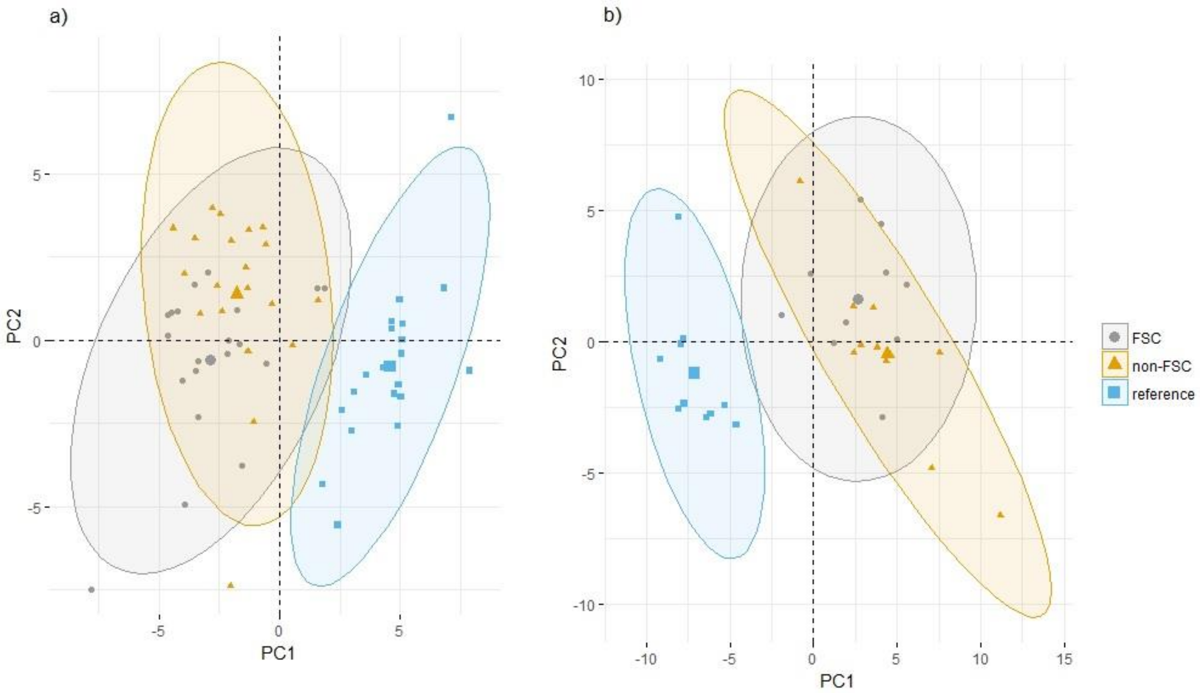

Figure 4: PCA: two-dimensional graph of individuals for model 1 (a) and model 2 (b). The figure illustrates the individuals by groups with point concentration ellipses, derived in R by using function fviz_pca_ind() from factoextra R package with ellipse level equal to 0.95, being the size of the concentration ellipse in normal probability (Kassambara, 2017).

In general, the contribution of particular variables was similar in both models, except when temperature and humidity data were taken into account, they showed the strongest contribution to the first principal component (Table A.5). The threshold for the variables' contribution importance was set to the expected average contribution. When taking into account temperature and humidity in model 2, these variables received the most attention in the PCA, followed by variables describing the biomass and frequency of rejuvenating tree species. However, in contribution to the first two dimensions, which store the highest variability in the data, right after the microclimatic variables other variables came to the lead: CSR-values, remaining biomass, and the composition and share of rejuvenating birch species.

5.5.2 Variable selection with use of random forests

In model 1, 17 variables with p-values less than the fixed threshold were obtained in the first step of the RF analysis. All respective p-values were close to zero. In model 2, the RF procedure identified 11 relevant variables, again with all p-values close to zero (p-value<0.05) (Figure 5). The final RF model for each of the two models, which included only the relevant variables, revealed that three out of the 11 initially selected variables (model 2) had negative values of importance ($_{Tmax20\_a}$, $T_{max1520\_a}$, $T_{\#days30\_a}$), which indicates that they were not predictive enough for the area and were possibly irrelevant.

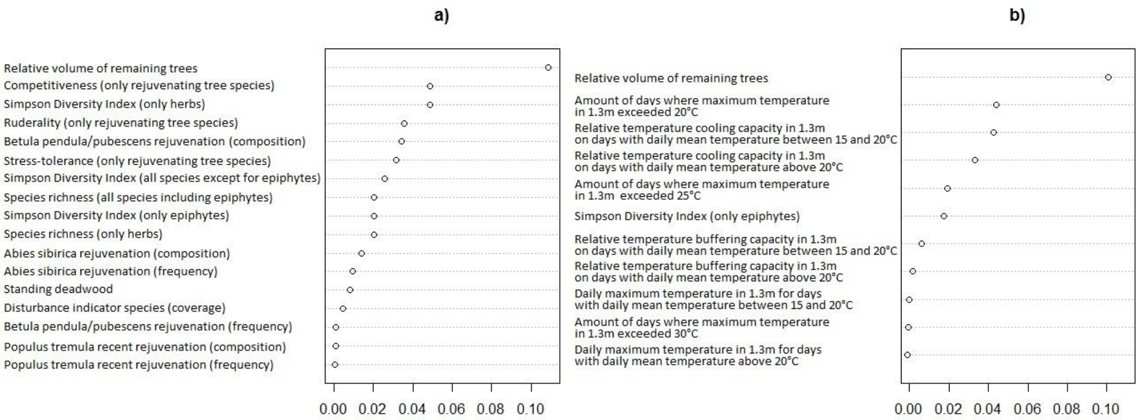

Figure 5: Variable importance plots for the final RFs of models 1 (a) and 2 (b). Positive importance values indicate important variables. Higher importance values indicate higher MDA between the model with original and permuted values of this particular variable.

5.5.3 Analysis of variance and effectiveness

Taking into account all variables, almost three-quarters of the analysed variables were not affected by FSC at all, as either all three areas did not significantly differ from each other or FSC and non-FSC did not differ from each other but did differ from the reference. A positive impact of FSC-certification was indicated for 7 % of variables by significant differences in medians between the FSC and non-FSC areas and at the same time between non-FSC and the reference, but without a significant difference between FSC and the reference (Figure 6, left). Three variables were clearly negatively impacted by FSC as the results for the FSC site differed from both the reference and the non-FSC without any distinction registering between primary forest and non-FSC sites. Considering only the 26 variables that were determined as important according to the random forest analysis, the majority were not impacted by FSC (Figure 6, right).

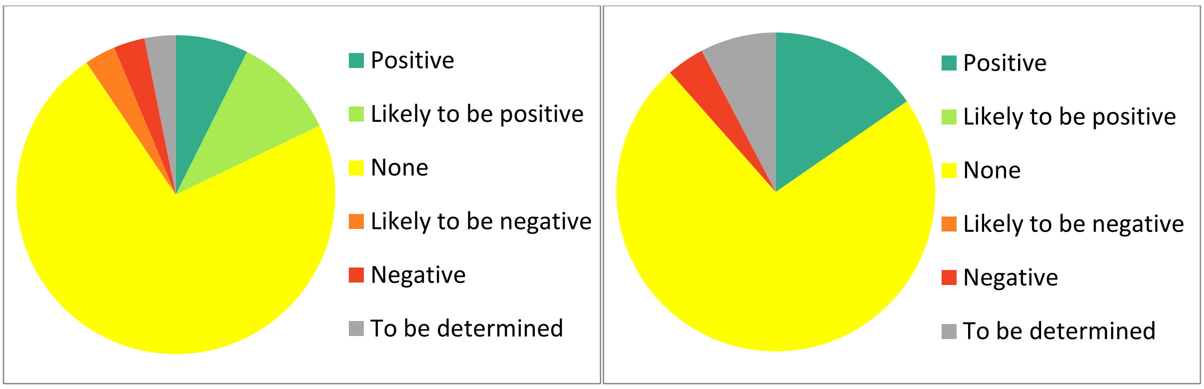

Figure 6: Share of effectiveness scores that were assigned based on ANOVA results indicating differences in variables between the three studied areas (FSC, non-FSC, and reference). Left: all 95 variables; right: 26 most important variables according to RF. Details can be found in Table A.6.

The impact of FSC was not targeting a specific thematic group of indicators, as the majority of variables of any group were not impacted by FSC (Figure 7).

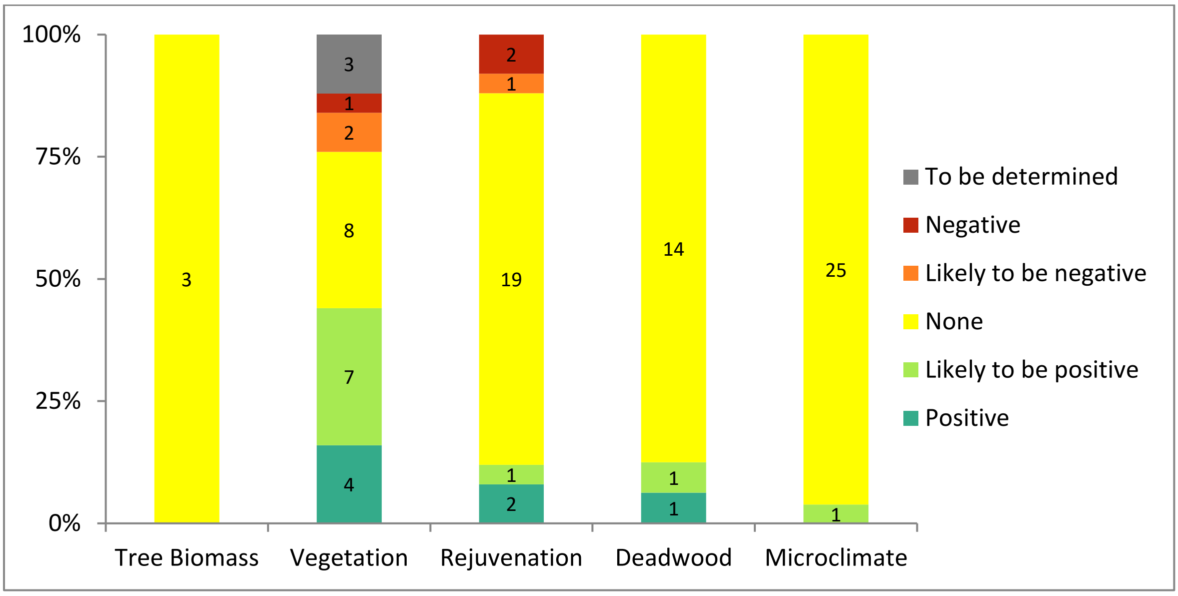

Figure 7: Distribution of effectiveness scores amongst the variables divided into the five indicators based on Table A.6. Numbers in the bars represent the number of variables considered within the specific indicator group.

The variable that was found to be the most important predictor for the area in both RF models was the volume of living tree biomass retained on site. In all plots associated with the reference area, the relative remaining tree biomass was 100 % in contrast to FSC (mean = 2.53 %, standard deviation = 7.80 %) and non-FSC (mean = 1.73 %, standard deviation = 2.32 %). Both clearcuts did not differ from each other (p-value = 0.68) and the volume of remaining living tree biomass was significantly lower compared to the reference ($p < 0.001$) (Figure 8a).

Of the 16 variables relating to deadwood, only standing deadwood turned out to be of importance for predicting the certification status of the area. FSC-certification did not impact that variable as the two clearcut areas did not differ from each other (p-value = 0.540) and the mean volume of standing deadwood was significantly lower in both clearcuts (FSC = 0.81 m^3ha-1; non-FSC = 1.21 m^3ha-1) compared to the reference (mean = 12 m^3ha-1; p-value < 0.001) (Figure 8b). The same applied to all other variables relating to deadwood. Fresh lying deadwood was the only variable relating to deadwood where FSC clearly contributed to an increase compared to the non-certified clearcut. Looking at the total amount of all types of deadwood recorded, the average volume of deadwood in the reference area was highest with a mean of around 53 m^3ha-1 and was significantly lower in the two clearcut areas (FSC = 33 m^3ha-1; non-FSC = 34 m^3ha-1).

Of the 26 microclimatic variables recorded, according to RF, eight were of highest importance: daily maximum temperature at 1.3 m above ground on days with daily mean temperatures above 20 °C, or between 15 and 20 °C, number of days exceeding 20, 25, or 30 °C at 1.3 m respectively, relative temperature cooling capacity (RTC) on days with daily mean temperatures > 20 °C, or between 15 °C and 20 °C, and relative temperature buffer capacity (RTB) at 1.3 m above ground. None of these temperature variables were affected by FSC-certification; in any case FSC did not differ significantly from non-FSC (p-value = 1.0), whilst both differed significantly from the reference forest (p-value < 0.001) (Figure 8c-j). Likewise, all other variables related to microclimate variables were not different under FSC compared to non-FSC, except for the number of days where maximum temperature at 1.3

m exceeded 40 °C. In this case, FSC did neither differ from the reference area (p-value = 0.233) nor from non-FSC (p-value = 0.508). However, the non-FSC was different compared to the reference area (p-value = 0.017). Maximum temperature, the number of days a certain temperature threshold was exceeded (e.g. 15, 20, 25, 30, 35 °C), and temperature fluctuations were highest in the two clearcuts compared to the reference.

Of the 22 variables relating to the frequency and distribution of rejuvenating tree species contributing to forest regeneration, six turned out to be important variables according to RF. In addition, the classification of tree species ecological traits, represented by CSR-values, was also found to be predictive. On the species level and taking into account all rejuvenating tree species with a diameter less than six cm at breast height, it turned out that FSC had no noticeable impact on either the frequency and composition of *Abies sibirica* (highest in the reference area and lowest in the two clearcuts) (Figure 8k-l), or on birch species (lower at the reference compared to the two clearcut areas) (Figure 8m-n). Similarly, FSC did not induce any change in the number of individuals of young *Picea abies* and their share amongst all rejuvenating trees. Without distinguishing between different tree species, no difference was found between the three sampled areas.

Regarding the most recent rejuvenation, including only those individuals with a height below 50cm, only the rejuvenation of *Populus tremula* was found to be important and was positively influenced by FSC (in a way that FSC was similar to the reference area but different from non-FSC, while non-FSC was different from the reference area) (Figure 8o-p). The share and total number of *Picea abies*, which was lowest in the two cleared areas, and of birch species, which was lowest in the reference area, were not impacted by FSC. Both clearcuts did not differ from each other but did differ from the reference area. Without distinguishing between the species but taking into account all species smaller than 50 cm at the same time, the lowest number of individuals was recorded in the FSC sites, which differed significantly from the reference area (p-value = 0.013), but not from the non-FSC sites (p-value = 0.398).

Rejuvenating trees that are more likely to favour stable conditions with low disturbance and abundant resources, and which are highlighted in the raised scores for competitiveness in the CSR plant function model, were recorded in greater abundance in the reference forest (Figure 8q). Similarly, species able to deal with severe environmental conditions, characterised by scarce resources and low disturbances, represented by higher Grime stress-tolerance-values, were more abundant in the reference area in comparison to FSC and non-FSC clearcuts (p-value < 0.001), which in turn did not differ from each other (p-value = 0.999) (Figure 8r). The share of ruderal rejuvenating tree species that adapted to intensive and frequent disturbances in moderate environmental conditions while resources are available, was equally high in FSC and non-FSC clearcuts (p-value= 0.999), compared to the reference area, where ruderal tree species were less present (p-value < 0.001) (Figure 8s).

In total, 246 different species were counted, of which 63 were classified as herbaceous vegetation. A minimum of 28 different species including vascular plants, bryophytes, and lichens per plot was detected in a FSC-certified area, while a maximum of 73 different species was counted in the reference area (Figure 8t). The lowest number of herb species was recorded in the reference area (6 spp.) as well as the highest (37 spp.) (Figure 8u). The highest number of epiphytic bryophytes and lichens was always encountered in the reference area. Concerning average species richness of herbaceous vegetation over all plots, there was an impact of FSC as the lowest number of species was counted in the non-FSC and reference area, whilst numbers were significantly higher in the area that was cleared under FSC. Taking into account all species (herbs, bryophytes, and lichens including epiphytes), species richness in the FSC and reference area were similarly high and significantly lower in the non-FSC area.

Diversity in herbaceous vegetation, when measured using the Simpson Diversity Index, was highest in FSC and lowest in non-FSC clearcuts (Figure 8w). Taking into account all species except for epiphytes (e.g. ground-covering herbs, grasses, bryophytes, and lichens), FSC-certification appeared to provide positive benefits for species diversity (Figure 8v). The Simpson Diversity Index was equally high in FSC and the reference area (p-value = 0.203), but lower in the non-FSC clearcut (p-value < 0.001). When looking only at epiphytic vegetation, FSC did not induce any impact compared to the non-FSC clearcut (p-value = 1.0), as both areas showed values higher than the reference (p-value < 0.001) (Figure 8x). The effects of FSC practice on the abundance of disturbance indicators species was unclear as the FSC and the non-FSC clearcuts did not differ from the reference area (p-value = 0.106; p-value = 0.799), but non-FSC showed a lower coverage of species representing a disturbed environment compared to FSC (p-value = 0.018) (Figure 8y). Herbaceous vegetation in the clearcuts established under FSC and without FSC was identical regarding the competiveness and stress-tolerance of species compared to the reference (Figure 8z-zz). The three sampled areas did not differ from each other in terms of ruderality of herbal vegetation (Figure 8zzz). All corresponding p-values, effect sizes for ANOVA tests, and values for variable importances can be found in Table A.6.

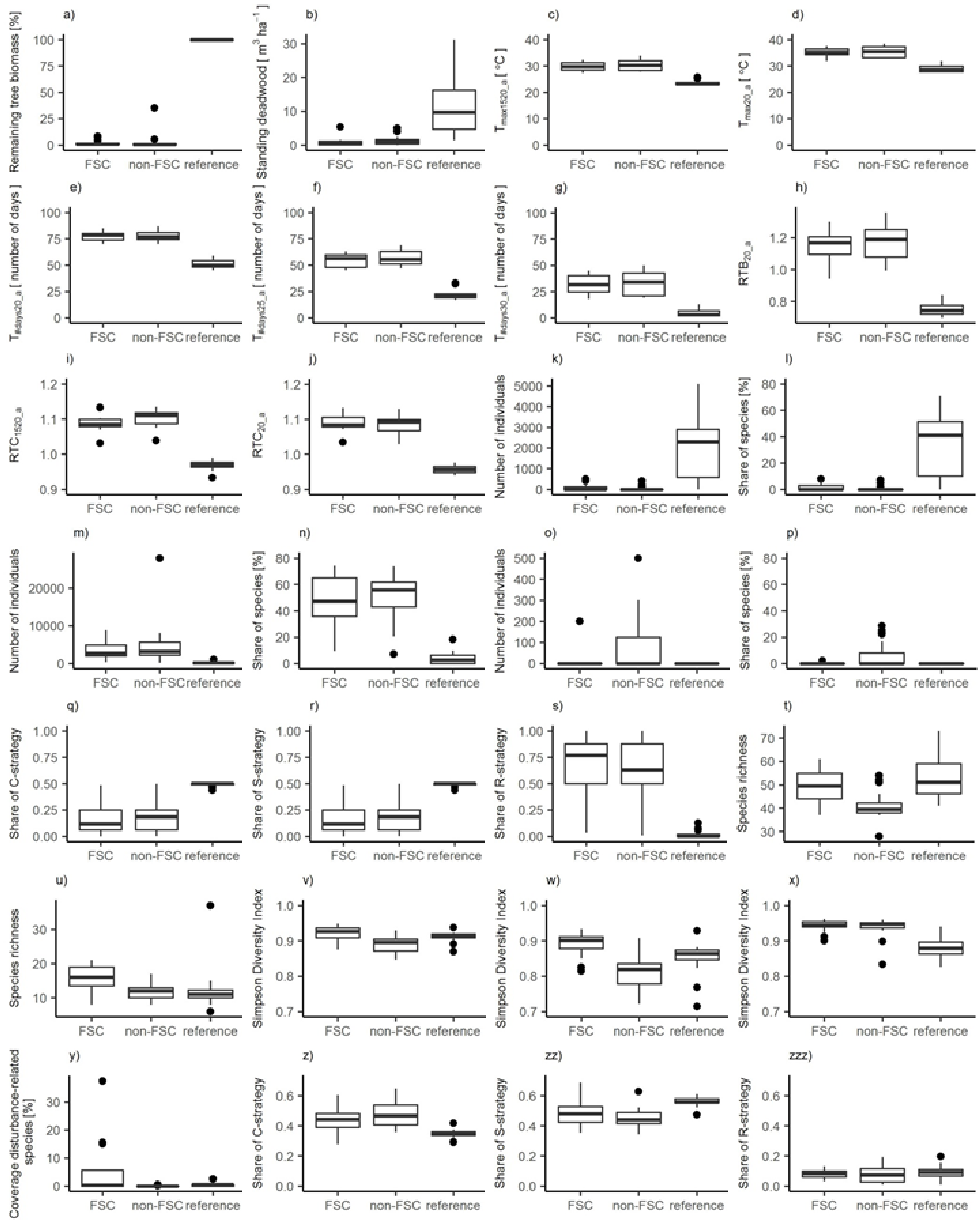

Figure 8: Boxplots showing the distribution of measurement results for 28 selected variables relating to the five indicators tree biomass (a: relative volume of remaining tree biomass), deadwood (b: volume of standing deadwood), microclimate (c: Tmax1520_a; d: Tmax20_a; e: T#days20_a; f: T#days25_a; g: T#days30_a; h: RTB20_a; i: RTC1520_a; j: RTC20_a), rejuvenation (k: frequency of Abies sibirica; l: share of Abies sibirica; m: frequency of Betula pendula and B. pubeszens; n: share of Betula pendula and B. pubescens; o: frequency of Populus tremula below 50cm; p: share of Populus tremula below 50cm; q: competitiveness of rejuvenation; r: stress-tolerance of rejuvenation; s: ruderality of rejuvenation), and vegetation (t: species richness including all species; u: species richness of herbs; v: Simpson Diversity Index of all species except for epiphytes; w: Simpson Diversity Index of herbs; x: Simpson Diversity Index for epiphytes; y: coverage of disturbance-related indicator species; z: competiveness of herbs; zz: stress-tolerance of herbs; zzz: ruderality of herbs). Respective p-values can be found in Table A.6. The values for q-s and z-zzz derive from Grime (1977).

5.6 Discussion

The determination and selection of important variables was conducted by applying a random forest analysis (RF). Although RF and PCA are different approaches with divergent goals, one procedure confirmed the selection of variables based on the other. In general, PCA allowed for the determination of the most explanatory variables, regardless of the area, whilst RF helps retrieving the most important variables that have the highest power in predicting the three areas (FSC, non-FSC, reference). The distribution of plots amongst the first and second principal component showed that no matter how many plots or variables were included in the analysis, non-FSC and FSC were mostly overlapping, but separated from the reference area. This indicates that the ecological performance of most of the plots within the two companies (with and without FSC certification) was quite similar but different from the primary forest.

It is important to acknowledge that commercial forestry in the Arkhangelsk Region, regardless of certification, is based on clearcutting primary forests (remaining Intact Forest Landscapes) (Karvinen et al., 2011, 2006). Clearcuts are mostly very large (often up to 50 ha, spatial design with consecutive clearings with a checkerboard-like structure (Blumroeder et al., 2018)). The empirical study makes obvious the point that clearcuts generate substantial changes in biomass, species composition and diversity as well as altering the functions of the forest, especially reducing regulating functions. Logically, it does not make any difference whether clearcuts are implemented under FSC-certification or not, as similar amounts of biomass are extracted and clearcuts are large. The Russian FSC standard does not recommend large-scale clearcutting, it encourages companies to reduce the size of clearcuts, but it tolerates clearcutting practices as long as the size of the clearings (up to 50 ha in production forests) is compliant with Russian legislation (Blumroeder et al., 2018; McDermott et al., 2010). Our case study refers to just two companies, but they are selected as representative examples in terms of general cutting practices and spatial design of cutting.

Frequently, companies and also FSC itself defend clearcutting as an effective practice for forest regeneration as it is believed to mimic natural dynamics. A large number of studies deal with the impacts of clearcut-based timber harvesting in boreal forests, but mostly in North America and Scandinavia. It has been pointed out that harvesting represents a mechanical disturbance that impacts the forest ecosystem in a very different way to natural dynamics such as wildfires, which are rather a chemical impact (Seedre et al., 2011). It has been found that clearcutting can induce changes to the status of soil nutrients that are different from those generated by wildfires (Simard et al., 2001) and that nutrient losses and shifts to other systems such as lakes represent impacts on biogeochemical cycles in the Boreal Shield forest (Lamontagne et al., 2000). Hydrological impacts, for instance, refer to the substantial increase of peak flows after precipitation events (Guillemette et al., 2005). It has also been shown that logging can change regeneration processes, e.g. towards a far greater proportion of poplars instead of conifers (Carleton and Maclellan, 1994). Payette & Delwaide (2003) pointed out that clearcutting as a non-natural process can lead to weak ecosystem resilience in forests faced with cascading perturbations, which tend to grow in intensively logged areas (Payette and Delwaide, 2003). Thiffault et al. (2011) concluded that site sensitivity to clearcutting would depend on a series of relevant factors such as climate and microclimate, mineral soil texture and organic C content, the capacity for soil to provide base cations and phosphorus, as well as tree species autecology (Thiffault et al., 2011). Taking into account these findings it would be logical that a more responsible forestry, certified by FSC, would try to avoid at least some negative impacts of clearcutting and try to leave harvested sites under conditions that are less distant to a non-managed forest.

In this context, the remaining biomass that is spared from felling appears to be the most important variable. The volume and share of extracted biomass are structural parameters that directly influence manifold ecosystem functions. For a forest management regime, promoted by a certification system for introducing and safeguarding ecologically responsible timber harvesting, would have to address the volume of biomass remaining on site. Still, in our case study, FSC-certification did not induce an increase in volume of remaining living tree biomass within the plots, in both cases less than 3 % of the initial stand was spared from felling.

Biodiversity depends not only on the volume, but also on the availability of various types of deadwood, e.g. large diameters and different decay stages (Angelstam et al., 2003; Jonsson et al., 2016). Regarding the volume of deadwood, FSC clearly addresses the ecological importance of deadwood (FSC indicator 6.3.9), but in our study the volume on certified clearcuts was comparable to quantities recorded for non-certified ones. Only one variable relating to deadwood was positively impacted by FSC-certification. The volume of fresh lying deadwood was equally high in the FSC and the reference area, and significantly lower in the non-FSC area. However, this variable turned out to be statistically insignificant, whereas the only important deadwood-related variable, standing deadwood, was not different in the FSC compared to the non-FSC clearcuts.

In this context, it is worth analysing functional indicators, such as microclimatic regulation, which is strongly influenced by living and dead biomass in the forest (Chen et al., 1999; Dynesius et al., 2008; Haughian and Frego, 2017; Li et al., 2015; Norris et al., 2012). Despite the fact that microclimate would be one of the most obvious site traits affected by clearcutting, there are hardly any studies that have systematically documented the changes. Low water potentials on 2- and 3-year-old clearcuts have been mentioned in the context of low survival of planted trees (Nilsson and Örlander, 1995), and heat and drought effects were addressed in the context of the reduction of certain organisms on clearcuts during extreme weather (e.g. Addison & Barber 2005). It was also confirmed that branch cover could buffer periods of extreme microclimates that would impact bryophytes (Dynesius et al., 2008).

Our findings, for the first time, quantify microclimatic impacts of clearcutting in a boreal forest in Russia. The statistical analysis also confirmed that microclimate is a strong indicator. The data show that the temperature regime of clearcuts differs dramatically from that in primary forests. Whilst maximum temperatures (at 1.3 m), during warmer days (> 20 °C daily mean) in the forest normally stayed well below 30 °C, it rose to levels above 33 °C and in extreme cases was higher than 36 °C in the clearcut areas. The number of days with high temperatures (> 25 °C) at least doubled on clearcuts. The difference for days with highest temperatures >30 °C is even more pronounced. Cooling and buffering capacities of clearcut areas are substantially reduced if compared to primary forest. RTC was reduced by up to 14 % in the clearcuts and RTB up to 60 % compared to the reference forest. This could be explained by the lack of dissipative, thermodynamically effective structures, by reduced shading structures (Kay et al., 2001; Luvall and Holbo, 1989; Maes et al., 2011; Schneider and Kay, 1994a, 1994b). In this study, forestry practices under FSC failed to encourage the retention of substantial amount of biomass at the harvested sites and provided no incentive for alternative spatial cutting designs. FSC-certification does not seem to have any positive impact on climatic regulation functions of the forest ecosystem. The findings on microclimate support published research findings on the relationship between ecosystem complexity and thermodynamic function, and how dismantling of complexity can lead to reductions in thermodynamic efficiency (Hobson and Ibisch, 2013; Norris et al., 2012).

These findings are of high ecological relevance, especially in times of rapid climate change where frequent temperature anomalies can affect the boreal forest in the region (in recent summers temperature readings have been warmer or much warmer than reference period 1981-2010; compare (NOAA National Centers for Environmental Information, 2018).

Such changes are driving boreal forests closer to the ecological threshold (Mann et al., 2012). High temperatures (and low humidity) cause heat stress to plants on recovering clearcuts and might impact forest regeneration (Allen, 2009; Allen et al., 2010; Coates, 2002; Dey et al., 2019; Hu et al., 2017). Indeed, it is possible to observe dieback of small trees and shrubs, such as Juniperus communis, on clearcuts, which might be related to heat and drought stress and fungal pathogens (Green et al., 2015, 2012) and needs further investigation. It is noteworthy that the spatial extent of the clearcuts, especially when forming the checkerboard-like structures with clearings that were generated in several consecutive years, in many cases summing up to hundreds of square kilometres, does not bear any resemblance to naturally disturbed areas in the region (Achard et al., 2006; Blumroeder et al., 2018; Dymov, 2017; Potapov et al., 2012; Simard et al., 2001). It is conceivable that human-induced disturbance, concomitant with reduction in microclimatic cooling and buffering capacity on such scale, will also affect meso-climatic patterns.

Certain vegetation-related indicators such as the Simpson Diversity Index and species richness were positively influenced by FSC-certification. But higher species richness and higher diversity of plants do not necessarily imply higher ecosystem functionality (Bengtsson, 1998). It is a known phenomenon that under certain circumstances clearcutting can increase species richness, especially in cases where human disturbance is moderate, and in particular, the removal of organic soil layers causes shifts from residual and resprouting understory species to ruderal species regenerating from seeds and spores (Haeussler et al., 2002).

The environmental conditions after cutting a forest allow for additional species to move in, while resident species might still persist, at least for a while, despite the rather less favourable growing conditions. Even within the studied clearcuts, a few remaining trees that were spared from felling can still be colonized by epiphytic lichens for at least a few years after the harvesting operation. When looking at the ecological traits, the vegetation in the reference area was dominated by stress-tolerant species followed by competitors. In contrast, the shares of stress-tolerant species and competitors in the two clearcut areas, both FSC and non-FSC, were similarly dominated by a few ruderal species. Species react differently to forestry-related impacts - where generalist species are sustained or are even favoured by changed conditions, and where more specialist species can be impaired (Bengtsson et al., 2000). In general, the composition of ground covering vegetation does not necessarily change immediately after altered environmental conditions or can recover within a given time (Palviainen et al., 2005). The seed pool is still present, even within a clearcut, and allows resident species to persist while the changed conditions tempt additional species (Česonienė et al., 2018; Jonason et al., 2014; Szabó and Ruprecht, 2018). The diversity or richness of species and their traits might not adequately reflect the ecosystem functions and processes, including productivity, which rather depend on the type of functional groups (Aerts and Honnay, 2011; Hooper and Vitousek, 1997; Tilman et al., 1997).

Ellenberg light values in the reference area did not significantly differ from the clearcuts, which may refer to the fact that also within the reference forests some plots were characterised by natural tree-fall gap dynamics, with light incidence increasing at least at some spots, which also enables light-demanding and light-tolerant species to grow. Typically, primary spruce forest in the Arkhangelsk Region is subject to natural ecological stresses such as severe winters with hard frost, water stagnation, short vegetation period, poor soils and fire - and this can also explain the presence and dominance of stress-tolerant species. Due to the rather low number of different species, especially herbal ones, quite small variations in composition or abundance can easily influence and change the outcome of some related variables. In the case of species richness of herb species, the FSC-certified area showed a higher diversity compared to the reference and the non-FSC clearcut.

To ensure the permanence and persistence of the forest ecosystem, the rate and success of tree rejuvenation are crucial factors. Russian forest legislation requires companies to ensure natural regeneration of the forest ecosystem after the completion of harvesting operations. More specifically, the quantity of viable undergrowth and rejuvenation of the main forest species must present at least 1,200 individuals per hectare. This may be achieved by natural forest rejuvenation or by artificial replanting. In all study plots, natural rejuvenation was occurring at a sufficient level without the need for replanting. Looking at the absolute number of rejuvenating trees, including all size classes, the three sampled areas did not differ. But regarding the most recent rejuvenation, including only individuals smaller than 50cm, the lowest number was counted in the FSC-certified clearcuts. Further investigation is needed regarding the abundance of rejuvenating trees in relation to the available space, which was not focus of this study. In the reference forest, tree rejuvenation is concentrated in canopy gaps, where space and sufficient light conditions are available on the ground. Therefore, the relative rate of rejuvenation on the clearcuts might be much lower when taking into account the available space and need for rejuvenation.

Another factor affecting forest rejuvenation is the proportional representation of tree species. The composition of rejuvenating tree species in the forest managed under FSC could be assumed to be more similar to the reference forest, at least under the hypothesis that more of the original tree layer would remain after harvesting, allowing for a faster return of Norway spruce (Picea abies). However, this was not confirmed and can be explained by the very high share of harvested trees. In case of forest rejuvenation with *Picea abies*, the success of seedling establishment depends on microhabitat availability, micro-relief, and interaction with other species including bryophytes (Hörnberg et al., 1997). In contrast to fire-induced natural disturbances that support the rejuvenation of Norway spruce and contribute to a multi-storeyed forest structure (Zackrisson, 1977), tree species composition in the early stage of succession after clearcutting (FSC or not) differs from the natural dynamics. Besides the impact on forest regeneration, various other old-growth forest characteristics, such as microhabitats associated with large, old and dead trees are affected by clearcutting much more negatively compared to natural dynamics (Bengtsson et al., 2000).

Regarding the ecological traits of rejuvenating tree species, it becomes clear that the reference is different from the two clearcuts, but FSC did not induce any change compared to the uncertified clearcut practices on the studied plots. C- and S-traits are equally present and abundant in the reference area with the apparent absence of R-traits. While the two clearcuts are clearly dominated by ruderal tree species, C- and S-traits are equally low.

5.7 Conclusion and outlook

With regard to most ecologically relevant parameters chosen to study the impacts of clearcutting forestry on the selected sites in the Arkhangelsk Region, there were no substantial differences between FSC-certified forestry operations and conventional practices. This can be explained with the equally high amounts of harvested timber as well as the practice of large-scale clearcuts, generating significant structural and functional ecological changes in the used forest ecosystems. Still, all observed timber harvesting, both in certified and non-certified areas, was compliant with the Russian legislation and the Russian FSC standard. This is mainly because the standard itself, in terms of ecological provisions, is often poorly formulated and allows for broad interpretation (compare Blumroeder et al. 2018). This can also contribute to insufficient implementation and surveillance of the standard on site. In general, important topics such as ecosystem functions, deadwood and biomass retention are addressed, but there is neither a sufficient quantification of thresholds, nor strict requirements and obligations.

FSC, in Russia, has become an important mechanism for conservationists to interrelate with logging companies and in some cases jointly promote conservation, e.g. by establishing protected areas. But according to our study, there is no substantial change in forest operations towards an ecologically responsible harvesting. Rather, FSC-certified forestry contributes to the ongoing loss of primary forests in the remaining Intact Forest Landscapes. From a consumers' perspective the weakness of the global FSC regime becomes evident, when the same label stands for extremely different harvesting practices, including even clearcutting primary forests. FSC-certification might have induced some positive changes in Russian forestry, especially regarding socially and economically responsible operations (which were not focus of this study). Nevertheless, if these changes come at the cost of long-term loss of functional landscape ecosystems, this does not seem to be tolerable. Rather, a re-launch of the FSC system with a clear priority given to safeguarding functional forest ecosystems seems to be unavoidable. One may argue that it cannot be the task of a voluntary, market-based instrument to make forestry ecologically sustainable. However, if this is not the ambition, what is the point of promoting a label that suggests to consumers a responsible choice?

A much-improved public access to information on FSC-certified areas and companies is another minimum requirement for a globally credible certification scheme. This includes free access for independent researchers to all certified forests and the possibility to publish the results transparently.

The facts that investigated companies (as in our case) need to stay anonymous, undermines FSC's transparency and credibility.

This study targets FSC certification and its ecological effectiveness. We selected FSC for our research as this scheme is known as one of the more ambitious and demanding ones. The critique resulting from our research does not imply that other forest certification labels are thought to be more effective.

As overall recommendation that goes beyond the scope of our study on FSC effectiveness, we urgently recommend revising logging practices in the Arkhangelsk Region. The large-scale clearcuts, timber mining on a landscape-scale, do not resemble any comparable natural disturbance regime. It is thought to produce risky ecological changes related to micro- and mesoclimate, increasing landscape sensitivity to heatwaves, drought and wildfires, and possibly affecting landscape hydrology. There are first hints towards secondary impacts on forests beyond the harvested areas that need further investigation.

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JSB led the methodological development, participated in the fieldwork, conducted the data processing and interpretation, wrote a first draft and compiled the final manuscript. PLI, UFG and JSB co-conceived the study; PLI supervised it as senior author, especially participating in the methodological development, interpretation of the results and writing. He benefitted from long-term research professorships 'Biodiversity and natural resource management under global change' (2009-2015) as well as 'Ecosystem-based sustainable development' (since 2015) granted by Eberswalde University for Sustainable Development. Katharina Luedicke (Eberswalde University for Sustainable Development) supported the preparation of the field study. NB coordinated the fieldwork activities, in which DD, IA, OI, TP, SW, and AV participated as well as Denis Klevtsov (Associate Professor of the Northern (Arctic) Federal University named after M.V. Lomonosov) and Alexey Ilintsev (Researcher of the Northern Research Institute of Forestry). NB, IA and TP prepared the vegetational results under consultation of Elena Churakova (Researcher of the Federal Center for Integrated Arctic Research, Bryologist) and Tatyana Pystina (Professor of the Institute of Biology of Komi Scientific Center, Lichenologist). We thank Elena Nakvasina (Professor of the Northern (Arctic) Federal University named after M.V. Lomonosov, Soil scientist) for interpreting soil samples. JSB, AG, and SW took care of the statistical analysis. All authors participated in the discussion of the results and revised earlier versions of the manuscript. The study was funded by WWF Germany. The authors thank the participating companies and their staff facilitating the research.

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6. Clearcuts and related secondary dieback undermine the ecological effectiveness of FSC certification in a boreal forest

Blumröder, J.S., M.T. Hoffmann, O. Ilina, S. Winter, P.R. Hobson & P.L. Ibisch (2020): Clearcuts and related secondary dieback undermine the ecological effectiveness of FSC certification in a boreal forest. Ecological Process 9, 10.

6.1 Abstract

6.1.1 Background

Over the last 25 years, the Forest Stewardship Council (FSC) established internationally as a prominent forest certification system used by many for claiming responsible forest management. The objectives of the Russian National FSC standard to decrease the size of clearcuts and the retention of forest elements such as residual seed trees need on-site validation to proof the effectiveness of FSC. To assess the ecological impacts of harvesting practices and benefits of FSC certification, we geospatially compared logging activities with and without FSC certification. Within a sample area covering approximately 3,000 km² in the east of the Russian Arkhangelsk Region, we used available data on tree cover loss and satellite images to assess secondary impacts of clearcuttings on adjacent remnant forests and to quantify the logging intensity. Additionally, the size and structure as well as the density of skidding trails of ten specific clearcuttings located within the sample area were surveyed using satellite images and in the field observation to delineate the boundaries of clearcuts and forested remnants within the clearcuts.

6.1.2 Results

We found a significant increase of small-scale tree cover loss in the proximity of the clearcuts. Patchy dieback is possibly linked to the scale and intensity of logging in the surroundings. On the investigated clearcuts, FSC failed to reduce the size, to increase the retention of forest remnants including seed trees on logged areas, and to maintain larger tracts of undisturbed ground and soil compared to clearcuts that were logged before they received FSC-certification.

6.1.3 Conclusions

Trees and forest remnants remaining inside an increasingly stressed forest ecosystem matrix may not resist further harvesting-relating and climate-change induced stresses and disturbances. Large-scale clearcuttings seem to have negative impacts even in adjacent forests and undermine the ecological effectiveness of FSC certification in the study area. The Russian FSC standard is not clearly setting effective guidelines that induce a change in clearcutting practices in order to reduce ecological risks.

6.2 Keywords

Ecological effectiveness, impact assessment, forest certification, sustainable forestry

6.3 Background

Commercial timber extraction has profound impacts on forest ecosystems by causing a deterioration in functional processes, which inevitably affect the provision of other ecosystem services (Thompson et al. 2011; Miura et al. 2015). Biodiversity and especially the number of forest-dependent species decline as intact forests are lost (Hanski and Haila 1988; Hanski and Ovaskainen 2000; Schmiegelow and Mönkkönen 2002). Forest fragmentation, habitat loss and deteriorated forest functionality change soil nutrient status and its ability to support plant growth and food supply for animals along the food chain (Bradshaw et al. 2009). Currently, intact boreal forest landscapes cover about one-third of the world's remaining forests and are characterised by vast areas with least human-induced disturbances and immense carbon sequestration (Bradshaw et al. 2009; Gauthier et al. 2015). The Russian Federation holds a large part of intact forest landscapes on its territory but at the same time suffers from rapid loss of such valuable forests due to economic activities as well as anthropogenic forest fires (Potapov et al. 2008, 2017). Efforts towards proactively preventing the loss of and prioritising the conservation and restoration of intact forests are of global concern for biodiversity, climate and sustainable development (Watson et al. 2014).

Forest certification systems were developed since the 1990s to safeguard biodiversity and ecosystem functions, and have operated as market-based and voluntary schemes to promote and label more sustainable forest exploitation and at the same time tried to reconcile economic interests and social responsibility (Rametsteiner and Simula 2003; Auld et al. 2008). Over the last 25 years, the Forest Stewardship Council (FSC) established internationally as a prominent certification system used by many in the timber business for claiming timber and woody products as responsibly produced. The FSC has gained global recognition and was approved as a measure for accomplishing at least 11 goals and 35 targets within the framework of the Sustainable Development Goals (SDG) (FSC 2016a; Ugarte et al. 2017). Despite considerable public, political and scientific interest to understand and evaluate the effective impact of FSC around the globe, there are only few findings to show the benefits it provides for forest ecosystems (Blackman and Rivera 2010; Marx and Cuypers 2010; Blackman et al. 2015; Burivalova et al. 2017). The effectiveness of forest certification can be defined as the success of changing and mitigating negative environmental and socio-economic impacts caused by forestry (Gulbrandsen 2005).

Almost 200 million ha of the world's forest distributed across 83 countries are FSC-certified, and the Russian Federation boasts greatest coverage with more than 45 million ha (FSC 2019). In the north west of the Russian Federation, in the Arkhangelsk Region, extensive areas of boreal forest are under certification that goes back many years encompassing almost all big companies (Lukashevich et al. 2016). The extent of forest brought under FSC certification has steadily increased since the scheme was first introduced to the region in 2004 (Blumroeder et al. 2018). Typically, forest in the Arkhangelsk Region is harvested under a clearcut regime and involves clearcuts of up to 50 ha in production forests (McDermott et al. 2010). Large areas of forest clear-felled in adjacent squares give rise to large 'chequerboard patterns' clearly visible in satellite images (Blumroeder et al., 2018; Potapov et al., 2017, 2009, Naumov and Angelstam 2014). The practice of clearcutting is endorsed by Russian forest legislation, and it can include primary forest. In the Arkhangelsk Region, private enterprises conduct clearcuttings in pristine boreal forest ecosystems (Achard et al. 2006). Forest cover in Russia has changed rapidly and extensively over the last decades as a consequence of commercial timber extraction especially in European Russia (Achard et al. 2006) and future projections are for further tree cover loss (Hewson et al. 2019).

Clearcuttings are typically conducted using modern harvesters and skidding machinery to cut and extract timber. Mechanical disturbance due to tree harvesting operations alters the physical structure and chemical composition of forest soils to the extent that it can take more than 100 years to recover (Dymov 2017). Heavy machinery impacts the soil morphology and causes soil compaction and loss of porosity; under these conditions aeration, water absorption and retention are diminished, which can reduce forest function and productivity (Startsev and McNabb 2009; Cambi et al. 2015). Increased water runoff can contribute to soil erosion while exposed soils show higher temperature and are more likely to emit carbon (Tan et al. 2005). Forestry, and clearcutting in particular, reduces microbial and fungal biomass in soil (Tan et al. 2008; Holden and Treseder 2013). The root system and growth of plants is disrupted by soil compaction with associated changes in ion uptake (Nawaz et al. 2012).

The Russian National FSC Standard advises reducing the size of clearcuts to maintain ecosystem functioning, but clear and binding thresholds are not given in the set of Principles, Criteria, and Indicators (Blumroeder et al. 2018). Tree cover loss is a suitable indicator for quantifying timber harvesting activities, but was shown not to be influenced by FSC in the Russian Far East (Nikolaeva et al. 2019). Almost 1 Million ha of the Arkhangelsk Region were affected by tree cover loss by 2014, of which more than half was recorded within concessions that had been FSC-certified at least once up to 2016, including logging prior and during FSC certification, while least tree cover loss was found in non-certified areas, in contrast to losses in certified forests (Blumroeder et al. 2018).

The present study was carried out to test the postulated outcomes and underlying assumptions of a *Theoretical Plausibility Analysis* (Blumroeder et al. 2018), and to complement an *Empirical Plausibility Analysis* (Blumroeder et al. 2019), which was undertaken earlier to assess the ecological effectiveness of FSC certification in a case study located in the Arkhangelsk Region. For example, the FSC-Indicator 6.3.7 invites the hypothesis that clearcuts are smaller in size when harvesting is operated under FSC and reads as *"The organization shall have a program to switch over from large-scale clearcuts to narrow clear-strip clearcuts and/or small-size clearcuts (up to several hectares), shelter-wood (multistage) cuts and/or selection cuts in forest types where it is feasible"* (FSC 2012). Concretely, this study spatially assesses the impact of FSC certification by comparing tree cover loss and logging activities in certified areas with non-certified forest operations at two different spatial scales: 1) analysing secondary impacts of clearcuttings on adjacent remnant forests and quantifying logging intensity in a sample area; and 2) assessing the size and exhaustiveness of clearcuttings as well as the density of skidding trails within clearcuts.

6.4 Methods

The Arkhangelsk Region is located in the northwest of the Russian Federation and covered by a complex network of rivers and mires surrounded by an extensive forest area (Yaroshenko et al. 2001).

The forest is of primary origin with large areas remaining intact and dominated by native spruce and pine species (Yaroshenko et al. 2001). Forestry is the main source of the economy in the region and most of the activities are carried out in primary forests (Kobyakov and Jakovlev 2013, Angelstam et al. 2017). Timber harvesting is mainly conducted as clearcuts of up to 50 ha in compliance with the Russian forest legislation, also in primary forests, with severe negative ecological impacts (Blumroeder et al., 2018; Potapov et al., 2017, 2009). In this study, clearcut is defined according to FSC as “harvesting in a designated area with retention of individual trees and shrubs (groups of trees and shrubs) to ensure forest regeneration” (FSC 2012).

In this study, information on the spatio-temporal distribution of FSC-certified forests in the Arkhangelsk Region as of May 2016 (FSC Russia and Transparent World 2016) was processed after revising issue dates of each certificate holder according to publicly available certificates (FSC 2016b). FSC-certificates are valid for a period of five years and terminate if renewal was not requested by the concession holder. Non-compliance with the standard requirements detected during annual surveillance audits can result in certificate suspension. In the Arkhangelsk Region, FSC-certification started in 2004 with two concession holders and proceeded to 41 certified concession holders in 2016. Due to termination or suspension of FSC-certificates some logging companies were not certified permanently and constantly (Blumroeder et al. 2018).

In this analysis, we distinguished between areas with no history of certification (*non-FSC* in the following); and forests that had been managed before they became certified (*before-FSC* in the following) and subsequently under FSC (*during-FSC* in the following). Within a sample area delineating approximately 3,000 km^2 in the east of the Arkhangelsk Region, data generated by Hansen et al. (2013) on changes in global forest cover between 2001 and 2014 was used to calculate annual tree cover loss and the size of clearcuts in relation to the certification status. Previous studies showed that the sample area and clearcutting is typical for the region’s forestry operations (Karvinen et al. 2006, 2011; Greenpeace International 2014, 2017; Blumroeder et al. 2018, 2019). Within the sample area**,** tree cover loss was classified manually from high-resolution (between 41 cm to 100 cm resolution) observation of Google Earth Pro satellite images (Google Earth Pro 2018) into five different categories according to their shape, structure and size, as follows: (1) clearcut logging (geometric quadrangle of cleared forest with visible signs of logging operations such as tree stumps and skidding trails); (2) forest fires (irregular burnt patches); (3) roads (straight lines); (4) diffuse small-scale canopy loss (covering less than one hectare); and (5) undisturbed forest (no apparent canopy disturbance) (Figure 1).

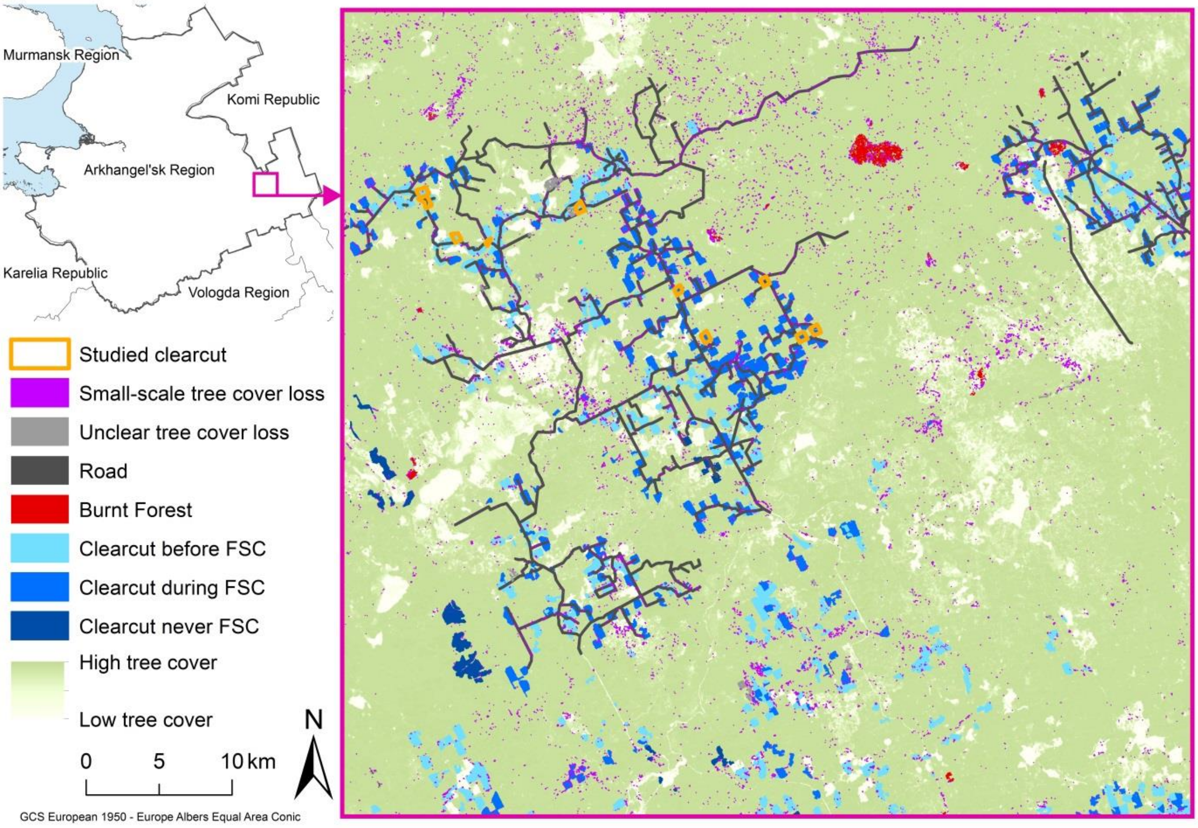

Figure 1: Location of the sample area and investigated clearcuts in the east of the Arkhangelsk Region. Different colours represent different types of tree cover loss (Hansen et al. 2013) such as small-scale (below 1 ha), forest fires and road as well as clearcut logging conducted before, during and without FSC certification.

All logging activities within the sample area were conducted as clearcuts by three different concession holders. During the period of study, one company was never FSC-certified (non-FSC), while another two became certified and comprise clearcuts that were logged prior to certification (before-FSC) and while they were FSC-certified (during-FSC). The mean area logged was calculated as the annual mean area of clearcut in relation to the area covered by the concession, and compared with the status of certification at the time of logging. Records of tree cover loss during the initial and final year of certification were excluded from the analysis to reduce uncertainty, as definite assignment to *before-FSC* or *during-FSC* seemed impossible. Furthermore, within the range of 1 km around each clearcut (n = 1096), the spatial distance to neighbouring small-scale tree cover loss polygons that occurred in the subsequent years (n = 4641), was determined. Spearman correlation coefficient was calculated to test the spatial interrelation between the clearcuts and the patches smaller than one hectare.

In addition, a total of ten clearcuts which were also object of a previous study (compare a related study conducted on the same clearcuts Blumroeder et al. 2019) were scrutinised more specifically. The studied clearcuts were randomly selected within two neighbouring logging concession holders who were cooperative in providing study plots but wished to remain anonymous. Clearcut harvesting was carried out between 2009 and 2011, while one company was applying FSC (certified since 2006 and thus cut during-FSC) and the other was operating without FSC (certified since 2013 and therefore logged before FSC was implemented). The edges of each clearcut, the alignment of skidding trails, and the configuration of forest remnants (defined as different types of forested patches within a clearcut, including so-called seed trees, group of trees, key biotopes, and immature forests) were mapped and delineated using data on tree cover loss (Hansen et al. 2013), satellite images (Google Earth Pro 2018), and obtainable forest management plans. Results for remote spatial analysis were subsequently followed up with in-field verification in July 2017 using GPS tracking. To calculate the mean distance between skidding trails, a point matrix was created with points set at equidistance along the skidding trails. The distance between the skidding trails was calculated as mean distance between two points of neighboring trails.

All data processing and statistical analyses were performed in ArcGIS (ESRI 2011) and RStudio Version 1.1.456 (R Development Core Team 2018). Non-parametric statistical Kruskal-Wallis and subsequent Conover post hoc test were applied as alternative to ANOVA using the package PMCMR to test for differences between groups (Pohlert 2014).

6.5 Results

A comparison between FSC-certified and uncertified forest using data on the proportion of annually logged to untouched areas within the concessions revealed no significant difference (p-value = 0.2975) (Figure 2).

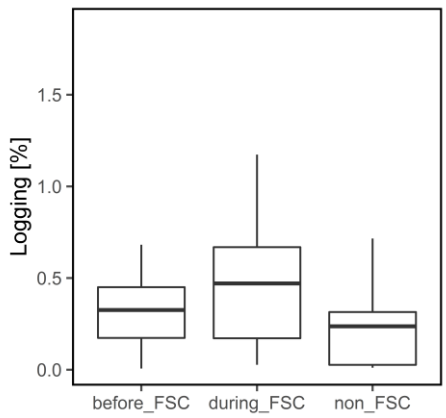

Figure 2: Logging intensity in the sample area differentiating between areas that were under FSC-certification during the logging operation (during-FSC), areas that were harvested before they became certified (before-FSC) and areas that were never under certification (non-FSC): Annual tree cover loss induced by logging in relation to the available area within the sampled study area.

Within the sample area, a significant, strong, and negative correlation between large-scale clearcuts and small-scale tree cover loss of less than 1 ha was detected, meaning that in the vicinity of large-scale patches of tree cover loss (including clearcuts) additional diffuse small-scale tree cover loss occurred (r = -0.89; p-value < 0.001) (Figure 3). Equally, the extent of the area affected by small-scale tree cover loss was higher in areas closer to the larger tree cover loss polygons (r = -0.9; p-value < 0.001).

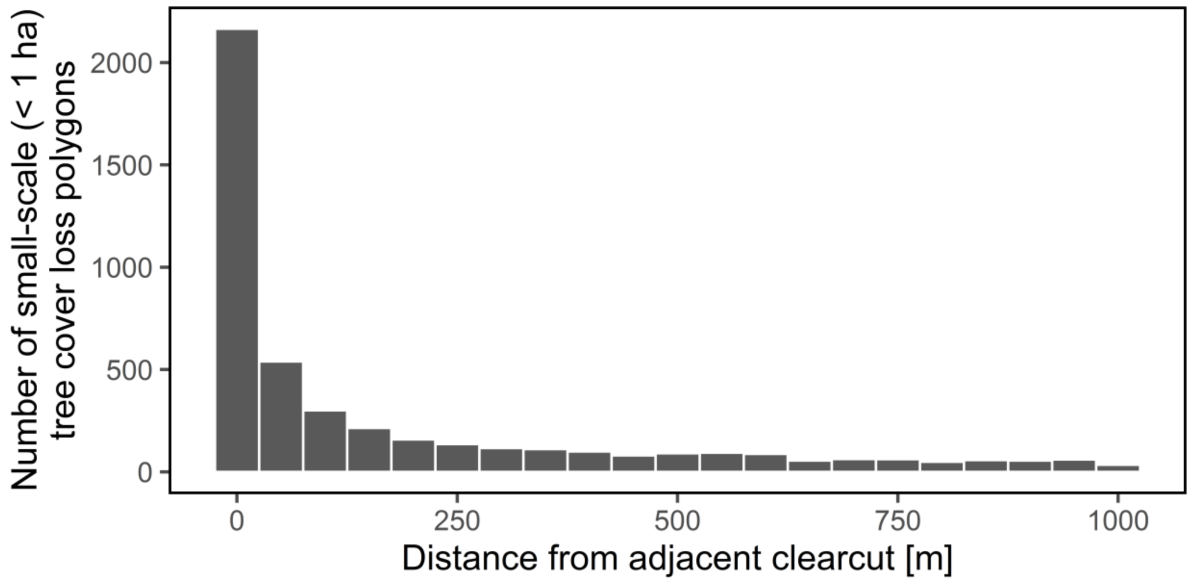

Figure 3: Relationship between small- and large-scale tree cover loss in the sample area.

The spatial dimension of the ten randomly selected clearcuts was approximately 30 ha on average (before_FSC: mean = 27.74 ha, median = 32.83 ha; during_FSC: mean = 30.12; median = 32.20 ha) without significant difference between clearcuts harvested before and during FSC-certification (p-value = 0.4647). However, *before-FSC* clearings varied much more in size, also comprising the smallest clearcut of 7.6 ha (Figure 4).

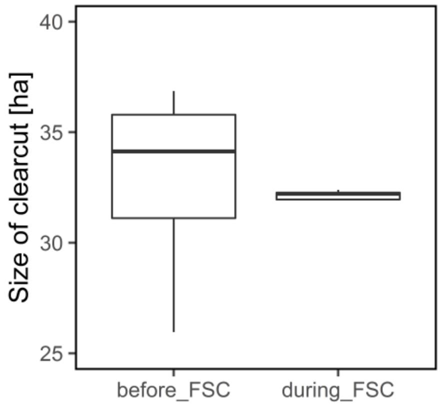

Figure 4: Size of clearcuts before FSC certification (n=5) and during valid FSC certification (n=5).

There was no evidence within the sampled area to indicate that the retention of forest remnants within the studied clearcuts increased in forests during-FSC (p-value = 0.77). In both certified and uncertified clearcuts, up to 97 % of the area was completely cleared (Figure 5). On two of the studied clearcuts that were cut during valid FSC-certification, 20 % of tree cover was retained on logged sites covering immature forest with little economic value. In the case of one site that was logged before it was registered under FSC, more than 17 % of the forest cover was spared from felling because of the presence of key biotopes and seed trees, while on other clearcuts less than 7 % of the initial tree cover was retained.

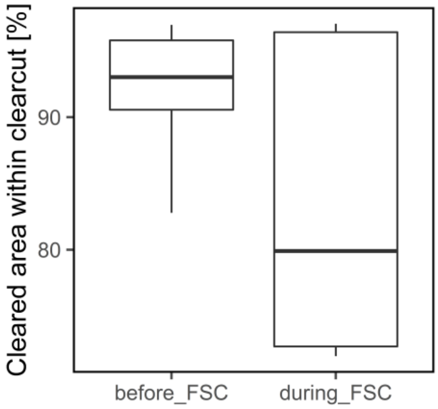

Figure 5: Share of cleared area within the studied clearcuts before FSC certification (n=5) and during valid FSC certification (n=5).

All skidding trails on the ten clearcuts were covered with felling residues as soil protection measure. The certification of forest under FSC made no significant difference to practices of harvesting and removal of trees and across the landscape skidding tracks were spaced on average less than 20 metres apart (p-value = 0.5) (Figure 6).

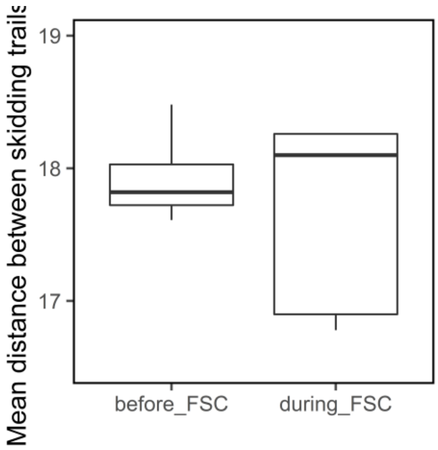

Figure 6: Mean distance between skidding trails on clearcuts before FSC certification (n=5) and during valid FSC certification (n=5).

6.6 Discussion

In this study, there was no evidence to indicate that FSC certification of forests leads to changes in harvesting practices in the studied clearcuts in the east of the Arkhangelsk Region. The extent of tree cover loss after the introduction of FSC remained equally high compared to as it was prior to certification or without certification within the sampled area. The results confirm the findings gained by Nikolaeva et al. (2019) showing that FSC certification did not induce changes in tree cover loss in the Russian Far East. The sixth FSC Principle, including FSC indicator 6.3.7, seems to be the most problematic in terms of non-compliance that was detected during audits (Lukashevich et al. 2016). The results are also in accordance with the findings of a previous study showing that FSC did not reduce annual tree cover loss (Blumroeder et al. 2018).

Our findings indicate that FSC failed to

(1) reduce the size of clearcuts significantly,

(2) to increase the retention of seed trees on logged areas, and

(3) to maintain larger tracts of undisturbed ground and soil on the investigated study sites and clearcuts represented by less skidding trails.

The practice of removing almost all economically profitable wood also contributes to further indirect effects of forest degradation and fragmentation, for example, an increase in edge effects as a result of opening the forest up to higher exposures of sunlight, wind as well as increased temperature variation and other disturbances (Greenpeace International 2014, Schmiegelow and Mönkkönen 2002). Dramatic changes in forest patch dynamics towards larger, geometrical patterns may contribute to tree mortality and decreased food availability along the edges (Schmiegelow and Mönkkönen 2002).

The observed diffuse small-scale tree cover loss deserves special attention. In these remote inaccessible and uninhabited areas, it is unlikely that it is related to tree felling or direct anthropogenic interventions. Rather, it is plausible that it can be attributed to dieback of desiccated, flooded, infested or windthrown trees. Apart from obvious natural dieback and gap formation, we observed further small-scale dieback in forest adjacent to clearcuts, which had not been included in harvesting activities. As the findings indicate, within a 1 km range around the clearcuts range a clear spatial relationship exists between diffuse dieback and larger clearcut areas. It is likely they represent secondary impacts of clearcuttings spreading into neighbouring stands. There is evidence that edge effects can reach hundreds of meters inside the remaining forest ecosystem (Laurance 2000; Ries et al. 2004). Changes in both micro- and meso-climate, such as greater fluctuations in temperature and elevated maximum temperatures, possibly causing and interacting with hydrological changes, would increase vulnerability in trees already growing under extreme conditions (Blumroeder et al. 2019). Not only the direct loss of tree cover within cleared forest areas, but also the catalytic losses in remaining untouched forests due to fragmentation and increased forest edges is known to threaten the maintenance of forest functions and the stability of the ecosystem (Riitters et al. 2016). So far, these indirect effects caused by the anthropogenic manipulation of the boreal forest ecosystem are insufficiently understood and can represent an enormous risk that was masked for a long time, when cuttings were smaller and less frequent and when climate was more moderate. The large-scale clearcuts could have the potential of driving irreversible changes of the mesoclimate, thus increasing the vulnerability of both uncut and legally protected forests. The diffuse dieback in unused areas next to clearcuttings could increase their burnability and the corresponding risk of further indirect anthropogenic degradation.

Clearcutting and concomitant mechanical disturbances by harvesting practices impact soils drastically, so much so, that scientists have classed these damaged soils as detritus turbozems (Dymov 2017). The combined effects of microclimatic and soil changes induced by the practice of large-scale and intensive ‘timber mining’ can hamper natural forest succession and regeneration, and create a long-term legacy of forest loss. In forest areas under FSC certification, the density of skidding trails within the studied clearcuts was not reduced. The initial ride on the forest floor has the most severe impact on the soil, especially on the topmost layer, while the wheel rut is impacted most (Tan et al. 2008; Cambi et al.

2015; Abdi et al. 2017). A combination of factors such as soil conditions and hydrology, as well as frequency and weight of mechanical disturbance, causes soil compaction that can take decades to recover (Cambi et al. 2015).

Tree retention can help to increase structural diversity of clearcuts to support biodiversity (Lindenmayer and Franklin 2003). Furthermore, increasing the level of retention enhances carbon storage (Santaniello et al. 2017). However, in our study, forest practices under FSC did appear to reduce the size range of forest clearings, but not the number of remaining trees or retained forest patches within the clearing. Larger volumes of remaining tree biomass would provide stronger support for biodiversity in terms of available habitats and regarding a reduction of severe threats to biota, but certain quantities of remaining biomass on clearcuts cannot substitute functions and services provided by primary forests (Gustafsson et al. 2010). The ecological effectiveness of voluntary set-asides is often poor, as mostly immature stands are spared from felling and because the structural and functional connectivity of forest ecosystems needed to maintain biodiversity are not considered (Elbakidze et al. 2016).

One of the main drivers for forestry companies in the Russian Northwest to engage with FSC is the increased access and sale to European markets (Rametsteiner and Simula 2003; Blackman and Rivera 2011; Romero et al. 2013; Henry and Tysiachniouk 2018). The attractions of lucrative markets in countries where there are strong public concerns for the environment encourages forestry companies to operate intensively under the umbrella of FSC. There is evidence to suggest FSC certification can even increase the rate and intensity of forest exploitation due to the high incentive for timber exports and sales market. This is also known from other biomes. For instance, in the Congo basin, tree cover loss in intact forest landscapes was higher in certified compared to non-certified concessions (Kleinschroth et al. 2019).

6.7 Conclusions

In order to induce quantifiable changes of the logging practices and safeguard ecosystem functionality, i.e., to increase the ecological effectiveness of FSC, current clearcutting practices would have to be replaced. The overexploitation of provisioning services, i.e. timber extraction, diminishes the ecosystems' capacity to maintain other services of global significance. It also reduces the ecosystem functionality important to cope with and adapt to other stresses and disturbances that are increasing under rapid climate change. In combination with earlier assessments (Blumroeder et al. 2018, 2019), this study confirms doubts that the Forest Stewardship Council is an appropriate mechanism for safeguarding ecologically responsible forest use in Russian forests. The Russian National FSC Standard fails to induce ecologically friendly cutting and harvesting methods in the studied area. As reaction to our earlier papers, FSC (Germany) accepted to a certain degree this critique (e.g., in Holz-Zentralblatt 30, 26 July 2019), but pointed out that an environmental benefit would be the protection of 19 % of the certified forests in Russia. Still, it was impossible to obtain spatial data from FSC that would confirm that such a value also applies to the Arkhangelsk Region. Furthermore, it was impossible to verify if the mentioned protected areas covered only forests, or also included (unexploitable) non-forest areas such as mires, and if the legal protection was permanent and independent from the period of certification. Fundamental questions to be raised refer to the burden of proof as well as to FSC's transparency policy. But even if long-term set-aside of forests in the vicinities of the clearcuttings was confirmed, their effectiveness has to be assessed in the light of apparent edge effects and secondary dieback potentially triggered by large-scale clearcutting practices.

6.8 Acknowledgements

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7. Forestry contributed to warming of forest ecosystems in northern Germany during the extreme summers of 2018 and 2019

Blumröder, J.S., F. May, W. Härdtle & P.L. Ibisch (2021): Forestry contributed to warming of forest ecosystems in northern Germany during the extreme summers of 2018 and 2019. Ecological Solutions and Evidence.

7.1 Abstract

1. Forest management influences a variety of ecosystem structures and processes relevant to meso- and microclimatic regulation, but little research has been done on how forest management can mitigate the negative effects of climate change on forest ecosystems.

2. We studied the temperature regulation capacity during the two Central European extreme summers in 2018 and 2019 in Scots pine plantations and European beech forests with different management-related structural characteristics.

3. We found that the maximum temperature was higher when more trees were cut and canopy was more open. Logging 100 trees per hectare increased maximum temperature by 0.21 – 0.34 K at ground level and by 0.09 – 0.17 K in 1.3 m above ground. Opening the forest canopy by 10 % significantly increased $T_{max,}$ measured 1.3 m above ground by 0.46 K (including pine and beech stands) and 0.35 K (only pine stands). At ground-level, T_{max} increased by 0.53 K for the model including pine and beech stands and by 0.41 K in pure pine stands. Relative temperature cooling capacity decreased with increasing wood harvest activities, with below average values in 2018 (and 2019) when more than 656 (and 867) trees per hectare were felled. In the pine forests studied, the relative temperature buffering capacity 1.3 m above ground was lower than average values for all sample plots when canopy cover was below 82 %. In both study years, mean maximum temperature measured at ground-level and in 1.3 m was highest in a pine-dominated sample plots with relatively low stand volume (177 m^3 ha^{-1}) and 9 K lower in a sample plot with relatively high stock volumes of *F. sylvatica* (> 565 m^3 ha^{-1}). During the hottest day in 2019, the difference in temperature peaks was more than 13 K for pine-dominated sample plots with relatively dense (72 %) and low (46 %) canopy cover.

4. Structural forest characteristics influenced by forest management significantly affect microclimatic conditions and therefore ecosystem vulnerability to climate change. We advocate keeping the canopy as dense as possible (at least 80 %) by maintaining sufficient overgrowth and by supporting deciduous trees that provide effective shade.

7.2 Abstract in German

1. Waldbewirtschaftung beeinflusst eine Vielzahl von Ökosystemstrukturen und -prozessen, die für die meso- und mikroklimatische Regulierung relevant sind, aber bislang ist weniger darüber bekannt,

inwiefern die Waldbewirtschaftung die negativen Auswirkungen des Klimawandels auf Waldökosysteme abmildern kann.

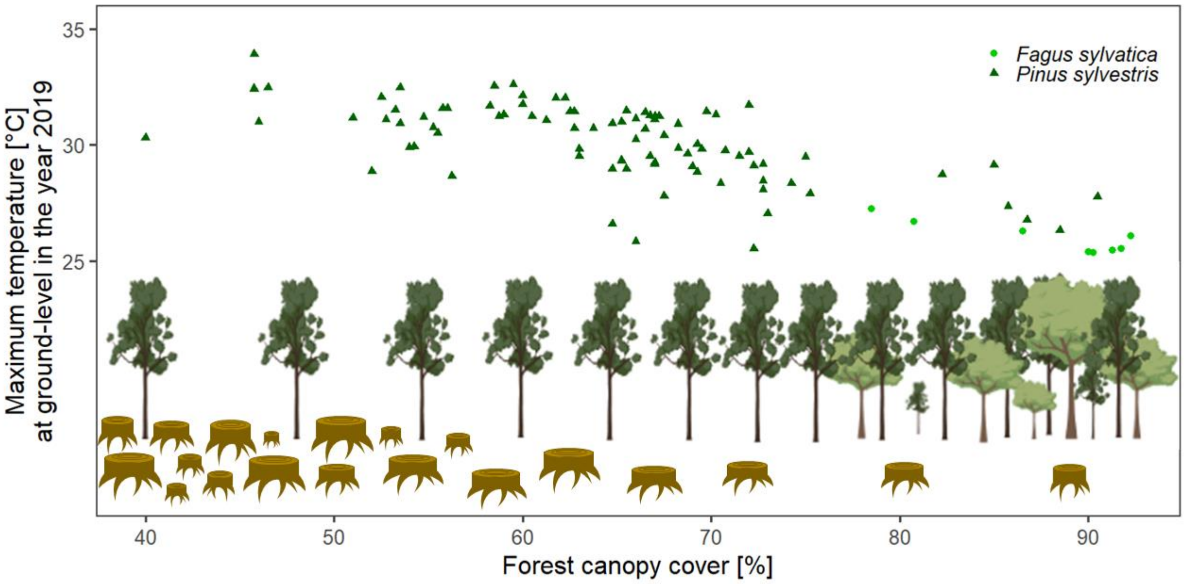
2. Untersucht wurde die Temperaturregulationsfähigkeit in unterschiedlich behandelten Kiefernforsten und Rotbuchenwäldern während der beiden mitteleuropäischen Extremsommer 2018 und 2019.

3. Dabei wurde herausgefunden, dass die Höchsttemperaturen höher ausfielen, wenn mehr Bäume gefällt worden waren und das Kronendach lichter war. Das Fällen von 100 Bäumen pro Hektar erhöhte die Höchsttemperatur in Bodennähe um 0,21 - 0,34 K und 1,3 m über dem Boden um 0,09 - 0,17 K. Das Öffnen des Kronendaches um 10 % erhöhte T_{max}, gemessen in 1,3 m über dem Boden, signifikant um 0,46 K (in Kiefern- und Buchenbeständen) beziehungsweise um 0,35 K (bei alleiniger Betrachtung von Kiefernbeständen). In Bodennähe erhöhte sich T_{max} für das Modell mit Kiefern- und Buchenbeständen um 0,53 K und in reinen Kiefernbeständen um 0,41 K. Die relative Temperaturkühlungskapazität fiel unterdurchschnittlich aus, wenn mehr als 656 (in 2018) (und 867 in 2019) Bäume pro Hektar gefällt wurden. In den untersuchten Kiefernwäldern war die relative Temperaturpufferungskapazität in 1,3 m über dem Boden (bei Betrachtung aller Probeflächen) niedriger als der Durchschnitt, wenn der Kronenschlussgrad unter 82 % lag. In beiden Untersuchungsjahren fiel die in Bodennähe und in 1,3 m gemessene mittlere Höchsttemperatur auf einer kieferdominierten Fläche mit relativ geringem Vorrat (177 m^3 ha^{-1}) am höchsten aus. Auf einer Probefläche mit relativ hohem Vorrat von *Fagus sylvatica* (> 565 m^3 ha^{-1}) war sie um 9 K niedriger. Während des heißesten Tages im Jahr 2019 betrug der Unterschied zwischen den Temperaturspitzen im Kiefernforst mit einem relativ geschlossenen (72 %) und einem offenen (46 %) Kronendach mehr als 13 K.

7.3 Keywords

Drought events, climate change, cooling, forest canopy, forest functionality, regulating ecosystem services, temperature buffering

7.4 Graphical Abstract



7.5 Introduction

In Central Europe, the weather extremes of the past years, in combination with insect outbreaks and other calamities, have already contributed to large-scale tree dieback (Seidl et al. 2017; Schuldt et al. 2020). Heat and drought stress, forest fires, storms, and late frost events, as well as associated pests and diseases often occur in complex interaction with each other and cause impacts with unpredictable outcomes (Allen et al., 2010; Carnicer et al., 2011). Extreme temperatures, for example, can cause physiological damage and have an impact on the vitality, growth and mortality of trees (Buras et al., 2018). This can trigger a decline in productivity, carbon sequestration, and woody biomass (Smith et al., 2020; Vieira et al., 2020). Warmer temperatures can directly impair organisms, but also drive a non-linear rise in water vapour deficit and contribute to the desiccation of plants (Hatfield & Prueger, 2015). Higher temperatures can increase the production of seeds by trees but compromise their establishment and survival due to increased water stress (Ibáñez et al. 2017). Although species have different mechanisms to cope with drought (Volaire 2018), tree vitality and productivity already declined in response to recent drought events (Rohner et al. 2021; Senf et al. 2020).

The extreme drought in 2018 severely affected forest stands in Germany (Ionita et al. 2021), and, as a consequence, about twice as many trees died in 2019 compared to 2018 and about 80 % of all living trees showed poor vitality (BMEL, 2020). Climate conditions, which are currently perceived as extreme (Büntgen et al. 2021), could represent the new 'normal' in the near future (Hari et al., 2020; Scharnweber et al., 2020). It is, therefore, of high interest, which practices of forest management such as thinning or keeping close canopies have the potential to attenuate the adverse effects of heat waves within forest stands.

Recent studies conclude that thinning can reduce drought impacts (Del Río et al. 2017; Sohn et al. 2016a; Giuggiola et al 2013; 2016; Ma et al. 2010; Primicia et al. 2013; Simonin et al. 2007; Gebhardt et al. 2014; D'Amato et al. 2013; Ameztegui et al. 2017). However, a critical challenge for forest management is to support the ecosystem capacity for microclimate regulation, especially in times of frequently recurring dry and hot years, when precipitation is absent for longer periods of drought. Here, microclimate regulation implies the attenuation of summer peak temperatures, moderation of mean temperatures and the buffering of temperature fluctuations in the forest interior. An important outcome of microclimatic regulation is the stabilization of habitat conditions for species affected by shifting microclimatic conditions (De Frenne et al., 2013; Milling et al., 2018; Suggitt et al., 2011; Tuff et al., 2016; Varner & Dearing, 2014; Zellweger et al., 2020). With growth and development of a forest, the canopy structure changes, water uptake potential improves, and transpiration reduces extreme temperatures (Holdaway et al., 2010). The canopy structure of a forest stand resulting from forest management directly influences temperature and vapour pressure deficit in the forest interior (Jucker et al., 2018), where the release of water vapour by plants is often the only source of humidity, particularly in seasons with deficient precipitation (Moreira et al., 1997). As a consequence, the forest canopy cools soil and air during warm days and buffers temperature fluctuations (Jin et al., 2019). In this way, forest interior temperatures are moderated across seasons (Zellweger et al., 2019), and temperature differences inside and outside forests are higher when macroclimatic conditions become more extreme (De Frenne et al., 2019). Structural characteristics that determine a within stand's microclimate include the predominant tree species (De Abreu-Harbich et al., 2015), tree vitality (Sanusi & Livesley, 2020), biomass volume (Norris et al., 2012) as well as elevation and canopy cover (Ma et al. 2010).

Microclimatic regulation is an important ecosystem service facilitated especially by trees, woodlands, or forests, which is increasingly appreciated and taken into account in urban development and planning (Fung & Jim, 2019). In the context of urban adaptations to climate change, microclimate regulation for the mitigation of heat island effects by green infrastructure has been investigated much more intensively (Kong et al., 2014; Lindén et al., 2016; Shashua-Bar et al., 2009; Wang et al., 2018) than in open landscapes and within forest ecosystems. Despite the fact that forest management influences a variety of forest ecosystem structures and processes relevant to meso- and microclimatic regulation, so far, there is a knowledge gap of how forest management could contribute to a reduction of temperature extremes, mean temperatures, and temperature fluctuations within forest stands and could thus improve climate change adaption at the stand or even at the landscape level.

There is plenty of evidence and several conceptual frameworks have been suggested that may encourage forest managers to reflect about temperature management in forests for stabilising the within-stand microclimate during extreme summer heat as contribution to preserving tree vitality and productivity under climate change. An open question is to what extent forest characteristics that are directly shaped by forest management operations (such as thinning, harvesting intensity and nature conservation) influence within-stand temperatures under extreme climatic conditions in exceptionally hot periods in a temperate region.

This study aims at analysing the effects of forest management on the microclimatic regulation of forest stands during the two extremely hot and dry summers in 2018 and 2019 (see e.g., Buras et al., 2020; Kornhuber et al., 2019; Vogel et al., 2019) by comparing forests in northern Germany across a gradient of different structural characteristics resulting from silvicultural treatments such as thinning and wood harvest. We conducted on-site microclimatic measurements in stands dominated by *Pinus sylvestris* and *Fagus sylvatica* with a high temporal and spatial resolution in order to quantify the temperature regulation of forest stands in relation to stand structural characteristics. We hypothesized that forest management activities, such as tree harvesting, would affect microclimate regulation negatively by causing higher within-stand temperatures.

7.6 Materials and methods

7.6.1 Study area

The study area is located in a post-glacial landscape in the north-eastern lowlands of Germany comprising forest stands on moraines and outwash plains (Fig. 1).

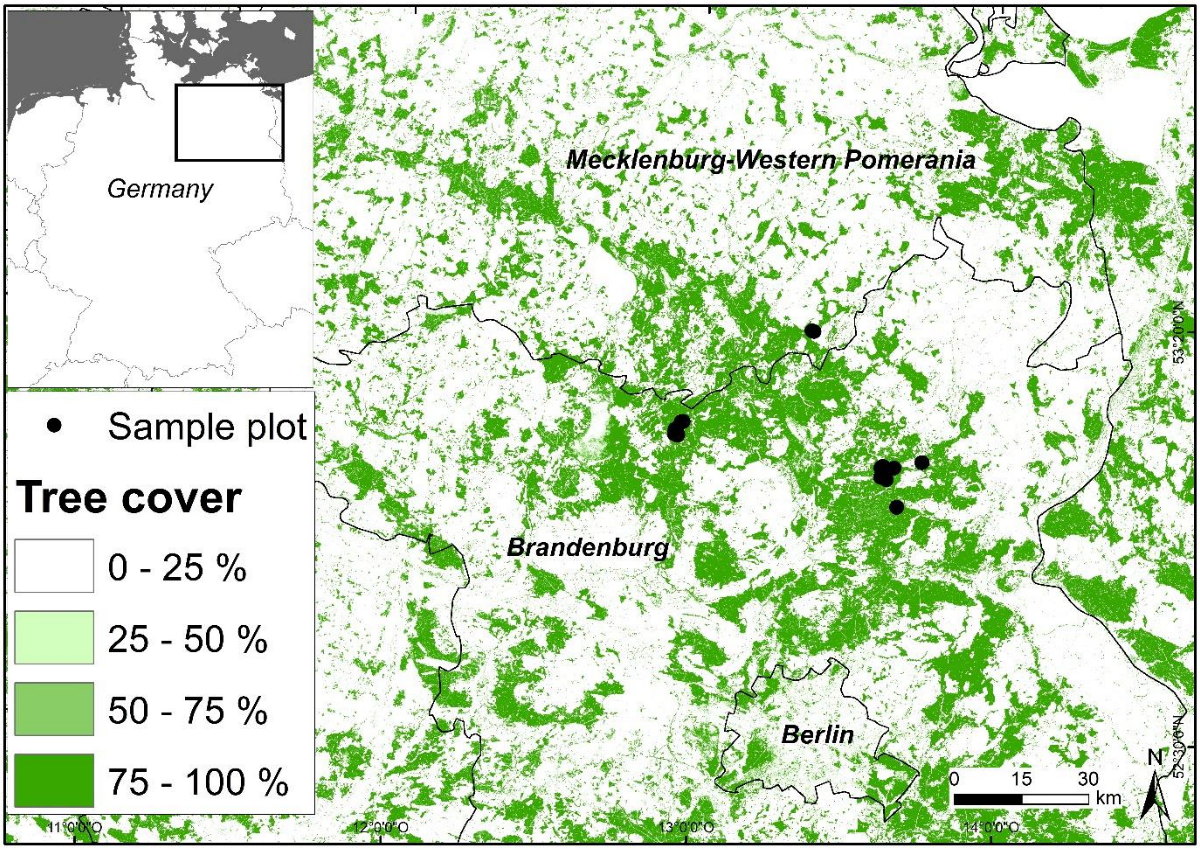


Fig. 1: Sample plots are located in the north-eastern lowlands of Germany belonging to the largest remaining forest landscape in northern Germany. Tree cover as of 2000 in green (Hansen et al. 2013).

The investigated forest sites mainly comprise monocultures of *Pinus sylvestris* (henceforth referred to as *P. sylvestris* or pine), but also pine stands with broadleaved understorey as well as stands of *Fagus sylvatica* (*F. sylvatica* or European beech). The forest stands are of different age (overstory trees with an age between ca. 20 and 300 years), which experienced different silvicultural management in the past including regular thinning (e.g. about every 5 years), harvesting, enlarging the volume of fresh downed deadwood by felling, and plantings but also include stands without interventions since 20 to

70 years. The diverse character of the different sites represents a gradient of management intensity rather than distinct treatments. The resulting differences in stand structure and compositional attributes were analysed in relation to microclimatic indicators.

Forest stands were codified as a specific *site*. Two to six sample plots were surveyed per site and located in the centre of forest stands with a minimum distance of 50 m to each other. A total of 68 sample plots were investigated in 2018 (thereof six beech sample plots within two sites) and 101 sample plots in 2019 (thereof nine beech sample plots within three sites) (Table 1).

Table 1: Number of sample plots in the study period for the three study areas.

YEAR	2018	2019
Wittwesee (*Pinus sylvestris*)	42	60
Reiersdorf		
Pinus sylvestris	20	32
Fagus sylvatica	3	6
Heilige Hallen (*Fagus sylvatica)*	3	3
TOTAL	68	101

All data were collected within concentric circular sample plots of 0.1 ha and 0.03 ha (Fig. 2, left). At the centre, a wooden pole was installed and two microclimatic data-loggers were mounted on the north-facing side (Fig. 2, right).

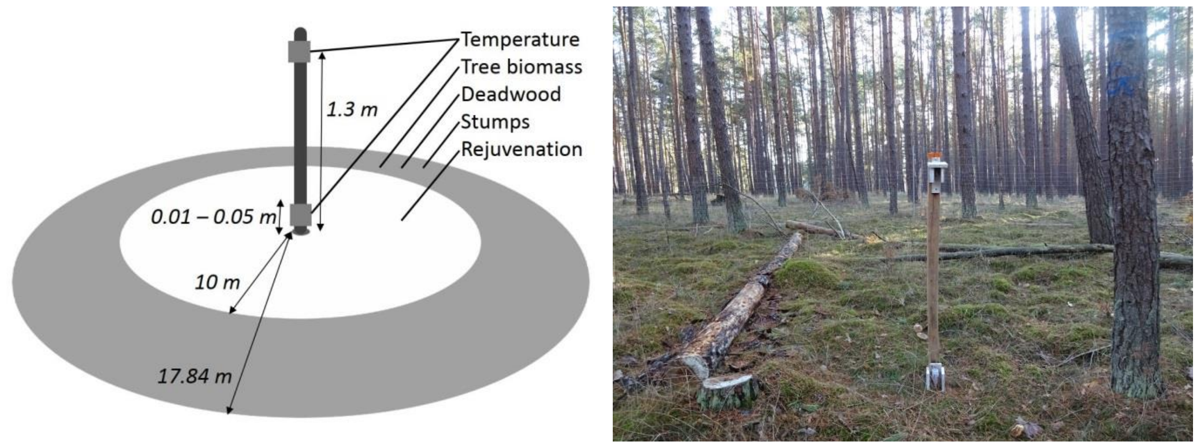


Fig. 2: Schematic visualisation of measurements taken in a sample plot (left) and sample plot with two data-loggers in a half-open wooden box (right).

Weather data from the closest weather station in Angermünde, located in ca. 30 - 80 km distance to the investigated sites, showed that the annual mean temperature was extremely high in the study period, i.e. 2 °C higher in the year 2019 compared to the reference period (8.9 °C averaged over 1981-2010) (DWD, 2020). In the year 2018, the daily maximum temperature was above 25 °C for 82 days, which is 45 days more than in the reference period (1981-2010). Mean summer temperature in the reference period was 17.3 °C (1981-2010), 19.9 °C in 2018, and 20.3 °C in 2019.

7.6.2 Microclimate

Temperature was measured at 1.3 m above ground using HOBO UA-001-64 Pendant data-loggers, and at ground-level with HOBO U23-001 Pro V2 data-loggers (Onset Computer Corporation, Bourne, USA). Data-loggers were protected from direct sunlight by a white-painted, half-open, wooden box. The data-loggers were initially left for at least 12 hours to acclimatise to ambient conditions before temporally synchronised records were taken at 30 minute intervals from May to October in 2018 and 2019.

As an ANOVA showed that the variables considered (T_{max}, RTC, and RTB, see definitions below) differed significantly between the two height levels ($p < 0.001$), they were analysed separately for each height level. For each year, all records of days with an average temperature above 20 °C (resulting in 45 days in 2018 and 39 days in 2019), calculated as mean over all sample plots and data-loggers of both height levels were extracted, and the following microclimatic indicators were computed following Blumroeder et al. (2019):

- *Maximum temperature* (T_{max}) calculated as mean of the five highest temperature records per day.
- *Relative temperature cooling capacity* (RTC) represents the capacity of lowering daily mean temperature records. It is calculated as reciprocal of the daily mean temperature of each plot divided by the daily mean temperature over all sample plots. Indicator values > 1 indicate that the daily mean temperature was lower than the average over all sample plots, meaning that a relative cooling effect was generated.
- *Relative temperature buffering capacity* (RTB) represents the deviation of temperature records from the daily mean temperature. It is calculated as reciprocal of the standard deviation of daily mean temperature of each plot divided by the standard deviation of daily mean temperature of all plots. Indicator values > 1 indicate that the temperature was less variable over a day compared to the average over all sample plots, meaning that a buffering effect was generated by stabilising the variation of daily temperatures.

7.6.3 Stand characteristics and forest management

Silvicultural treatments such as tree felling and tree biomass extraction directly or indirectly impact forest stand attributes. We surveyed indicators that are primarily influenced by forest management activities and tree harvesting in particular (i.e. canopy cover, stand volume, Stand Density Index, number of cut stumps, deadwood volume, and regeneration density).

Canopy cover was assessed during the vegetation period in the year 2019, using a spherical crown densiometer with a convex mirror (Model A, Forestry Suppliers, Inc., Mississippi, USA) showing 24 squares of 0.25 inches engraved on the surface (Lemmon, 1956). The number of squares in the mirror occupied by tree crowns and stems was counted at the centre of each sample plot into the four cardinal directions, multiplied by 1.04 to obtain the estimated overstory density percentage and averaged per sample plot to determine the density of the overstory by tree crowns (Lemmon, 1956). This indicator represents the proportion of sky that is covered by the tree crowns.

In wintertime, all tree individuals with a diameter at breast height of at least 6 cm were recorded within a 0.1 ha circular sample plot around the data-loggers. Tree species, apex height and circumference at 1.3 m height was determined. Tree volume was calculated for each single living tree based on diameter and height (Lockow 2007), and was aggregated per sample plot and extrapolated to one hectare to quantify the stand volume.

Stand Density Index (SDI) (Reineke, 1933) was calculated based on the number of trees per unit area and quadratic mean diameter (Curtis et al. 2000) and indicates the stocking density of trees in a stand. The higher the index value, the more crowded is a stand.

Tree stumps are defined as snags of less than 1.3 m height. Stumps result either by harvesting operations (cut stems) or natural disturbance and dieback (broken stems). All cut tree stumps within the 0.1 ha sample plots were counted, extrapolated to one hectare and used as proxy indicator for management history and harvesting intensity in the further analysis.

Standing and downed deadwood were also recorded within a sample plot encompassing a 0.1 ha circle around the data-loggers. For each snag taller than 1.3 m within a sample plot, volume was calculated similarly to stand volume for unbroken snags and based on minimum and maximum diameter as well as length for broken snags. The volume of downed deadwood with a minimum diameter of 5 cm and minimum length of 1.3 m was determined on the basis of the diameters at both ends and length. For the further analysis, all types of standing and downed deadwood were combined as the total volume of deadwood per hectare, similar to stand volume.

Trees with a diameter smaller than 6 cm at breast height were classified as tree regeneration. Regeneration density (N/ha) was recorded as the number of trees within a sample plot encompassing a circle with 10 m radius and extrapolated to one hectare.

7.6.4 Statistical analyses

Stand characteristics (canopy cover, stand volume, SDI, number of stumps, deadwood volume, and regeneration density) were tested for correlations to avoid multicollinearity and used in the further analysis because correlation coefficients between all predictor variables were < 0.7 (Dormann et al. 2013).

Linear mixed effects models fitted by REML and t-tests using Satterthwaite's method of the R-package lmerTest (Kuznetsova et al., 2017) were used to analyse the relationships between structural stand characteristics resulting from forest management and the microclimate indicators from the two height levels (Nakagawa & Schielzeth, 2013). Canopy cover (only available for the year 2019), stand volume, SDI, number of stumps, deadwood volume, and regeneration density were modelled as fixed effects; sites were modelled as random effect to account for spatial autocorrelation, and the response variable was a microclimatic indicator per height level. Due to the limited sample size of 68 (2018) and 101 (2019) plots and the relatively high number of six (2018) to seven (2019) fixed-effect predictor variables, we did not model and test interaction terms.

The models were fitted separately for the years 2018 and 2019 because data for canopy cover was available only for 2019. All models were fitted once using the entire dataset including all sample plots and once again for the pine monocultures only, because the dataset for beech forests was too small to be considered separately (only six sample plots within two sites in 2018 and nine sample plots within two sites in 2019).

We assessed the assumptions of linear (mixed) models, including the normal distribution and homoscedasticity of the residuals, using QQ-plots and residuals vs. fitted values plots. For each year and microclimatic indicator, we generated figures for the significant fixed effects of the model with the highest marginal R^2. All statistical analyses were conducted in R Studio (R Development Core Team, 2008).

7.7 Results

7.7.1 Maximum temperature

In both years, T_{max} measured at ground-level and in 1.3 m was highest in a pine-dominated sample plot with relatively low living tree biomass (177 m^3 ha^{-1}). In a sample plot with relatively high stock volumes of *F. sylvatica* (> 565 m^3 ha^{-1}) T_{max} was 9 K lower than in the warmest plot.

Linear mixed effects models showed that the proportion of variance explained by the fixed factors was highest for the datasets including only pine sample plots. The number of stumps, regeneration density and SDI were significant in the year 2018 for T_{max} in 1.3 m and in 2019, when also data for canopy cover was available, canopy cover was significant as well (Table 2; Fig. 3).

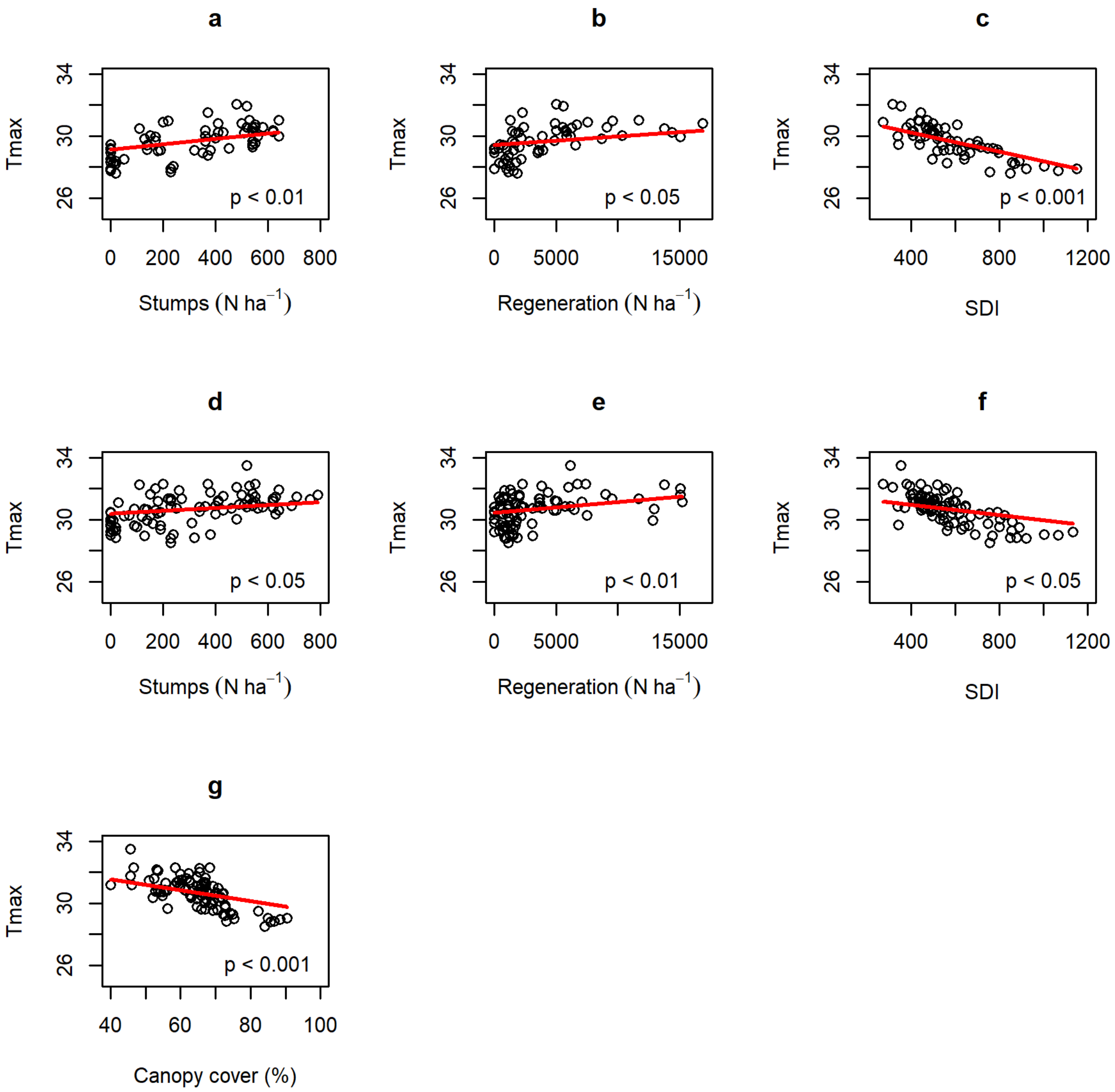


Fig. 3: Maximum temperature in 1.3 m above ground in sites dominated by *Pinus sylvestris* in 2018 (a-c; $R^2_{marginal} = 0.71$; $R^2_{conditional} = 0.74$) in 2019 (d-g; $R^2_{marginal} = 0.63$; $R^2_{conditional} = 0.65$) in relation to the number of cut trees (stumps; a and d), the number of trees < 6 cm DBH (regeneration; b and e), Stand Density Index (SDI; c and f) and canopy cover (g). The points show the data and the red lines model predictions. The predictions were generated by only varying the variable shown at the x-axis, while all other variables were fixed at their observed mean value. The p-values refer to the test that the slope estimate of the variable shown on the x-axis equals 0. The degrees of freedom were approximated using Satterthwaite's correction method.

The number of stumps resulting from harvesting activities was significantly associated with T_{max} (Table 2). Across all years and sample plots, when the number of stumps increased by 100, maximum temperature increased by 0.21 – 0.34 K at ground level and by 0.09 – 0.17 K in 1.3 m (Table 2, Fig. 3a). Since the number of stumps is a strong proxy for the intensity of harvesting, this indicates a strong effect of tree harvesting on maximum temperature.

In 2019, when data for canopy cover was available and included in the linear mixed effects models, canopy cover influenced the average maximum temperature (T_{max}) in all tested datasets (Table 2). Opening canopy cover by 10 % increased T_{max} 1.3 m above ground by 0.46 K (including pine and beech stands) and 0.35 K (only pine stands) (Fig. 3g). At ground-level, T_{max} increased by 0.53 K for the model including pine and beech stands and 0.41 K in pure pine stands.

Tree regeneration also showed significant effects on T_{max} across all datasets, except for T_{max} in 1.3 m with the dataset including all sample plots in 2018 (Table 2). An increase by 1,000 regenerating trees per hectare was related to an increase in maximum temperature by around 0.1 K (Fig. 3b).

Decreasing stand volume by 100 m³ per hectare significantly increased T_{max} by 0.31 – 0.33 K at ground-level and by 0.15 – 0.27 K in 1.3 m above ground in the models including all sample plots but not for the dataset comprising only pine stands (Table 2). When only stands dominated by *P. sylvestris* were considered, SDI had a negative effect on T_{max}, meaning that the denser a forest stand is stocked the lower the maximum temperature (Table 2, Fig. 3c, Fig. 3f).

7.7.2 Relative temperature cooling capacity

The intensity of harvesting - indicated by the number of cut stumps - results in a significantly lower relative temperature cooling capacity (RTC) at ground level for all models with all datasets (Table 2). At 1.3 m above ground, only in 2019 the number of stumps showed an effect on RTC (Table 2).

The two models with the highest marginal R^2 (RTC at ground level including all sample plots) showed that only the number of stumps had a significant effect (RTC decreased with more trees being cut). RTC fell below the average in 2018 (and 2019) when more than 656 (and 867) trees per hectare have been logged (Fig. 4).

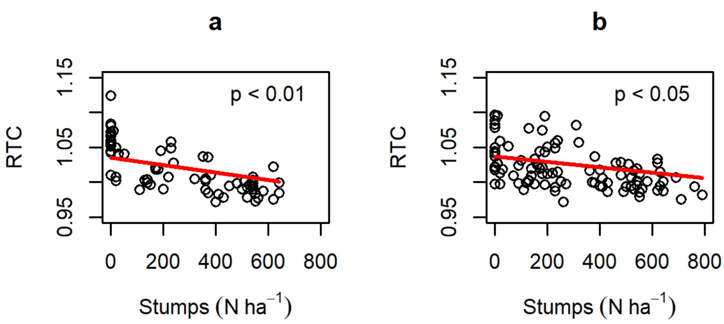


Fig. 4: Relative temperature cooling capacity at ground-level across all study plots including sites dominated by *Pinus sylvestris* and *Fagus sylvatica* in 2018 (a; R^2marginal = 0.26; R^2conditional = 0.75) in 2019 (b; R^2marginal = 0.23; R^2conditional = 0.72). The points show the data and the red lines model predictions. The predictions were generated by only varying the variable shown at the x-axis, while all other variables were fixed at their observed mean value. The p-values refer to the test that the slope estimate of the variable shown on the x-axis equals 0. The degrees of freedom were approximated using Satterthwaite's correction method

7.7.3 Relative buffering capacity

In 2018, the model that best explained the variance of RTB showed that the number of stumps, regeneration density and SDI were significant predictors (Table 2). RTB was lower when more trees were felled, more trees regenerate, and stands are less dense (Fig. 5). In 2019, when canopy cover was also tested, this was significant for all datasets (Table 2). In the studied pine forest, RTB in 1.3 m was lower than the average of all sample plots when canopy cover was below 82 % (Fig. 5g). RTB in pine forests at ground-level was lower than the average if canopy cover was less than 49 %. Including beech plots into the dataset, lmer showed that temperature fluctuation in 1.3 m above ground was above average when canopy cover was below 65 %.

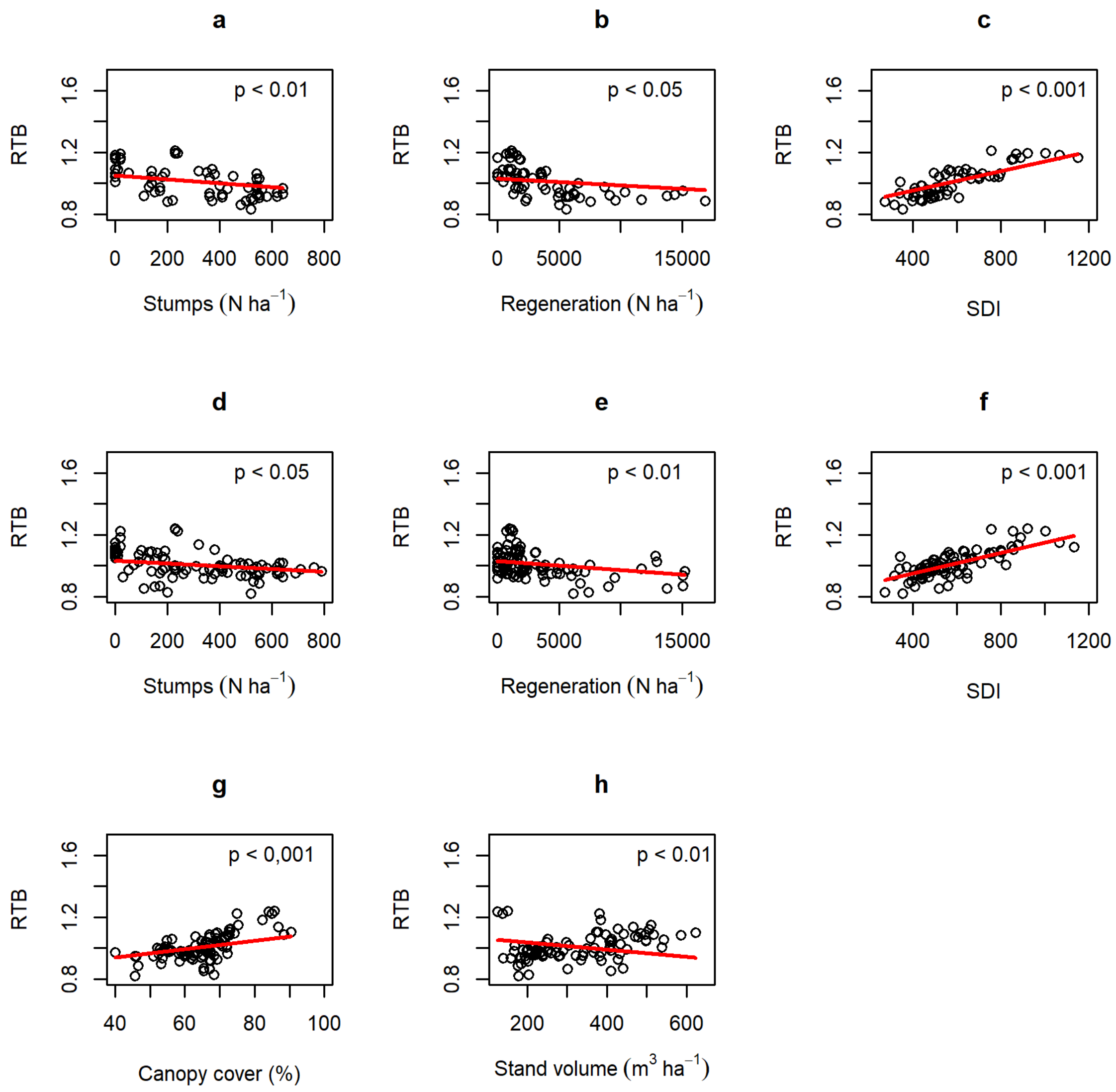


Fig. 5: Relative temperature buffering capacity measured in 1.3 m above ground in sites dominated by *Pinus sylvestris* in 2018 (a-c; R^2marginal = 0.72; R^2conditional = 0.87) in 2019 (d-h; R^2marginal = 0.67; R^2conditional = 0.79) in relation to the number of cut trees (stumps; a and d), the number of trees < 6 cm DBH (regeneration; b and e), Stand Density Index (SDI; c and f), canopy cover (g) and stand volume (h). The points show the data and the red lines model predictions. The points show the data and the red lines model predictions. The predictions were generated by only varying the variable shown at the x-axis, while all other variables were fixed at their observed mean value. The p-values refer to the test that the slope estimate of the variable shown on the x-axis equals 0. The degrees of freedom were approximated using Satterthwaite's correction method

7.7.4 Diurnal temperature variation

The highest daily mean temperature in the year 2019 was measured on June 26, with 26.6 °C calculated over all measurements. On that day, peak temperature values at ground level differed by more than 13 K between pine-dominated sample plots with relatively dense and open canopy (72 % vs. 46 %, respectively) (Fig. 6). Considering only pine stands, canopy cover significantly influenced temperature over the course of a day ($p < 0.05$). The highest peak temperature in 2019 was measured on June 30 in a pine stand (177 m^3 ha^{-1}) and exceeded 45 °C, while maximum temperatures on the same day in beech stands remained below 35 °C. On the same day, the range between minimum and maximum temperatures in beech stands was below 20 °C, while the variation in pine plots was up to 35 °C.

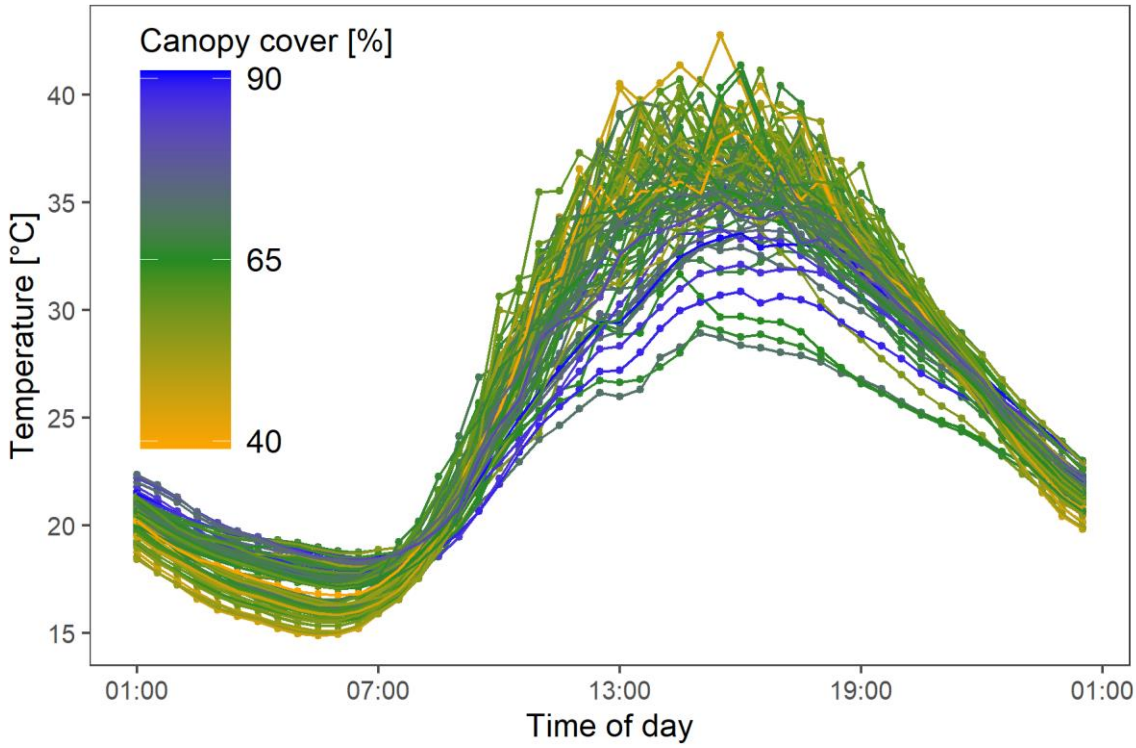


Fig. 6: Diurnal temperature variation on the hottest day in the year 2019 measured in pine-dominated sample plots (n = 88) at ground-level.

Table 2: Estimates of all fixed effect parameters of the linear mixed effect models. Each line in the table corresponds to a different model. For each model, the parameter estimates as well as the marginal and conditional R^2 are reported. The significance of the estimates is indicated by the font: bolt for $p < 0.05$ and italics for $p < 0.1$. (ns = non significant)

Microclimate indicator	Year	Sample	Level	Canopy cover (%)	Stand volume (m^3 ha^{-1})	Stand Density Index (Reinecke 1933)	Stumps (N)	Deadwood volume (m^3 ha^{-1})	Regeneration (N)	Marginal R^2	Conditional R^2
T_{max}	2018	All plots	top	NA	**-2.69E-03**	ns	**1.48E-03**	ns	ns	0.44	0.85
			ground	NA	**-3.05E-03**	ns	**3.41E-03**	ns	**1.20E-04**	0.62	0.79
		Only pine	top	NA	ns	**-3.09E-03**	**1.74E-03**	ns	**5.51E-05**	0.71	0.74
			ground	NA	ns	*-2.42E-03*	**3.48E-03**	ns	**1.03E-04**	0.57	0.73
	2019	All plots	top	**-4.60E-02**	**-1.53E-03**	ns	*9.56E-04*	ns	**5.37E-05**	0.58	0.84
			ground	**-5.31E-02**	**-3.31E-03**	ns	**2.11E-03**	ns	**7.81E-05**	0.5	0.81
		Only pine	top	**-3.51E-02**	ns	**-1.66E-03**	**9.22E-04**	ns	**6.92E-05**	0.63	0.75
			ground	**-4.07E-02**	ns	ns	**2.11E-03**	ns	**1.01E-04**	0.39	0.73
RTC	2018	All plots	top	NA	ns	ns	ns	*-3.75E-05*	ns	0.02	0.96
			ground	NA	ns	ns	**-5.34E-05**	ns	ns	0.26	0.75
		Only pine	top	NA	ns	ns	ns	ns	ns	0.02	0.92
			ground	NA	ns	ns	**-4.47E-05**	*1.39E-04*	ns	0.14	0.74
	2019	All plots	top	**3.08E-04**	ns	ns	**-1.82E-05**	ns	*-6.05E-07*	0.16	0.87
			ground	ns	ns	ns	**-3.92E-05**	ns	ns	0.23	0.72
		Only pine	top	ns	ns	ns	**-1.77E-05**	ns	**-1.02E-06**	0.12	0.82
			ground	ns	ns	ns	**-4.00E-05**	ns	**-1.56E-06**	0.1	0.66
RTB	2018	All plots	top	NA	**2.18E-04**	ns	ns	ns	ns	0.07	0.97
			ground	NA	ns	ns	ns	ns	ns	0.09	0.91
		Only pine	top	NA	ns	**3.14E-04**	**-1.25E-04**	ns	**-4.42E-06**	0.72	0.87
			ground	NA	ns	*2.66E-04*	**-2.27E-04**	ns	*-7.67E-06*	0.44	0.79
	2019	All plots	top	**3.39E-03**	*1.67E-04*	ns	ns	ns	*-3.12E-06*	0.31	0.9
			ground	**5.47E-03**	**4.83E-04**	ns	*-1.66E-04*	ns	*-5.63E-06*	0.52	0.87
		Only pine	top	**2.71E-03**	**-2.22E-04**	**2.66E-04**	**-7.88E-05**	ns	**-5.29E-06**	0.67	0.79
			ground	**4.55E-03**	ns	ns	**-1.73E-04**	ns	**-8.47E-06**	0.46	0.79

7.8 Discussion

Our findings confirm our hypothesis that forest management can significantly mediate forests' ability to dampen extreme temperatures, moderate mean temperature, and temperature variability. Forests with high volumes of living trees, for example due to high stand age and low rates of timber extraction in the past, are effectively cooling landscape elements (compare Chen et al., 1999; Frey et al., 2016; Norris et al., 2012). For the reduction of maximum temperatures in the forest interior, the most decisive driver is the degree of canopy openness, but also the quantity of logged trees is relevant, and both variables are directly controlled by forest management (in terms of reducing harvesting activities and by developing denser, multi-layered forest stands). Our finding that a 10 % reduction in canopy closure causes an increase in forest interior temperature is consistent with results from Thom et al. (2020), who found that an increase in surface light by 10 %, resulting from the opening of the canopy in European beech forests caused an increase in maximum temperature by 0.42 °C. A study in Chinese forests revealed a 0.83 K increase in surface temperature (Kong et al., 2014). Minimizing the temperature of the forest interior contributes to climate regulation in the wider landscape and positively influence water and carbon cycles (Ellison et al., 2017). Microclimate regulation can therefore buffer adverse effects of climate change (Thom et al., 2020).

In the two record heat and drought years 2018 and 2019, denser, and less thinned forests showed substantial microclimate regulation. Effective forest management aiming at a continuous forest cover and more complex structures instead of homogenous even-aged monocultures thus allows for stabilization of microclimatic conditions in the forest interior and counteracts extreme macroclimatic conditions to be expected under climate change. This is not only of direct relevance for the growth and survival of all woody species, but also for other forest organisms such as the ground vegetation or the forest edaphon on the edge of their thermal tolerance limits (De Frenne et al. 2013; Duffy et al. 2015; Martius et al. 2004). However, other ecosystem services such as cultural services, and species richness (e.g. beetles) can be lower in forests with denser canopies and high carbon stocks (Sabatini et al. 2019; Seibold et al. 2016, Felipe-Lucia et al. 2018).

Differences in morphological characteristics between the tree species *P. sylvestris* and *F. sylvatica*, such as the shape of leaves, specific crown architecture and density, may explain species-specific shading properties and corresponding signatures of microclimate regulation (compare De Abreu-Harbich et al., 2015). The availability of water is also crucial for temperature regulation mechanisms (Davis et al., 2019). The overall decrease of heat and the avoidance of high maximum temperatures is of physiological relevance for forest trees and other forest organisms (Suggitt et al., 2011, Hatfield & Prueger 2015), but also effectively contributes to the reduction of water deficits as evaporation increases nonlinearly with increasing temperatures (Nkemdirim, 1991).

Studies showed that certain drought impacts can be mitigated by thinning as thinned stands recover faster from growth reduction, but thinning also reduces wood quality, volume increment, litter mass and stand structural diversity (Del Río et al. 2017). Short-term improvements in the resistance of radial growth of trees to drought stress are more likely to be observed at wetter than at drier sites and therefore also depend on water supply (Laurent et al. 2003) and tree age as younger stands show that stand density reductions improved drought resistance and resilience but at higher age higher densities showed greatest drought resistance and resilience (D'Amato et al. 2013). Although thinning supports the recovery of radial growth after drought events, it hardly affects the resistance to drought and can lead to higher evaporation in the short term due to higher wind exposure (Sohn et al. 2016a). In addition, the magnitude of short- and medium-term resistance, recovery and resilience of radial growth was affected by thinning (Sohn et al. 2016b), whereas thinning did not improve leaf level efficiency and intrinsic water use efficiency (Sohn et al. 2016b; Fernández et al. 2015). Under certain conditions, the competition for water and water stress levels in forest stands can be reduced by thinning (Giuggiola et al. 2013; Sohn et al. 2016b). Although air and soil temperature as well as wind speed increase by thinning, soil moisture was found to be higher in thinned forest stands (Ma et al. 2010). However, higher transpiration rates of thinned canopies can lead to lower soil humidity despite increased throughfall (Primicia et al. 2013). For example, Lagergren et al. (2008) found that thinning can elevate transpiration by 20 % compared to unthinned stands and induce a 7-fold increase of transpiration at the peak of a drought. Higher evaporation in turn can compensate for the positive effect of thinning related to increased throughfall of precipitation and lower overstory transpiration (Simonin et al. 2007). Despite short-term decreases in stand-level transpiration (25 % by moderate, 50 % by heavy thinning) and higher soil water availability due to lower interception and transpiration, single tree transpiration and additional understorey evapotranspiration can be observed in the mid-term after thinning (Gebhardt et al. 2014). Also water vapor pressure deficit increases by thinning across heights in a stand (Rambo & North 2009).

The benefits of thinning depend on the local climate conditions and cannot be generalised (Ameztegui et al. 2017). Clearly, it must be reflected more critically in times of frequently recurring dry and hot years, when precipitation is absent for longer periods of drought. Then, potential advantages of thinning can turn into a disadvantage, because higher water losses through evaporation become the decisive stressor in forests that experience more intense heat. It is also known that forest openings and clearings increase ambient and soil temperatures, which in turn negatively impact water availability, especially during periods of low precipitation (Redding et al., 2003). The larger the openings of forest canopies, the higher the air and soil temperature (Latif & Blackburn, 2010). At forest edges, soil moisture can be similar to open areas (Erdős et al., 2019). As a consequence of our findings, we recommend minimising heating and evaporation effects within the forest interior by avoiding the creation of artificial canopy gaps due to silvicultural operations, including intensive thinning and clearcutting as well as introducing road and skidding trail infrastructure. In this context, the fragmentation of the forests by roads and infrastructure as well as the opening of the canopy by the construction or maintenance of skidding and extraction trails must be discussed. Typically, wood harvest in production forests in Germany takes place every five years, and usually skidding trails with 20 m to 40 m distance to each other are cut through the forest. The concomitant opening of the canopy creates internal forest edges and potential edge effects within a forested area that can reduce the microclimate regulation capacity and increases the risk of heat and drought stresses from the edges towards the forest interior (Duncan et al. 2019; Reed et al. 1996). Road infrastructure causes higher air and canopy temperatures as well as vapour pressure deficit (Pohlman et al. 2007; Delgado et al. 2007). Although increased evaporation on edges of fragmented forests can contribute to landscape cooling, in dry seasons the effect intensifies desiccation of the forest interior (Mendes & Prevedello, 2020). Increased tree mortality at forest edges indicates higher stress level in times of water shortage and heat influence (Brun et al. 2020).

Adapting forest management to climate change means, first and foremost, reducing the sensitivity of trees to drought events as much as possible. Extremely low precipitation and high temperature, depleted soil moisture and increased evapotranspiration were responsible for recent mid-spring droughts in central Europe and are supposed to continue in the long term due to climate change induced phenomena of atmospheric circulation (Ionita et al., 2020). According to our results, high stock and dense canopy provide an insurance against heat and drought events. This is in contrast to a promotion of thinning as management strategy to adapt forests to climate change and reduce related drought impacts. We argue that microclimate management for cooler and less volatile forest interior temperature is a crucial element of ecosystem-based adaptation to climate change.

Forest microclimate regulation can be used as a proxy indicator for forest functionality (Chen et al., 1999) and ecological effects of forest management and forest certification (Blumroeder et al., 2019). The evident patterns of cooling intensity can be transferred to other forests although different ecosystems in other geographic regions exhibit divergent microclimatic features due to differences in albedo and evaporation (Li et al., 2015).

In some regions in Germany, especially in the federal state of Brandenburg, pine plantations cover about 70 % of the forested area and urgently need to develop into diverse mixed and more self-regulating, cooler and resilient forest ecosystems in order to reduce their vulnerability to climate change. This is also in line with the insurance hypothesis that highlights the importance of biodiversity for maintaining ecosystem functions and processes (Loreau et al. 2001; Naeem & Li 1997; Yachi & Loreau 1999). On the one hand, tree rejuvenation is an ecosystem process that depends on suitable microclimatic conditions (Aussenac, 2000; Dingman et al., 2013). On the other hand, supporting tree regeneration by thinning can induce higher temperature extremes in the forest interior. Our findings are relevant for the implementation of forest management to transform such structurally homogenous stands. We advocate keeping the canopy as dense as possible, specifically with a cover of at least 80 %, by maintaining sufficient overgrowth and by additional layers of any native deciduous tree species to establish multi-layered uneven-aged stands that provide effective shade. The trade-off between adequate light availability for understory plant growth, which is necessary for the forest to evolve into more resilient ecosystems, and the need to maintain protective shade, is becoming increasingly apparent under climate change conditions, especially in extremely hot and dry years. Of central importance is the risk that additional heat, critically high temperatures, soil dehydration or even sunburn of exposed trees (e.g. *F. sylvatica*) can jeopardize the success of forest development.

Forest microclimate regulation is a key ecosystem service that influences other services (Tuff et al., 2016); its socioeconomic importance goes far beyond timber production and also has relevance for human health and recreation. Thus, foresters should assume increased responsibility for mitigating the landscape microclimate crisis that is exacerbating the negative impacts of the global climate crisis.

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7.10 Conflict of interest

All authors declare that they have no conflict of interest.

7.11 Authors' contributions

JB and PLI conceived the study and the conceptual framework. JB developed the research design, conducted the fieldwork, prepared the data, computed the data analysis, and wrote the manuscript. PLI supervised all working steps and contributed to writing of the manuscript. FM provided support for data pre-processing and statistical analyses. WH provided specific advice. All authors contributed to the revision and finalization of the manuscript.

7.12 Data availability statement

Data is deposited at Zenodo (Blumroeder, 2021).

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8. Synthesis and conclusions

8.1 Main findings

The results of this dissertation present a holistic conceptual framework for the assessment of forest functions especially relevant under climate change impacts and the evaluation of forest management and certification systems. It provides comprehensive empirical findings on the ecological effectiveness of FSC-certification in Arkhangelsk, Russian Federation as well as pine and beech forest management in northern Germany.

In theory, the Russian FSC standard has the potential to improve forestry and ecological impacts, but there are shortcomings in the precision of targeting actual problems and the ecological commitment. The postulated success in reducing identified environmental threats and stresses, e.g. through a smaller size of clearcuts, could not be verified on site. The empirical assessment does not support the hypothesis of effective improvements in the ecosystem. In practice, FSC-certification did not contribute to change clearcutting practices sufficiently to effectively improve the measured ecological indicators.

Sustainability standards that are unable to translate principles into effective action with measurable positive outcomes fail in meeting the intended objectives of safeguarding the ecosystem functioning. Clearcuttings carrying sustainability labels are ecologically problematic and ineffective for the intended purpose. The overexploitation of provisioning services, i.e. timber extraction, diminishes the ecosystems' capacity to maintain other services of global significance. It impairs ecosystem functions relevant to cope with and adapt to other stresses and disturbances that are rapidly increasing under climate change.

This can be transferred into forest management practices in Germany, where vulnerable forests – mainly coniferous plantations – die off from climate change induced pests and diseases. Attempts to avert the catastrophe include the immediate clearance and preparation of the areas for new planting but other direct and indirect ecological effects such as rapid heating up and desiccation during summer, soil compaction and reducing water storage capacity, and CO_2 release amongst others, are ignored for the sake of economic profits, which often fail to materialise.

Microclimate regulation is a suitable proxy to evaluate the effectiveness of forest management in safeguarding forest functions that are especially relevant under climate change. It is the most crucial factor that distinguishes the impact of clearcutting on forest functions compared to primary forests that provide the baseline of functionality. The assessment of forest microclimate regulation serves as a suitable tool to describe key aspects of forest functionality, especially under the effects of climate change. In the boreal and temperate forests studied in the frame of this thesis, timber harvesting reduced the capacity to self-regulate forests' microclimate and thus impair ecosystem functionality. Structural forest characteristics influenced by forest management and silviculture significantly affect microclimatic conditions and therefore ecosystem vulnerability to climate change. Canopy coverage and the number of cut trees were most relevant for cooling maximum summer temperature in the forest interior of pine and beech forests in northern Germany.

Forest management under climate change needs to apply precautionary principles and reduce further ecological risks such as secondary dieback and a deterioration of regulating services that are relevant for the functioning of forests. Forest managers have to apply strict ecological principles with effective outcomes in order to maintain functional forests also as a basis for economic benefits and avoid disimprovements.

Forest management needs to account for the complex interactions of the various components and emergent properties of forests instead of focussing on optimising and maximising timber production and harvest. Learning from nature and supporting the natural development of forests is fundamental to maintain forest functions in the long-term. The mistakes of the past can present a basis for success in the future if learning effects and non-knowledge were tolerated and integrated into a framework of adaptive management.

The following section answers the specific research questions of this thesis in detail (3.3 Research questions).

*8.1.1 Research question I: What are the actual drivers of forest management and the impacts on forest functions in a case study in the Arkhangelsk Region, Russian Federation and how can FSC-certification potentially contribute to mitigate threats and stresses to the ecosystem in order to safeguard forest functions and services? (**Chapter 4**)*

A theoretical plausibility analysis was conducted as the initial methodical step of the ECOSEFFECT method and helped to increase the understanding of the character of and the complex interrelations between the underlying components and processes as well as the impacts of timber harvesting on ecosystems and their functions in the Arkhangelsk Region of the Russian Federation. The collected knowledge and expert opinions that were systematically illustrated in a conceptual model represents the fundament for evaluating the potential effectiveness of FSC-certification.

Especially activities related to timber harvesting and the current large-scale clearcut practices, forest infrastructure, resulting deforestation and forest degradation are critical threats for the functioning of the boreal forest ecosystems in the Arkhangelsk region. The desire to generate economic income and the increasing demand for timber are the main drivers for large-scale forest exploitation. The demand for sustainably produced timber especially by European markets stimulates FSC-certification.

In theory, FSC would transform forest management practices and induce positive changes and effective outcomes by addressing 75 % of the identified contributing factors including highly relevant factors and threats including large-scale (temporary) tree cover loss, which contributes to reducing about half of the current ecological stresses. It is theoretically plausible that FSC prevents logging in *High Conservation Value Forests* and *Intact Forest Landscapes*, reduces the size and number of clearcuts, and prevents hydrological changes in the landscape. However, it was perceived that the standard was not sufficiently explicit and compulsory to generate a strong and positive influence on the identified problems and their drivers. Moreover, spatial data revealed, that the typical regular clear-cut patterns of conventional timber harvesting continue to progress into the FSC-certified boreal forests, also if declared as *Intact Forest Landscape*. This results in the need to verify the assumptions and postulates on the ground as it remains unclear and questionable if functions and services of boreal forests are maintained when FSC-certified clear-cutting continues.

This study helped to design an empirical study to verify the postulates on the ground and to assess relevant indicators to scrutinize measurable FSC-induced outcomes in the forest ecosystem as presented in Chapter 5 and Chapter 6.

*8.1.2 Research question II: Which indicators adequately describe the differences in forest management as they result from FSC certification, and how effective is FSC certification in reducing negative impacts of forest management in the Arkhangelsk region, Russian Federation? What role does microclimate regulation play in quantifying the loss of forest functions resulting from clearcutting or management with and without certification? (**Chapter 5**)*

An empirical plausibility analysis (Chapter 5) followed the theoretical assessment (Research question I; Chapter 4) of FSC impacts to verify postulates and assumptions on site. In order to demonstrate benefits that do not only concern trade and market access but effects that occur in the actual ecosystem, differences between certified and conventional harvesting practices must be noticeable and quantified. Therefore, five different types of ecological forest indicators (living tree biomass, deadwood, rejuvenation, vegetation, microclimate regulation) were surveyed and compared between sites (clearcut under FSC-certification, conventional clearcut without certification, primary forest without logging activities).

Microclimatic indicators were most prominent in characterizing the differences between the sites. Clearcuts caused a tremendous increase in temperature compared to the reference forest and FSC-certification did not alleviate the ecological relevant heat stress. Maximum temperature during in the closed forest stayed below 30 °C but exceeded 36 °C on clearcuts. The number of days with temperatures above 25 °C at least doubled on clearcuts. Temperature cooling capacity was reduced by up to 14 % and temperature buffering capacity up to 60 %. The main reason why FSC-certified clearcuts do not differ from conventional clearcuts is that in both cases about 97 % of trees within equally large clearcut sites of up to 50 ha were removed.

Clearcut forest areas – no matter if FSC-certified or not – cannot maintain forest functions related to the studied ecological indicators and do not provide regulating ecosystem services at least for a certain time until forests recovered, which can take decades (or even up to centuries) and it is becoming increasingly difficult or even impossible to maintain forest functions and services relevant under climate change as environmental conditions become less favourable for tree growth. FSC fails to improve forest management and to avoid adverse effects of management, as it does not induce substantial changes in logging practices that deteriorate the studied ecosystem functions and processes.

In this study, a comprehensive set of ecological indicators was assessed on sample plots and detailed data was gathered within the cleared area. However, the study was conducted on selected clearcuts managed by only two different forestry companies (one with and the other without FSC-certification at the time of logging) and needs further verification on a larger scale covering a larger sample of clearcuts to further assess the practices of clearing. Moreover, clearcutting practices may induce secondary impacts in the vicinity of the harvested sites and cause further negative changes that may compromise forest functions on a larger scale. Therefore, a geospatial analysis was designed and conducted (Chapter 6) covering the surrounding of the study area of this case study and the main findings are described in the following section (Research question III).

*8.1.3 Research question III: Does FSC-certification change clearcutting practices on a spatial scale as contributions to preserve forest functions? (**Chapter 6**)*

A geospatial analysis was conducted to complement the theoretical and empirical plausibly analysis. The outcomes of the study falsify the postulates of the first assessment, the theoretical plausibility analysis that suppose a positive ecological impact of FSC-certification and support the findings of the second study, the empirical assessment that demonstrate shortcomings of FSC.

The spatial design of clearcuts, their size and the intensity of clearing as well as the density of skidding trails for timber extraction was not positively influenced by FSC-certification. Annual tree cover loss was lowest in non-certified areas. This means, that FSC may even contribute to an increased biomass removal within the clearcuts, which compromises the ecosystems' capacity to recover and maintain ecological functions and services. The increased security to purchase timber to European markets by FSC-certification may intensify the exploitation of boreal forests instead of fostering ecological precaution. The analysis of satellite-based data on tree cover loss showed that clearcutting causes secondary dieback in the surrounding of the cleared area. FSC-certification does not prevent the various negative impacts of clearcutting and thus fails to safeguard ecosystem functions.

*8.1.4 Research question IV: How does forest management and silviculture influence the regulating forest functions and the capacity to attenuate and buffer extreme summer temperatures in the forest interior? (**Chapter 7**)*

Forest management and silviculture shape the structural characteristics of forest ecosystems. Natural forest ecosystems that are unimpeded by forest interventions differ from artificially planted and economically harvested forests in many aspects. Especially timber plantations, such as Scots pine monocultures in Brandenburg, Germany that are managed to maximise economic profits from wood production, are structurally poor and mainly comprise trees of only one species and one age class. Especially in years with extreme high summer temperatures and low precipitation, forest functions that support the mitigation of negative effects of climate change are crucial.

Tree cutting and the opening of the forest canopy compromises the capacity to attenuate maximum temperature and impairs the temperature regulation and buffering capacity. Compared to the Scots pine monocultures, forest stands comprising European beech have a typically closer forest canopy and show a cooler forest interior. The effect was strongest at ground level where maximum temperature rose by 0.21 – 0.34 K when 100 trees were cut. Opening the forest canopy by 10 % significantly increased maximum temperature at ground-level by 0.53 K (including pine and beech stands). Relative temperature cooling capacity decreased with increasing wood harvest activities; with below average values in 2018 (and 2019) when more than 656 (and 867) trees per hectare were felled. Considering only pine forest stands, the relative temperature buffering capacity 1.3 m above ground was lower than average values for all sample plots when canopy cover was below 82 %. Mean maximum temperature measured at ground-level and in 1.3 m was highest in a pine-dominated sample plots with relatively low stand volume (177 m^3 ha^{-1}) and 9 K lower in a sample plot with relatively high stock volumes of *F. sylvatica* (> 565 m^3 ha^{-1}). During the hottest day in 2019, the difference in temperature peaks was more than 13 K for pine-dominated sample plots with relatively dense (72 %) and low (46 %) canopy cover.

8.2 Conclusions and recommendations

8.2.1 Assessing forest functionality

This thesis contributes to improving the understanding of forest management and its implications for ecosystem functioning. With increasing climate change induced impacts that are threatening the sustainable functioning of forest ecosystems, forests need to be managed as complex ecosystems that ever more depend on the microclimate-regulation capacity for their own resistance and resilience. Consumers of forests' goods and services can only take what forests can afford and price for timber sales must reflect actual costs independent from markets and trade. The preservation of forest functions is also crucial to maintain timber production in the long term and the supply of the manifold services of forests and needs to be prioritised as one of the main targets of forest management. It should be given greater consideration as key component in status reports as proxy for monitoring ecosystem functionality and the ability to provide (self-)regulating ecosystem services under climate change.

Several ecological indicators were proposed and assessed to identify and estimate forest functions. Microclimate is one of the proxy indicators with particular importance especially under climate change and represents a crucial and suitable indicator to quantify the effects of forest management and to assess the functionality of forests.

This study demonstrates that microclimatic indicators are relevant in both, temperate and boreal forests, that increasingly suffer from climate change impacts and forest management activities driven by an ever-increasing timber demand. Temperature data is relatively easy to assess and allows for objective comparisons between sites of different management history and harvesting intensity across different biomes.

8.2.2 Effectiveness of forest management

Active forest management activities, such as thinning, are not necessarily ecologically effective in terms of fostering ecosystems' functionality as they reduce the microclimate regulation of forests. Less active interventions can contribute to a higher capacity of forests to self-regulate and adapt to changing climate conditions and to recover after disturbances. This also implies a responsible use of wood as natural resource and the prevention of further intensify timber demands with consequent increasing pressure on timber production and forest exploitation. Burning wood for energetic use and the current increasing demand of roundwood for construction of buildings compromises the stewardship of available timber resources.

Clearcutting has the worst impact on forest functions and impacts surrounding forests critically. Thinning and timber harvesting open forest canopies and contribute to heating up the forest interior. However, former and recent forest management and forestry practices were designed to maximise profits generated by forest harvesting and timber sales. Today and in the future, a transformation of forest management is urgently needed in order to adapt forests and forest management to climate change. This implies that forest managers and policy makers reconsider timber as the only source of financial income. Innovative approaches to encourage this transformation and the support of (especially regulating forest) ecosystem services are need as incentive for ecosystem-based adaptation to climate change. This can include the development of (state or private) funding programs to promote natural development and cautionary treatments of forests that focus less on timber yields. Financial compensation could be a strategy to pay forest owners not only for the wood they can sell at the market with fluctuating prices, but to reward those who developed forests that provide manifold ecosystem services and especially that exhibit functional regulating ecosystem services such as cooling of summer maximum temperatures.

8.2.3 Effectiveness of certification

Well-meant intentions to improve management without effective impacts on the ground can no longer be afforded and can even exacerbate the problem at the expense of valuable time needed to develop and implement effective strategies. This also includes labelling products as being produced sustainably that do not induce positive ecological impacts. Additional financial benefits for timber products can only be paid if true ecological benefits are generated. Therefore, certification must be reconsidered or even abolished if positive effects in the ecosystem do not substantiate.

8.2.4 Outlook

The interplay of current and historical forest management practices and the impacts of climate change on forest functions need further investigation, including water storage capacity and the resilience and resistance of forests to disturbances and changed climatic conditions. This also includes time-series on forest development and restoration of disturbed forests including tree rejuvenation and mortality. The role of deadwood in microclimate regulation could not be demonstrated in the frame of this thesis but is expected to be of high relevance for improving and safeguarding forest functions. In addition, the importance of microclimate regulation for adjacent ecosystems, biodiversity and land-use types such as agricultural fields needs to be quantified and could be applied as strategy for ecosystem-based adaptation of landscapes to climate change.

9. Acknowledgements

First, I would like to thank Prof. Dr. Dr. h. c. Pierre Ibisch. Pierre, thank you for always believing in me and giving me the opportunity to develop and conduct the projects at the Centre. Thank you Prof. Dr. Werner Härdtle for the supervision and the support to develop this thesis. This thesis was accomplished and supervised in the context of the graduate school at the Biosphere Reserves Institute, established at Eberswalde University for Sustainable Development in cooperation with Leuphana University Lüneburg. I also would like to thank all co-authors for their valuable inputs during the development of the single publications. Thanks to all site owners and sponsors who made the work possible. I also thank my family, including the living and especially the dead ones.

10. Appendix

10.1 List of publications

1. **Blumröder**, J.S., P.R. Hobson, U.F. Gräbener, J.-A. Krüger, D. Dobrynin, N. Burova, I. Amosova, S. Winter & P.L. Ibisch (2018): Towards the Evaluation of the Ecological Effectiveness of the Principles, Criteria and Indicators (PCI) of the Forest Stewardship Council (FSC): Case study in the Arkhangelsk Region in the Russian Federation. Challenges in Sustainability 6(1): 20-51.
2. **Blumröder**, J.S., N. Burova, S. Winter, A. Goroncy, P.R. Hobson, A. Shegolev, D. Dobrynin, I. Amosova, O. Ilina, T. Parinova, A. Volkov, U.F.Gräbener, P.L. Ibisch (2019): Ecological effects of clearcutting practices in a boreal forest (Arkhangelsk Region, Russian Federation) both with and without FSC certification. Ecological Indicators 106.
3. **Blumröder**, J.S., M.T. Hoffmann, O. Ilina, S. Winter, P.R. Hobson & P.L. Ibisch (2020): Clearcuts and related secondary dieback undermine the ecological effectiveness of FSC certification in a boreal forest. Ecological Process 9, 10.
4. **Blumröder**, J.S., F. May, W. Härdtle & P.L. Ibisch (2021): Forestry contributed to warming of forest ecosystems in northern Germany during the extreme summers of 2018 and 2019. Ecological Solutions and Evidence. 10.1002/2688-8319.12087

10.2 Article Overview and authors' contribution to articles

Table A1: Overview table of the articles in this thesis, the contributions of the authors, article publication status and the authors' contribution to each article.

Article	Blumröder et al. (2018): Towards the Evaluation of the Ecological Effectiveness of the Principles, Criteria and Indicators (PCI) of the Forest Stewardship Council (FSC): Case study in the Arkhangelsk Region in the Russian Federation.	Blumröder et al. (2019): Ecological effects of clearcutting practices in a boreal forest (Arkhangelsk Region, Russian Federation) both with and without FSC certification.	Blumröderet al. (2020): Clearcuts and related secondary dieback undermine the ecological effectiveness of FSC certification in a boreal forest.	Blumröder et al. (2021): Forestry contributed to warming of forest ecosystems in northern Germany during the extreme summers of 2018 and 2019.
Journal (Impact factor – June 2021)	Challenges in Sustainability (-)	Ecological Indicators (4.229)	Ecological Processes (1.642)	Ecological Solutions and Evidence (-)
Status	published	published	published	published
Citations since publication (June 2021)	0	5	2	0

Specific contribution of authors				
Research question	JB; PI	JB; PI	JB; PI	JB; PI
Study design	JB; PI	JB; PI;	JB; PI	JB; PI
Data collection	JB; PH; UG; DD; NB; IA; SW; PI	JB; NB; SW; AS; DD; IA; OI; TP; AV;	JB; MH; IO	JB
Data analysis	JB	JB; AG; SW	JB	JB; FM
First manuscript preparation	JB	JB	JB	JB
Final manuscript	JB; PH; UG; JAK; DD; NB; IA; SW; PI	JB; NB; SW; AG; PH; AS; DD; IA; OI; TP; AV;UG; PI	JB; MH; IO; SW; PH; PI	JB; FM; WH; PI
Weighting factor	1	1	1	1

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Ich versichere, dass alle in diesem Anhang gemachten Angaben jeweils einzeln und insgesamt vollständig der Wahrheit entsprechen.

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10.3 Erklärungen und Versicherungen

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Hiermit erkläre ich, dass ich mich noch keiner Doktorprüfung unterzogen oder mich um Zulassung zu einer solchen beworben habe.

Ich versichere, dass die Dissertation mit dem Titel „Assessment of forest functionality and the effectiveness of forest management and certification" noch keiner Fachvertreterin bzw. Fachvertreter vorgelegen hat, ich die Dissertation nur in diesem und keinem anderem anderen Promotionsverfahren eingereicht habe und, dass diesem Promotionsverfahren keine endgültig gescheiterten Promotionsverfahren vorausgegangen sind.

Ich versichere, dass ich die eingereichte Dissertation „Assessment of forest functionality and the effectiveness of forest management and certification" selbstständig und ohne unerlaubte Hilfsmittel verfasst habe. Anderer als der von mir angegeben Hilfsmittel und Schriften habe ich mich nicht bedient. Alle wörtlich oder sinngemäß entnommenen Stellen habe ich kenntlich gemacht.

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