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Reconstruction of fire and forest history on several investigation sites in
Germany, based on long and short-term investigations - Multiproxy approaches
contributing to naturalness assessment on a local scale

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Declaration about the realization and content of this thesis

- This thesis has been realized in accordance to the Rules of Good Scientific Practice of the German Research Foundation.
- Apart from the supervisor's guidance the content and design of the present thesis is all the Vincent Robin's own work.
- This thesis has been not submitted to any other examining institution that the one concerned by this dissertation.

If we consider that a human life span, on an average, 80 years, and three years (and a few months more) represent only 3.75 % of one's life. This is not so much. However, when those three years are those spent earning a PhD, they represent far more. Those years have been marked indelibly in my mind for many reasons. This piece of my life would not have been possible without people around me. Consequently, I am thankful to everyone with whom I collaborated, directly or indirectly, whether once or daily during those three years and even before.

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Reconstruction of fire and forest history on several investigation sites in Germany, based on long and short-term investigations - Multiproxy approaches contributing to naturalness assessment on a local scale

Key words

Forest naturalness, multiproxy, temporal and spatial scales, environmental changes, human impact, tree ring analysis, forest characterization, soil charcoal analysis, peat macro-charcoal analysis

Abstract

Considering two global observations in Central Europe of, firstly, the need for, and development of, sustainable and biological conservation practices for forest and/or woodland areas and, secondly, the lack of long-term fire history, an attempt has been made to reconstruct the fire and the forest history at several investigation sites in Germany. The overall data set gathered and analyzed has been used for on-site naturalness assessment. This latter notion is crucial for forest system conservation/restoration planning, considering the past human impact on forest dynamics. Also, in view of this past human impact on forest systems, which is well-documented for Central Europe, as occurring on a multi-millennium scale, an historical perspective perceptive that combined a long and short temporal scale of investigation was used.

Nine investigation sites were selected, in order to include various and representative types of Central European forest. Therefore, the investigation sites were located in two main investigation areas. One is in Northern Germany (Schleswig-Holstein) and includes four investigation sites. The other is in Central Germany (Harz Mountains) and includes five investigation sites. Four main approaches were used. To assess the current state of the investigated site, forest stand characterization was undertaken (i.e. based on various forest attributes that concern stand structure and composition). Tree ring series were analyzed to provide insights about short-term forest tree population dynamics. Then, charcoal records from soil (combined with soil analysis) and peat sequences were qualitatively and quantitatively analyzed. These last two approaches also provide information about the past fire history.

Forest current and short-term dynamics illustrated various levels of stand complexity, often corresponding to various levels of human impact that had been postulated. Eight mean site tree-ring chronologies, standardized in high and mid-frequency signal, spanning at a maximum of up to AD 1744 and at a minimum of up to AD 1923, were obtained. The insight, about the identification of events of growing changes and the correlated temporal and, if possible, spatial patterns, was discussed. Charcoal analysis provided a long-term insight about fire history. Based on 71 charcoal radiocarbon dates, it was shown on a macro-scale that there were two phases that had a greater frequency of fire - one during the transition from the late Pleistocene to the early Holocene, and one during the mid- and late Holocene. A strong human control during the most recent fire phase has been postulated. This is supported by on-site soil and peat charcoal record analysis, allowing one to point out the event of environmental changes (disturbances), at local scales. In the end, the on-site data from the various indicators were combined to assess the fire and forest history and the naturalness level of the investigated sites, based on past insights, thereby contributing to a better understanding of the present and helping to anticipate the future.

Rekonstruktion der holozänen Feuer- und Waldgeschichte ausgewählter Untersuchungsflächen in Norddeutschland entlang verschiedener Zeitskalen – Multiproxy-Ansätze zur Ermittlung der Natürlichkeit von Waldbeständen

Schlüsselwörter

Natürlichkeit, Multiproxy, zeitliche und räumliche Skalen, Umweltveränderungen, menschlicher Einfluss, Baumring-Analyse, Waldcharakterisierung, Boden-Holzkohle-Analyse, Torf-Holzkohle-Analyse

Zusammenfassung

In Mitteleuropa besteht einerseits ein Bedarf an Entwicklung und Etablierung von Naturschutzmaßnahmen für Wälder, zum anderen herrscht ein Mangel an der Untersuchung von holozänen Bränden in Wäldern. Daher wurde im vorliegenden Projekt der Versuch unternommen, in ausgewählten Untersuchungsgebieten in Norddeutschland die Feuer- und Waldgeschichte zu rekonstruieren. Die aufgenommenen und analysierten Daten sind die Grundlage für die Bemessung der Ursprünglichkeit des jeweiligen untersuchten Waldes und geben Information über das Auftreten von Feuern als Störungsereignisse in Wäldern. Die Berücksichtigung des historischen menschlichen Einflusses auf die Waldökosysteme, der in Mitteleuropa über Jahrtausende nachweisbar ist, hat eine hohe Bedeutung für die Planung von Wald-, Naturschutz und Renaturierung. Dafür wurde ein Ansatz gewählt, der eine historisch langfristige (Jahrtausende) wie kurzfristige (100 – 200 Jahre) Analyse des menschlichen Einflusses auf Wälder insbesondere unter der Berücksichtigung von Brandereignissen zum Inhalt hat. Es wurden vier Untersuchungsgebiete in Schleswig-Holstein und fünf im Harz, als nördlichstem Mittelgebirge in Zentraleuropa, ausgewählt. Dies gewährleistet das Einbeziehen verschiedener und für Mitteleuropa typischer Wälder für einen überregionalen Vergleich. Es wurden vier Ansätze angewendet: 1. Aktuelle Bestandesanalyse: Zur Analyse der aktuellen Situation wurden die Waldbestände hinsichtlich Struktur und Zusammensetzung erfasst; 2. Dendroökologie: Zur Erfassung der kurzfristigen Baumentwicklung und Bestandesdynamiken wurden Baumjahresringserien analysiert; 3. Pedaanthrakologie: Holzkohlen wurden aus Proben von Bodenprofilen gesiebt bzw. geschlämmt, quantifiziert und taxonomisch bestimmt; 4. Holzkohlen > 200 µm wurden aus Moorborkernfolgen quantifiziert. Die beiden letztgenannten Methoden lieferten Informationen über vergangene Feuerereignisse.

Derzeitige Walddynamiken, sowie die in jüngster Vergangenheit, zeigen verschiedene Niveaus der Bestandeskomplexität, die auf verschiedene menschliche Eingriffe zurückgeführt werden können. Acht gemittelte Bestandesjahrringchronologien reichen maximal bis in das Jahr 1744 und minimal bis in 1923 zurück. Mit ihrer Hilfe lassen sich Veränderungen in der Bestandesdynamik zeitlich und räumlich fassen. Die Holzkohle-Analyse lieferte Informationen von Feuerereignissen über einen Zeitraum von bis zu 12 000 Jahren. Anhand von 71 Radiokohlenstoffdatierungen zeigte sich, dass es zwei Perioden mit häufigen Feuerereignissen gab. Eine Phase lag im Übergang vom späten Pleistozän zum frühen Holozän, die Andere befand sich zwischen dem mittleren und dem späten Holozän. Die jüngere Feuerphase konnte auf Grundlage von Holzkohleproben aus Böden und Mooren auf anthropogene Einflüsse zurückgeführt werden. Abschließend wurden die von den verschiedenen Indikatoren gewonnenen Daten zusammengeführt, um zum einen die Wald- und Feuergeschichte zu rekonstruieren und zum anderen die Natürlichkeit der untersuchten Bestände zu evaluieren. Mit der Untersuchung des Vergangenen trägt die Studie dazu bei, die Gegenwart besser zu verstehen und zukünftige Entwicklungen der Wälder besser einschätzen zu können.

Reconstruction de l'histoire des feux et de la dynamique forestière d'un ensemble de sites d'étude en Allemagne basée sur de longues et courtes échelles temporelles – Evaluation de la naturalité à l'échelle locale par une approche pluridisciplinaire

Mots clés

Naturalité, pluri-indicateurs, échelles temporelle et spatiale, changements environnementaux, impact humain, dendroécologie, caractérisation forestière, pédoanthracologie, macro-charbons sédimentaires

Résumé

Sur la base de constats globaux concernant l'importance d'appliquer des modes de gestion durable des zones forestières et le manque d'investigation concernant l'histoire passée des feux en Europe centrale, il a été entrepris de reconstruire l'histoire des événements de feux et de la dynamique forestière pour des sites d'étude en Allemagne. L'ensemble des données obtenues et analysées ont été utilisées pour l'évaluation du niveau de naturalité des sites étudiés, cette notion étant essentielle pour la mise en place d'une gestion durable, et/ou pour des projets de conservation et / ou de restauration des systèmes perturbés. Concernant les dynamiques des écosystèmes en Europe centrale, il a été souvent mis en évidence que l'homme joue un rôle essentiel depuis des millénaires. Par conséquent, l'approche historique des événements de feux et de la dynamique forestière a été réalisée sur de longues échelles temporelles.

Neuf sites d'étude ont été sélectionnés incluant une large gamme de systèmes forestiers d'Europe centrale. Les sites d'études sont répartis dans deux zones générales d'étude : le nord de l'Allemagne (Schleswig-Holstein), qui comprend quatre sites d'étude, et le centre de l'Allemagne (le Harz), qui comprend cinq sites d'étude. Quatre disciplines ont été principalement utilisées. Pour définir l'état actuel des sites d'études ceux-ci ont été caractérisés, utilisant divers indicateurs dendrométriques concernant la structure et la composition des parcelles analysées. Pour obtenir des informations à propos de la dynamique forestière des peuplements forestiers en place des analyses dendroécologiques ont été utilisées. Pour analyser la dynamique forestière sur une longue échelle temporelle, à une échelle spatiale comparable, des analyses pédoanthracologiques ont été menées, combinées à des analyses de sols. De plus, des analyses anthracologiques de séquences de tourbes ont été réalisées, fournissant, combinées avec les données pédoanthracologiques, des enseignements à propos de l'histoire des incendies.

L'état actuel et la dynamique forestière récente des sites étudiés indiquent divers niveaux de complexité des peuplements forestiers, correspondant souvent à divers niveaux postulés d'impact anthropique. Il a été obtenu huit chronologies moyennes, standardisées en haute et moyenne fréquences, âgées au maximum de 1744 et au minimum de 1923 ans. A partir de ces chronologies des changements dans les conditions de croissance de peuplements forestiers ont été mises en évidence. Basées sur un ensemble de 71 charbons de bois datés par radiocarbone, il a été mis en évidence, à l'échelle locale et globale, deux principales phases présentant plus d'événements de feux datés, une durant le Pléistocène supérieur/Holocène inférieur, une autre durant l'Holocène supérieur. Pour les deux phases identifiées des forçages climatique et anthropogénique ont été respectivement postulés comme déterminisme des occurrences de feux. Finalement, les différentes données collectées ont été utilisées de façon combinée pour reconstruire l'histoire des feux et des forêts des sites étudiés, afin de contribuer à l'évaluation de leur niveau de naturalité.

*RECONSTRUCTION OF FIRE AND FOREST HISTORY ON
SEVERAL INVESTIGATION SITES IN GERMANY, BASED ON
LONG AND SHORT-TERM INVESTIGATIONS - MULTIPROXY
APPROACHES CONTRIBUTING TO NATURALNESS ASSESSMENT
ON A LOCAL SCALE*

Part 1.

Global Framework

1. Introduction

The present document has been developed as a result of Ph.D. level research work done within the framework of the Human Development in Landscapes graduate school of the Christian-Albrecht University of Kiel, Germany. This work is based on interdisciplinary and multidisciplinary investigations. This research employs multiproxy analysis aiming to (1) reconstruct long and short-term fire and forest history of several sites in Central Europe, and (2) contribute to their biological conservation, by assessing the naturalness of those selected sites. This document, therefore, represents not only fundamental research, but may be considered as applied research in some of its parts.

The conceptual framework and the general questioning of the research is presented in Part 1, entitled “Global Framework”, and is followed in Part 2, “Study Sites and Methods”, by a presentation of the investigation areas and sites (Chapter 3), and of the various methods employed in gathering and analyzing data (Chapter 4). These two parts present an overview, while Part 3, “On-Site Investigations”, is comprised of chapters presenting in detail the investigations per site and/or per specific issue. The concept of naturalness is developed in Chapter 5.1. Contributions to forest biological conservation are developed in Chapter 5.2, and those aspects are the specific issues of Chapters 6.3 and 6.4. The reconstructions of fire history and of the correlated long-term forest dynamic changes are the specific issues of Chapters 5.3, 6.1 and 6.2. Those chapters are written in the form of manuscripts for publication. Finally, by comparing results and main indications from the on-site investigations, there is an attempt to identify general trends and global scale patterns by detecting synchrony and asynchrony in the analyzed data set. This is presented in the chapters of Part 4, entitled “Synthesis and Conclusion”. The Appendix 1 presents an overview of the sampled material and analyzed data set. The appendix 2 presents additive and/or complementary data which are not detailed in the previous parts, but which have been gathered and analyzed, and are therefore useful for the global scale identification of general trends.

2. General Concepts

2.1. Principles of dynamic processes and disturbances in forest systems

Aiming to investigate the histories of forest systems, it is crucial to take into consideration dynamic processes of ecological systems.

As all ecological systems, forest and/or woodland are complex dynamic systems (Tansley 1935, Odum 1969, Odum 1994, Peterken 1996, Meyers 2009, Dawson *et al.* 2010). This means that the state of the system, at any time “t” and at any organization level “l”, is a result of interacting processes and parameters occurring at interdependent temporal and spatial scales (Fig. 1). Such processes and parameters are continually shaping the state of the ecological systems by forcing changes and inducing permanent dynamics over various temporal and spatial scales (Rand and Wilson 1995, Peterson *et al.* 1998, Whittaker *et al.* 2001, Bengtsson *et al.* 2003).

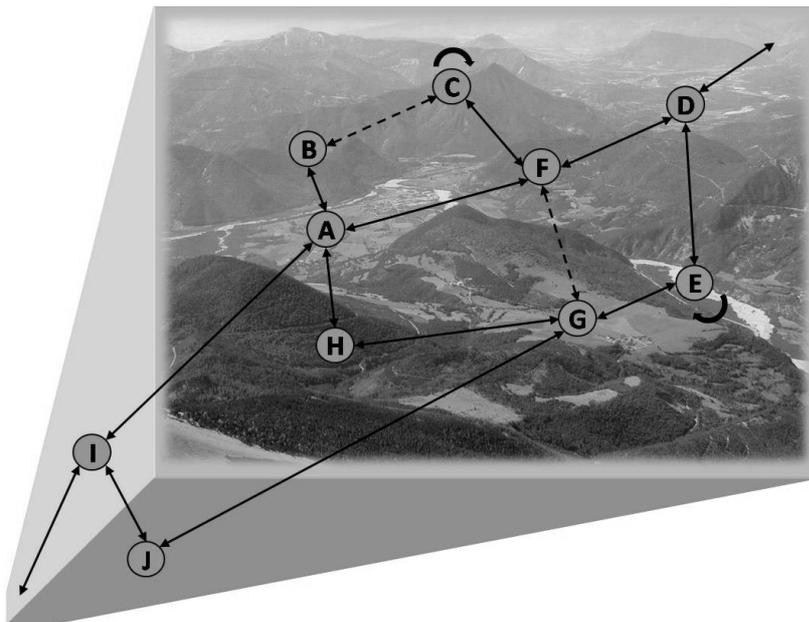


Figure 1. Landscape mosaic “connectivity” (big letters are ecosystem continuants of the landscape mosaic).

Considering a virtual starting state of these dynamics, the system increases in biomass and in structure, organization, and functioning complexity, following a “trajectory” corresponding to the “domain of attraction” (Grimm and Wissel 1997). Such domain of attraction includes occurrences of changes (Davis *et al.* 2005). This is not a determined, fixed trajectory, but depends strongly on dominant factors of dynamics at “t” and “l”. Some authors use the term “steady state” to represent the idea of continuous change of ecosystems (Chapin III *et al.* 2002). As long as those changes occur within thresholds of variation, the system stays in its

trajectory. Such changes are “stable changes” endogenous to the system, reflecting the dynamic equilibrium of the ecological systems (Sprugel 1991, Larsen 1995). They are due to disturbance occurrences (White 1979).

“Like so many other features and factors in the natural environment, disturbances cannot be precisely defined. Their key features are the creation of space and their episodic character.” (Peterken 1996)

Such non-predictable events remove all or part of the biomass of the system (Sousa 1984, Pickett and White 1985, Turner *et al.* 1993, Peterken 2001) and therefore constitute a self-regulation of the dynamic equilibrium by renewing the system (Walleczek 2000, Solé *et al.* 2002). The capacities of the systems to resist (i.e. ecosystem resistance; Brang 2001) and/or to answer (i.e. resilience; Holling 1973, Gunderson 2000) to the disturbance event condition the stability of the domain of attraction (i.e. within the threshold level; Willis *et al.* 2010).

“This interrelation between resistance and resilience seems to reflect the development of the ecosystem as response to the types of perturbation (i.e. disturbance) commonly encountered by the system and their distribution in time and space” (Larsen 1995)

If a disturbance event causes changes over the threshold values of domains of attraction, the system trajectory changes. This is the occurrence of exogenous disturbance, over the endogenous capacities of resistance and resilience of the system. With this new trajectory of dynamic equilibrium, a new domain of attraction emerges, allowing a new state of “stable variation” (Fig. 2) through succession processes (Tilman 1985).

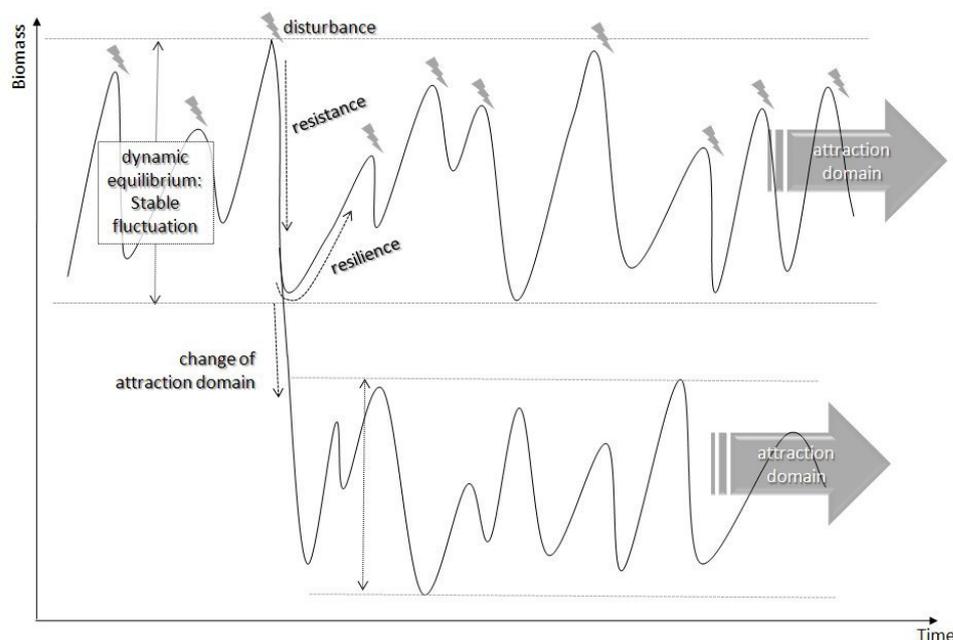


Figure 2. Simplified representation of ecosystem biomass change through time.

Through the previously simplified description of the dynamic(s) of ecosystems, it can be pointed out that to investigate the history of an ecological system (e.g. forest and/or woodland), it is of primary importance to study the occurrences of disturbance events and their consequences. This implicates reconstruction of the past regime of disturbance(s) of the investigated ecological system. The regime of a disturbance is characterized by its variability of occurrence, i.e. distribution, frequency, return interval, magnitude, etc.; (Pickett and White 1985, Peterken 2001). A disturbance regime may vary widely, depending on the disturbing factor itself and on the environmental conditions. These variations span large ranges of spatial and temporal scales (Peterken 1996; Fig. 3).

For example, fire disturbance and consequences on ecosystems dynamics through time and space have been quite well documented (Patterson III and Backman 1988, Thonicke *et al.* 2001, Bowman *et al.* 2009, Whitlock *et al.* 2010). This is especially true concerning fire sensitive biomes such as boreal forest and Mediterranean ecosystems (Bergeron *et al.* 2004, Linstädter and Zielhofer 2010), while in Central Europe, long-term past fire regimes and consequences on ecosystems history are still poorly documented, despite some existing broad scale syntheses (Carcaillet *et al.* 2002, Power *et al.* 2008). This aspect is further developed in the chapters of Part 3 dealing with long-term fire and forest history reconstruction.

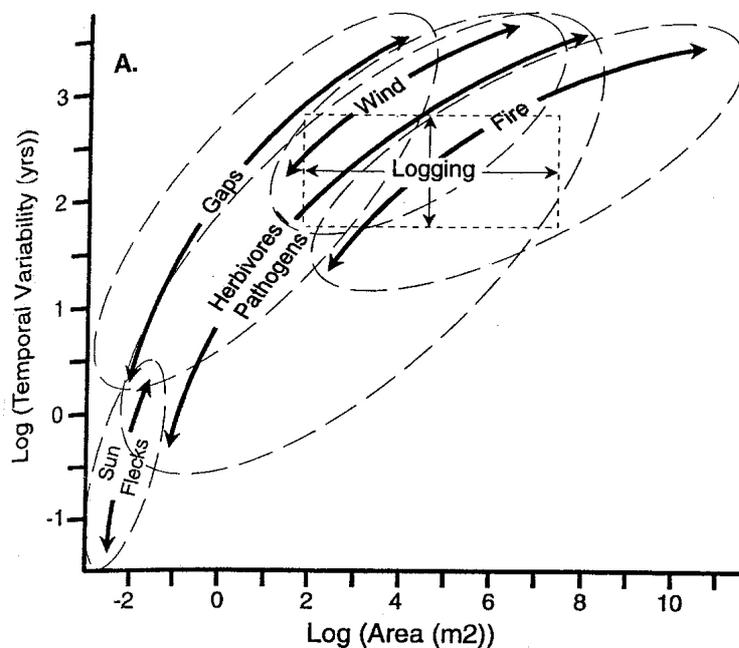


Figure 3. Various disturbances; temporal and spatial distribution (from Hunter 1999).

2.2 Notion of scales

To study forest systems history, it is important to take into consideration the time and space variations of disturbance regimes. Moreover, since forest systems are complex dynamic systems, processes of change and consequences occur at multi-temporal and spatial scales, with reciprocal interacting correlations (i.e. hierarchical levels; Bailey 1996, Whittaker *et al.* 2001, Blaschke 2006).

“[...] to understand the behavior of a complex system we must understand not only the behavior of the parts, but how they act together to form the behavior of the whole. It is because we cannot describe the whole without describing each part, and because each part must be described in relation to other parts, that complex systems are difficult to understand.”

(Bar-Yam 1997)

Therefore, to investigate the history of a forest system, and also to assess its current state, the selection of the investigation scale(s) is of first importance (depending on the spatial and temporal resolution of the data available). However, there is no “best” scale of investigation. Time and space of analysis must be adapted to the investigation questions and to the data/indicator resolution.

“[...] there is no natural level (ie, scale) of description [...]. One must recognize that the description of the system will vary with the choice of the scales [...]” (Levin 1992)

“The upper and lower boundaries of an ecosystem also depend on the question being asked and the scale that is appropriate to the question.”

(Chapin III *et al.* 2002)

Nevertheless, to work at macro-spatial scales implies dealing with data having large scale of spatial resolution, and so implies a “reduction” of the representativeness of the data set to such level, and so to “reduce” the precision of the investigation, while:

“A study of universal principles does not replace detailed description of particular complex systems.” (Bar-Yam 1997)

Considering those previous aspects, for the investigation presented in this document, data relevant to the local spatial scale was used. However, the investigation was not restricted to one level of interpretation. Indeed, large-scale analyses are needed in order to interpret and extrapolate local scale data with insight from supra- and infra-systemic levels (Levin 1992, Whittaker *et al.* 2001). Also, macro-scale insights are needed into ecology and palaeoecology

to identify and define rules of structure, function, and organization of ecological systems (Hughes 2002, Whitlock and Tinner 2010).

“Universal principles and tools guide and simplify our inquiries into the study of specifics. For the study of complex systems, universal simplifications are particularly important.” (Bar-Yam 1997)

Nevertheless, local scale data present the interest to constitute a “basic scale” of investigation (i.e. forest stand scale within the landscape mosaic; Bailey 1996, Palik *et al.* 2000, Chapin III *et al.* 2002). From this basic scale can be obtained large scale insight by comparing signal synchrony and asynchrony from the local data of various sites of investigation (the distance between the site and a number of other sites conditions the level of data interpretation). Moreover, such local scale of investigation fits into the “patch dynamic” theory (Pickett and White 1985, Roxburgh *et al.* 2004, Barnes *et al.* 2006), which stresses the importance of fine spatial scales of disturbance occurrences, notably, for example, changing the stand canopy structure (e.g. Nowacki and Abrams 1997, Valverde and Silvertown 1997, Rentch *et al.* 2002, Podlaski 2008). Stand scale (i.e. local scale) is the basic unit of forest management. Indeed, even if “nature” planning is being done or should be done at the landscape level, the stand feature must be taken into consideration as a landscape constituent (e.g. biodiversity alpha vs. beta level; Waldhardt and Otte 2003, Jost 2007) or “basic unit of forest operational planning” (Baskent and Keles 2005, Andersson *et al.* 2006). This is especially true concerning the naturalness assessment (Gilg 2004). Indeed, the human impact on the dynamic of ecological systems (past and present) is especially identifiable at the stand level, while it is more “blurred” within other forcing factors at macro-scale levels (Magri 1995).

“Stand scale indicators are critical for explaining this [human modification] additional variation.” (McElhinny *et al.* 2005)

This aspect of human impact and/or influences is further developed in the following chapter (see Chapter 2.3).

To investigate histories and current states of forest systems, it is important to use data that allow taking into account the continuity of the dynamics of change (Ohlson and Tryterud 1999, Chapin III *et al.* 2002, Sverdrup-Thygeson and Lindenmayer 2003). Therefore, multiproxy data sets providing indications of variable temporal range have been used. Indeed, a first global data set provided information on short temporal scale, and a second global data set provided information on long temporal scales. Both data sets are spatially “connected”, and, in some cases, are even directly temporally connected i.e. chronological data may “overlap” in some cases (see Part 3, Chapter 5.2). The notions of long and short-term

temporal scale are variable, depending on the investigation questions and on the resolution of the data set used (Willis *et al.* 2010, Rull and Vegas-Vilarrubia 2011). However, in this present framework, short-term scale has been defined as dealing with the on-site, living forest tree population, and with its transition from the previous population (i.e. a resolution of years to centuries). The long-term scale has been defined as dealing with previous on-site forest tree populations (i.e. millennium resolution; Fig. 4).

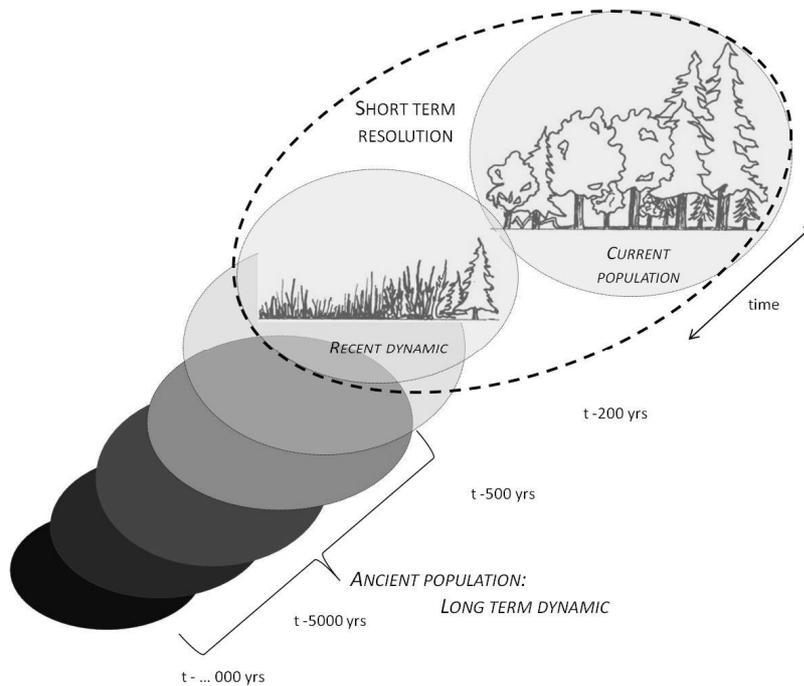


Figure 4. Ecosystems continuity at stand scale level. In the dash-line circle the current tree forest population and the source forest succession is represented. In the darker circles the various past successive forest vegetations (i.e. cohort) are represented.

2.3 Notion of Human roles in forest systems changes

Human activities have great direct and/or indirect influences on the dynamics of ecological systems (Peterken 1996). "Human activities" refers to a large range of human action dealing with the usage and/or management of natural resources provided by ecological systems. These human activities influence the dynamics of ecosystems through two main aspects:

First, anthropogenic impacts may be assimilated to disturbance factors, having comparable occurrence processing and consequences to ecosystem dynamics than natural disturbances (Hannah *et al.* 1995, Lindenmayer and McCarthy 2002, Bradshaw 2004, Neuwirth *et al.* 2007). Timber production, for example, implies forest management action to change forest stand structure at every stage of forest development, aiming to produce the best possible timber quality fitting timber commercialization standards (e.g. thinning, clear cutting; Reich

et al. 2001, Rosenvald and Löhmus 2008). Such human disturbances may be important factors influencing forest system dynamics, inducing, secondary succession processes and stand structure changes (Larsen 1995).

Secondly, human activities and their consequences on the state of the ecological system may influence the regime of natural disturbance (Christensen and Emborg 1996, Rosenvald and Löhmus 2008).

“The effects of disturbance regimes greatly modified by human activity also need to be documented.” (Pickett and White 1985).

Existing regimes of natural disturbance(s) may be changed by the human use and management of natural resources, changing the system's capacities to “answer” the occurrences of natural disturbances. This means that by influencing the structure, the functioning and the organization of ecological systems, human activities change the resistance and resilience capacities of the system. Because the regime of a disturbance depends on notably the latter parameters, several components of the natural regime of disturbance may change. A very simplified example would be the reforestation of mountain land in order to diminish the frequency of landslides (Kalaora and Savoye 1986, Wohl 2006).

Another way in which human activities change the regime of natural disturbance is in use of the disturbance factor itself. This is typically the case with fire disturbance. The regime of disturbance by fire is primarily under climatic control (Hunter 1993, Carcaillet *et al.* 2001, Bond and Keeley 2005, Carcaillet *et al.* 2007, Marlon *et al.* 2008, Bowman *et al.* 2009, Daniau 2010, Whitlock *et al.* 2010). As a human cultural and technological development, fire is used as a tool to manage landscapes (forest canopy opening to gain agricultural land area; Pyne 1994, Moore 2000, Marlon *et al.* 2010). Fire “tools” were also used for domestic purposes, notably in settlements (Gowlett 2006) and in the process of charcoal production (Nelle 2003, Ludemann 2010). Such fire usages may have been ignition sources of “accidental” fire occurrences, even in small areas. Human fire ignitions increase forest fire frequency therefore, it can be highlighted that fire disturbance was strongly connected to human activities, especially in areas where climatic context and fuel type was not so favorable to natural fire occurrence, in the temperate forests of central Europe, for example (Luterbacher *et al.* 2004, Tinner *et al.* 2005). Whichever the fire ignition factor may be, human or climatic, it can be observed that fire events, occurring mostly at the landscape level (Marlon *et al.* 2008, Bowman *et al.* 2009, Whitlock *et al.* 2010), have great influences on the state of ecological systems. This happens also at the stand scale by changing the canopy structure, or by completely removing it (e.g. Schweingruber 1996, Bilgili 2003, Gavin *et al.*

2006). Deforestation for land usage requiring canopy-free area, i.e. open land, however, diminishes fuel availability (Ryu *et al.* 2004). Because of this, the fire frequency may decrease. Therefore, it can be observed that this human impact on natural ecosystems is not linear, but highly variable.

More globally, either from a sociological, philosophical, or natural science point of view, the human relation to “nature” is quite complex and ambiguous, at least as complex as are ecological systems (Kalaora and Savoye 1986, Messerli *et al.* 2000, Wilson 2006, Head 2008). In central Europe, the complexity of this relation varies during the Quaternary, a period characterized by human cultural and demographic development (Gibbard *et al.* 2005, Lumley 2006a, b). This development of human populations in central Europe has had especially significant influences on “nature” over the last 7000/6000 yrs. It refers to the crucial “step” of the Neolithic Revolution, with the change from hunter-gatherer to farmer settled societies (Gkiasta *et al.* 2003, Pinhasi *et al.* 2005, Shennan and Edinborough 2007). From this crucial phase, the human influences on natural systems increase continuously from past to present, inducing deep and increasing changes in ecosystem structuring, organization, and functioning. These long-term dynamic changes due to human influence on ecosystems of central Europe have been quite well documented over the last decades, based on various palaeoecological approaches (e.g. Behre 1988, Magri 1995, Berglund *et al.* 1996, Kalis *et al.* 2003, Berglund 2011). Nevertheless, some discussions are still open. The debates over the role of mega-herbivores and the hypothesis of “wood pasture” in forest structures of the early Holocene (i.e. “Vera hypothesis”; e.g. Bradshaw *et al.* 2003, Mitchell 2005), and over the determinism of the mega-fauna extinction (Alroy 2001, Johnson 2009), for example, continue until today. Another active debate concerns the influences on vegetation dynamics of the Holocene, and of the abrupt events of climate change identified by several authors for this period, considered previously as globally “climatically stable” (e.g. Bond *et al.* 1997, Bond *et al.* 2001, Mayewski *et al.* 2004, Wanner *et al.* 2008). Both human and climatic determinism played roles in the past long-term dynamics of ecological systems of central Europe. Human activities were perhaps major determinants and climatic control was a pejorative factor, even if those two factors are not so simple, linear model. Such abrupt climatic change may have also played a role in the Holocene fire history of central Europe, even if the fire determinism can also be correlated to human development. This would fit with global scale patterns of fire history for central Europe (Carcaillet *et al.* 2002, Power *et al.* 2008). Nevertheless, only a few works have been published that treat this last factor of ecosystem change (Clark *et al.* 1989,

Goldammer and Page 2000, Tinner *et al.* 2005). The issue of long-term fire history is discussed in some chapters of Part 3.

Finally, it is important to highlight that human activities are still strongly influencing the current state of the ecological system of central Europe, and consequences of long-term and short-term disturbances are still visible. Ongoing and future processes of ecosystem changes that are connected mainly to human land use change and global warming will have great consequences for ecological system structures, functions, and organization (e.g. biodiversity “erosion”; Novacek and Cleland 2001, Thomas *et al.* 2004). Sustainable management and biological conservation are therefore crucial issues for current and future ecological system management. These issues are developed in the following chapter.

2.4 Sustainable management, conservation, and assessing naturalness

In the main, consequential decisions concerning nature protection are issues of politics and economics. Nevertheless, natural sciences may contribute concretely by providing scientific facts to debates.

“The degree to which old-growth forests and old-growth structures should be maintained or restored at the landscape level is a complex, political question that requires an assessment of the trade-offs between different landscape values.” (Bauhus *et al.* 2009)

It has been demonstrated that ecological systems are valuable, through the notion of biodiversity (Aylward and Barbier 1992, Costanza and Daly 1992, Williams *et al.* 1996, Costanza *et al.* 1998). Ecological values may be simplified into the following categories: scientific (biological), educational, and patrimonial (Howard and Chamberlain 2011). The formalization of such values, the importance of ecosystem protection, and global objectives for “nature” conservation emerged in 1992 for the first time from the United Nations Convention on Biological Diversity (United Nations 1992).

“Conscious of the intrinsic value of biological diversity and of the ecological, genetic, social, economic, scientific, educational, cultural, recreational and aesthetic values of biological diversity and its components.[...]States are responsible for conserving their biological diversity and for using their biological resources in a sustainable manner.” (United Nations 1992)

Old-growth forest systems, as an example, are frequently protected because of inherently high ecological values (Gilg 2004, Wirth *et al.* 2009).

From this international convention arose the notion of sustainable management. The resultant, globally applicable philosophy of management aimed to reconcile the various usages of natural resources by human societies to the long-term conservation of ecological values (Egoh *et al.* 2007). This is typically the type of management promoted by wood production standards of international certification systems (e.g. Rametsteiner and Simula 2003, Forest Stewardship Council 2006, Damette and Delacote 2011) emphasizing multifunctionality of forest and/or woodland areas (Kilchling *et al.* 2009, Carvalho-Ribeiro *et al.* 2010).

Since then, management practices progress toward integrating these notions of sustainability and biological conservation (Kessler *et al.* 1992, Larsen 1995, Hunter 1999, Hauhs and Lange 2000, Häusler and Scherer-Lorenzen 2001, Kenk and Guehne 2001, Andersson *et al.* 2004, FAO 2005, Siry *et al.* 2005). Such change in forest management policy was also motivated by the aim to apply more stable management systems in regard to economic issues (i.e. investment and future benefit). This financial aspect emerged in Western Europe after the occurrences of several storms during the last decade which destroyed large areas of forest and caused large economic losses in the forestry sector (e.g. Dobbertin 2002, Kenk 2002). Therefore, the model proposed by natural forest systems, increased interest for many forest and woodland owners and managers, and was useful for guiding forest management (Schnitzler and Borlea 1998, Gamborg and Larsen 2003, Brang 2005). Moreover, in parallel to this increasing consideration for sustainable management, the recognition of a need for “strict” biological conservation and a need for ecological systems restoration emerged (Ehrlich 1996, White and Walker 1997, Zerbe 2002, Sayer *et al.* 2004, Chazdon 2008, Davies 2011). Such change in “nature” management philosophy indicates a better definition for “natural” in answering the question, “What is natural”? (Willis and Birks 2006). This question, not so new as a scientific issue (Anderson 1991), rose to high level of interest regarding forest management and conservation guidance principles. This question also rose as a crucial issue in ecological systems restoration (e.g. Wallenius *et al.* 2007, Willard and Cronin 2007, Orsi *et al.* 2011). Indeed, for any biological conservation/restoration project, and to apply sustainable management, there is a need to define what is natural, meaning an assessment of degree of naturalness of a given ecological system (Uotila *et al.* 2002, Schnitzler *et al.* 2008, Renetzeder *et al.* 2010). This concept of naturalness, further developed in Part 3, Chapter 5.1, deals with the assessment of the level of natural functioning, structuring and organization of the ecological system considered (in the case of the research

presented here, it is referred to forest stands). This assessment of naturalness, implicates to identify and assess the level of human disturbance on the ecological system considered. This means to assess the level of hemeroby (Brentrup *et al.* 2002; Fig. 5).

“[...] assessments of naturalness should be backed by evidence of human influence [...]” (Rouvinen and Kouki 2008)

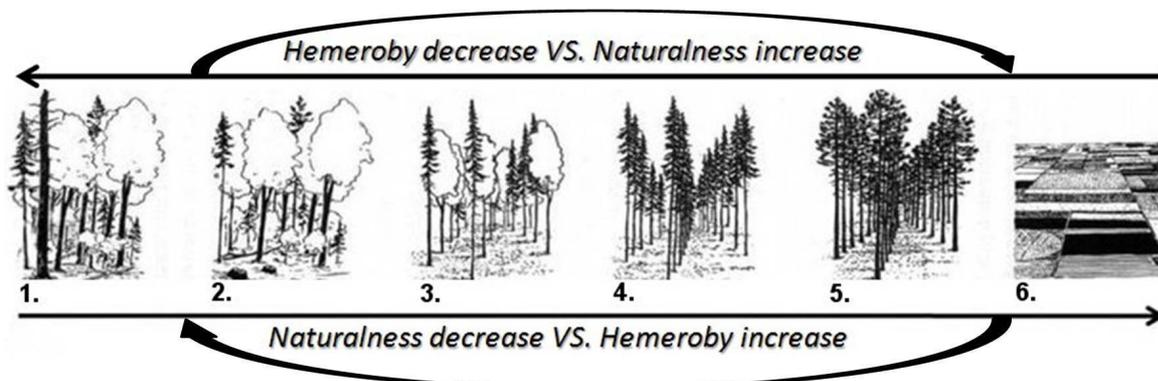


Figure 5. Example of various ecosystem stages of naturalness versus hemeroby. 1. “natural” forested stage, with mixed broadleaf and conifer trees, big deadwood pieces, various vertical levels; 2. Mixed irregular forest management system, from natural regeneration (extensive, or close-to nature, forestry); 3. Mixed high forest management system, from planted regeneration; 4. High forest management system of planted conifer trees; 5. High forest management system of planted exotic conifer trees in high density (intensive forestry); 6. Agricultural land. Naturalness decrease from 1. to 6., Hemeroby increase from 1. to 6. (from Hunter 1999, modified).

For assessments of naturalness, it is necessary to define the reference state of the ecological system considered, which means identifying the natural state of the system. Because stable states do not exist properly in nature (see this part, Chapter 2.1; Chapin III *et al.* 2002), it is necessary to reconstruct past dynamic and forcing factors (Sprugel 1991). However, it is quite difficult to define such natural states, especially in central Europe where natural forests (i.e. pristine forests) are rare, and on restricted areas with abiotic features not necessarily transferable over large scale (Parviainen 2005, Winter *et al.* 2010). Therefore, use of on-site indicators is needed to assess naturalness, and so to define reference state(s) (Anderson 1991, Reif and Walentowski 2008, Laarmann *et al.* 2009, Renetzeder *et al.* 2010). However, when considering ancient human impacts in central Europe, historical perspectives of ecological systems over long temporal scale are highly important (e.g. Foster 2002, Feurdean and Willis 2008, Renberg *et al.* 2009). Such long-term historical perspective allows to consider the continuity of the ecological systems dynamics, reach the short-term insights, with at least a connection by the fact that both long and short-term indicators used have comparable spatial resolution.

In the end, defining reference states, assessing naturalness, and identifying past regimes of disturbances contributes to the conservation and management of ecological systems, mainly by providing guidelines for planning (Siipi 2004, Willard and Cronin 2007, Winter *et al.* 2010; Fig. 6). Insights from the past are useful for understanding the present and anticipating the future (Anderson 1995, Swetnam *et al.* 1999, Farrell *et al.* 2000, Anderson *et al.* 2006, Willis *et al.* 2007). This is the global basis of the methods and investigations presented in the following parts.

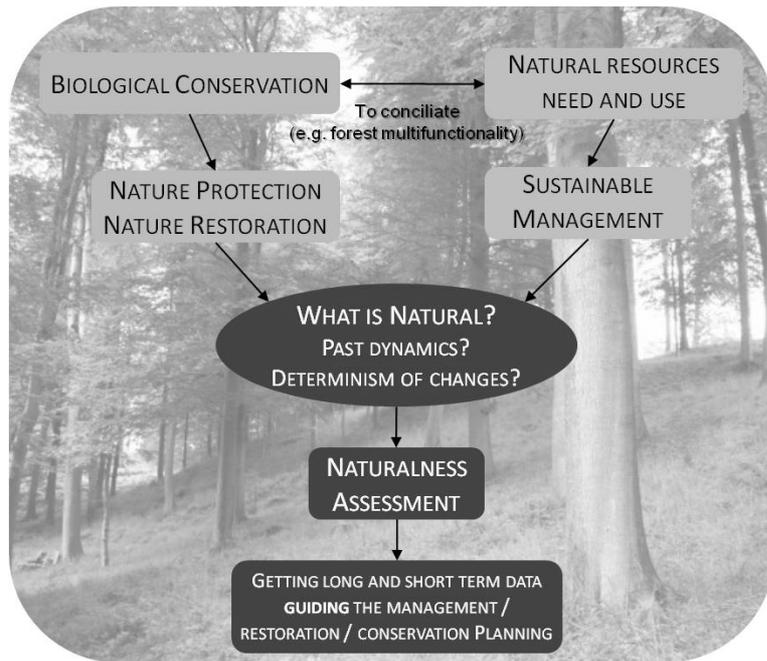


Figure 6. Stake and issue about ecological system values.

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*RECONSTRUCTION OF FIRE AND FOREST HISTORY ON
SEVERAL INVESTIGATION SITES IN GERMANY, BASED ON LONG
AND SHORT-TERM INVESTIGATIONS - MULTIPROXY
APPROACHES CONTRIBUTING TO NATURALNESS ASSESSMENT
ON A LOCAL SCALE*

Part 2.

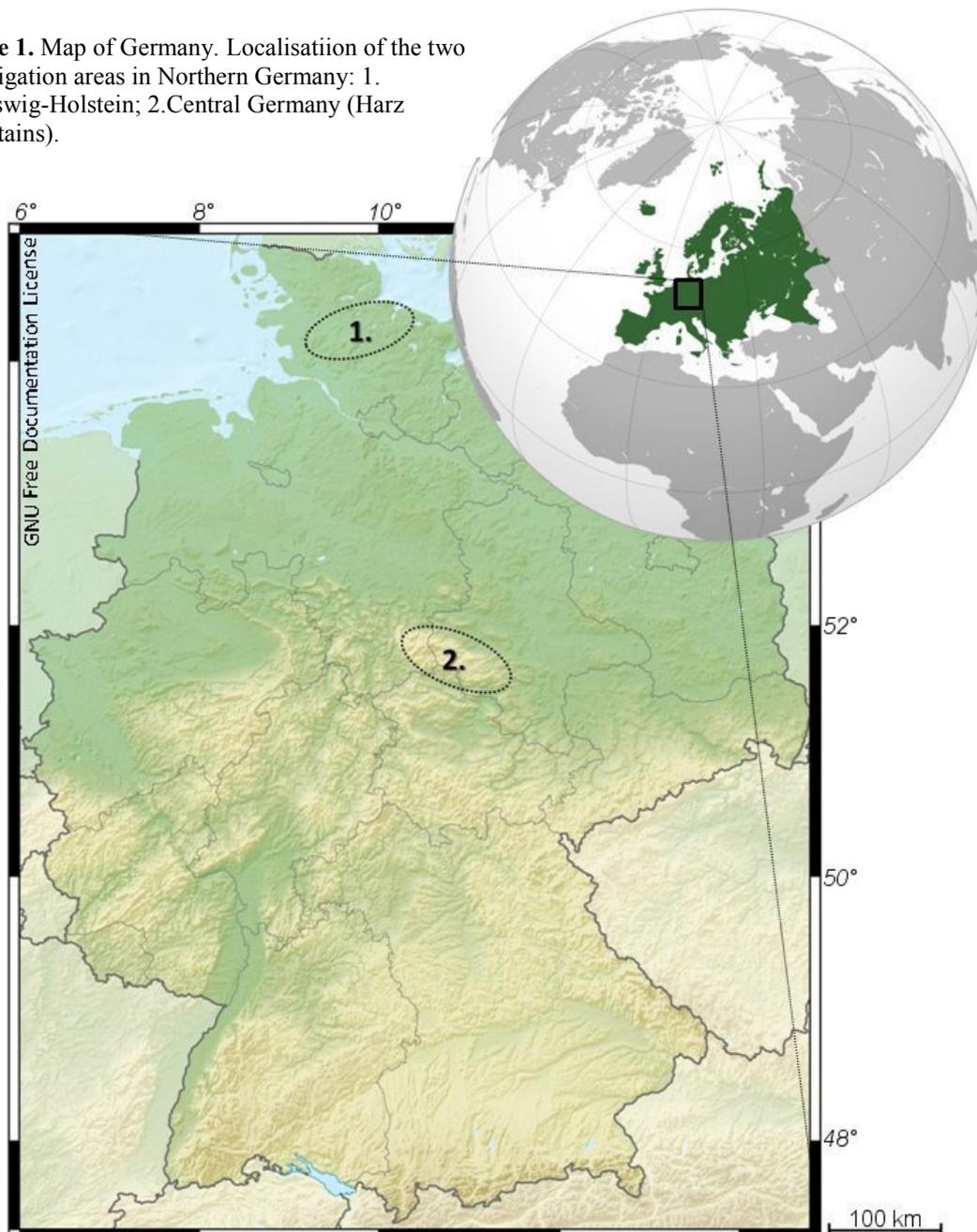
Study sites and methods

3. Study area

Intending to consider a large range of forest system types of central Europe, nine investigation sites were selected in two large areas of Germany (Fig. 1, Table 1). These selected sites do not represent the entire range of diversity of forest systems of central Europe, or even of Germany. However, their respective locations and site characteristics allow inclusion of a large variety of biotic and abiotic features in the investigation framework.

This heterogeneity of representativeness of the investigation sites, in the large investigation areas, guided their selection, taking also into consideration field criteria, like general stand aspects, such as tree species and stems dimensions, topographical feature, accessibility, etc.

Figure 1. Map of Germany. Localisation of the two investigation areas in Northern Germany: 1. Schleswig-Holstein; 2. Central Germany (Harz Mountains).



Area	Site (site code)	GPS coordinates	Mean altitude (m a.s.l.)	Mean slope (°)	Annual mean T°	Annual mean precipit° (mm)	Dominant Forest trees	Topographical feature	Related mire	Altitude related mire (m a.s.l.)	Distance site - mire (ca.)
Schleswig-Holstein	Stodthagener Wald (STO)	54°25'168"N 10°03'626"E	25	0	9.1	880	<i>Fagus sylvatica</i>	heterogeneous smooth slope	SHN	24	on-site
	Westensee (WES)	54°14'263"N 9°58'527"E	45	40	8.5	807	<i>Fagus sylvatica</i>	regular hills slope	MDK	26	on-site
	Riesewohld North (RIEN)	54°09'009"N 9°13'262"E	50	0	8.3	930	<i>Fagus sylvatica</i> <i>Fraxinus excelsior</i>	flat/regular	SFM	45	2 km
	Riesewohld South (RIES)	54°07'936"N 9°13'200"E	55	8				smooth slope			on-site
Harz Mountains	Heinrichshöhe (HEI)	51°47'444"N 10°38'135"E	920	27	2.9	1814	<i>Picea abies</i>	regular slope	BBM	900	200 m
	Renneckenberg (REB)	51°47'73"N 10°39'65"E	700		5.3	1275	<i>Picea abies</i>		BTM	670	100 m
	Rosentalskopf (ROS)	51°42'609"N 10°52'245"E	500	0	6.4	789	<i>Fagus sylvatica</i>	flat/regular	ROM	420	800 m
	Sieben Gemeinde Wald (SIE)	51°33'030"N 11°00'019"E	430	8	6.8	669	<i>Fagus sylvatica</i> <i>Quercus ssp.</i> <i>Carpinus Betulus</i>	regular hills slope	OEB	400	5 km
	Das Große Holz (DGH)	51°28'400"N 11°10'995"E	290	12	8.2	617	<i>Quercus spp.</i>	heterogeneous hills slope			30 km

The nine investigation sites are grouped into two large investigation areas, one in northern Germany (four sites; Fig. 2), and the other one in central Germany (five sites; Fig. 3).



Figure 2. Map of localization of the investigation and sampling sites on Northern Germany (Schleswig-Holstein), ▲ investigation site, ● peat sampling sites. STO: Stodthagener Wald, SHN: peat sequence of Stodthagener Wald; WES: Westensee, MDK: peat sequence of Westensee; RIEN: Riesewohld North; RIES: Riesewohld South, SFM: peat sequence of Riesewohld South.

In both areas, the investigation sites are located along a “transect” of abiotic parameters and correlate biotic variation. To express the site biotic and abiotic variability, several features between the nine selected sites were compared. As biotic aspects, the current or recently practiced human management changes and the changes in on-site dominating forest tree species have been compared (Fig. 4).

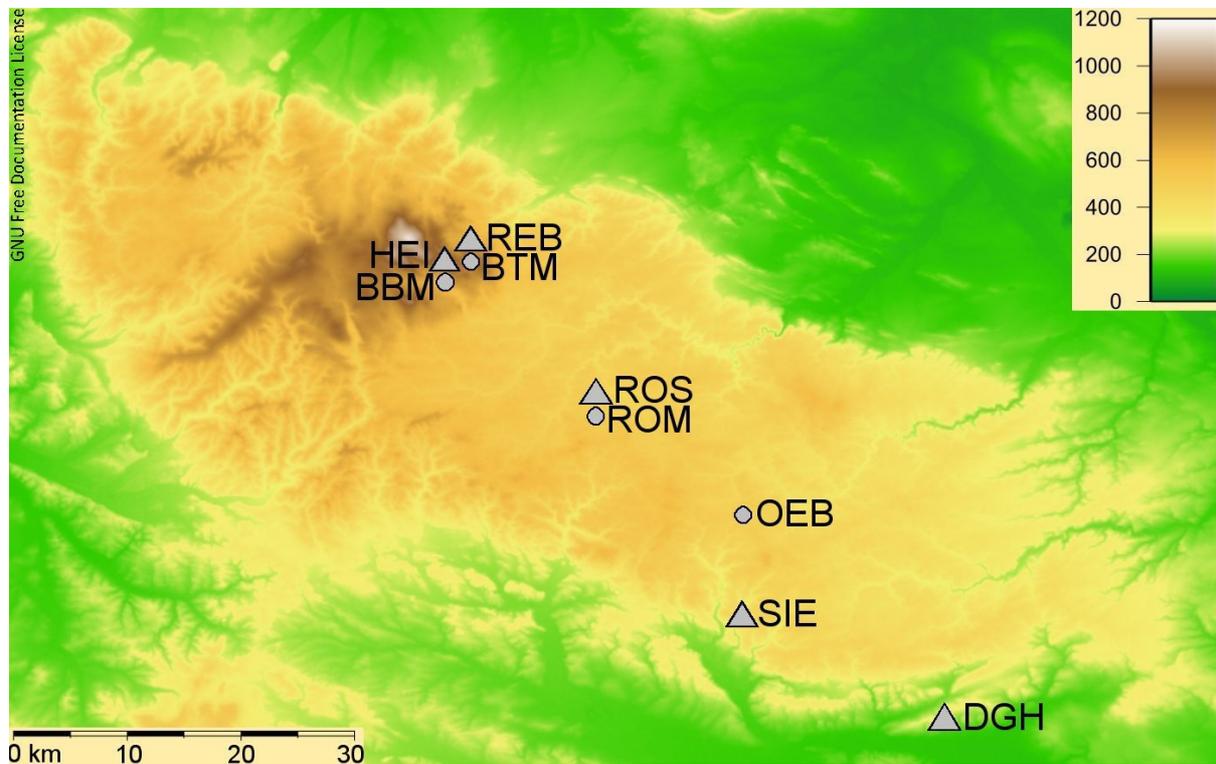


Figure 3. Map of localization of the investigation and sampling sites on Central Germany (Harz Mountains), ▲ investigation site, ● peat sampling sites. HEI: Heinrichöhe, BBM: peat sequence of Heinrichöhe; REB: Renneckenberg, BTM: peat sequence of Renneckenberg; ROS: Rosentalskopf, ROM: peat sequence of Rosentalskopf; SIE: Siebengemeindewald, OEB: peat sequence of Siebengemeindewald; DGH: Das Grosse Holz.

Management statue / Dominant forest tree species	Strict and ancient protection	Recent protection statue	Timber wood production
<i>Picea abies</i>	→REB / HEI		
<i>Fagus sylvatica</i>		→STO / WES	→ROS
<i>Quercus</i> spp.			→DGH
Mixed forest		→RIES / RIEN	→SIE

Figure 4. Investigation site feature comparison, biotic aspects: current (or recent) management system vs. dominating forest tree species [Mixed forest: the forest area presents more than one forest tree species dominating, either in abundance or in space occupancy].

As abiotic site features, climatic context (Fig. 5, in detail in Appendix 3), altitude, mean degree of site slope (Fig. 6), and the dominant on-site soil texture (Fig. 7, in detail in Appendix 4), have been compared. Moreover, to gain chronologically referenced fire signals, peat sequences have been cored from mires correlated to one or more of the investigation sites.

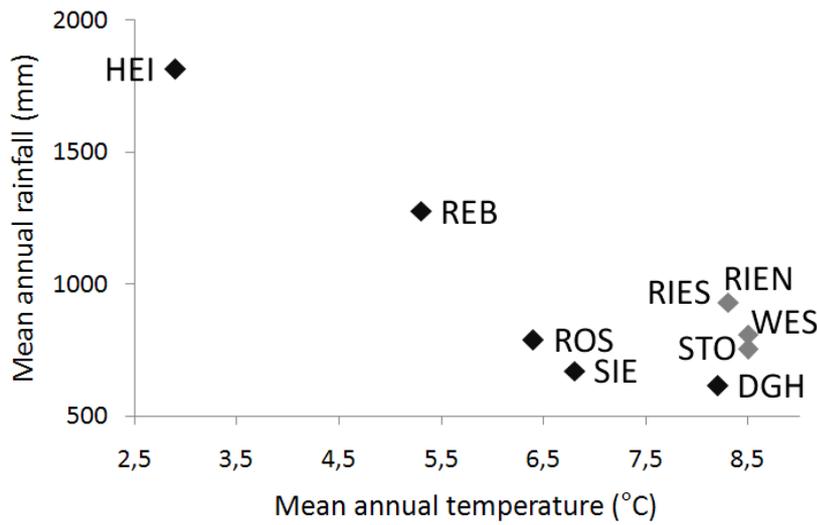


Figure 5. Investigation site feature comparison, abiotic aspects: rainfall vs. temperature (black rhomb: Harz Mountains sites; grey rhomb: Schleswig-Holstein sites).

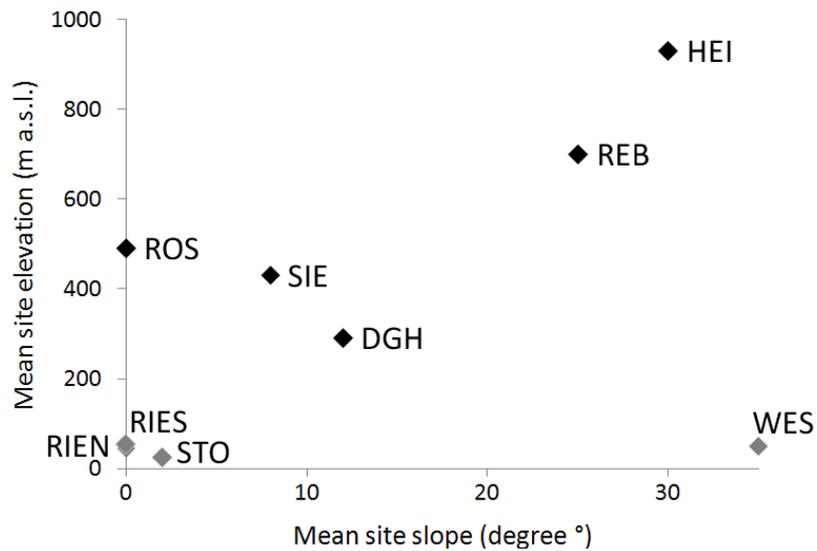


Figure 6. Investigation site feature comparison, abiotic aspects: site elevation vs. site slope (black rhomb: Harz Mountains sites; grey rhomb: Schleswig-Holstein sites).

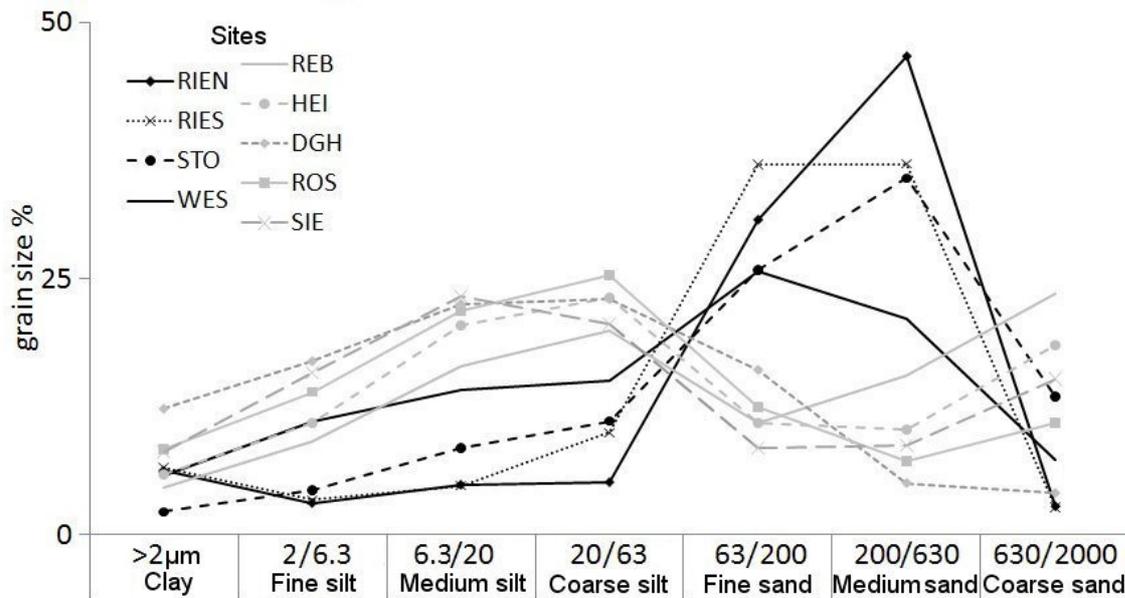


Figure 7. Investigation site feature comparison, abiotic aspects: dominant on-site soil texture (grey lines: Harz Mountains sites; black lines: Schleswig-Holstein sites; for sites code meaning see figures 12 and 13).

3.1 Northern Germany

The four investigation sites of northern Germany are located in the northernmost German federal state, Schleswig-Holstein (Fig. 2). This state extends up to 53° North latitude from north of the Elbe River, and is located at the “bottom” of the Jutland peninsula. It is situated between the North Sea on its western coast and the Baltic Sea on its eastern coast. The climate of the area is oceanic, characterized by low variation in temperature over the year and relatively warm winters and cool summers. Rainfall is evenly dispersed throughout the year. Described on a broad scale, the natural vegetation corresponds to lowland beech (*Fagus sylvatica*) forest, or mixed beech forest with some pockets of mixed oak (*Quercus* spp.) forest on poor soils (Bohn *et al.* 2004, Dierssen 2004).

During the last maximum glacial phase, the eastern part of Schleswig-Holstein was covered by the Scandinavian ice sheet, from ca. 20 000 to 15 000 yrs BP (Lang 1994, Nelle and Dörfler 2008). This glacial phase and the following glacial retreat deposited sandy moraine sediments and shaped landscapes by creating topographical heterogeneity and a multitude of lakes and mires of various sizes. The western part of Schleswig-Holstein was not under the ice sheet during the Weichselian phase, but it was so during the previous glacial phase (i.e. the Saalien). Consequently, sandy moraine sediment deposits are older and therefore finer and results currently in a less marked relief. The landscapes there are more homogenous and

flatter than in the eastern part, especially in the marsh lands of the extreme western part of the state (Meier 2004).

Still, a considerable number of lakes and mires of various sizes are present throughout northern Germany. These natural archives provide relevant context to gain suitable material for palaeoecological reconstruction. Therefore, the vegetation history of Schleswig-Holstein and of northern Germany has been until now quite well documented (Behre *et al.* 1996, Wiethold 1998, Bogaard *et al.* 2002, Rickert 2006, Nelle and Dörfler 2008). However, aspects such as long- and short-term forest dynamics at local scale (i.e. for considered sites), long-term fire history, and forest naturalness assessment remain poorly documented. These aspects are quite important issues for current and future forest management and conservation (see Part 1, Chapter 2.2.3). Indeed, in Schleswig-Holstein, the human impact on forest systems and on landscapes is quite important. Forested and/or wooded surfaces represent only about 10% of the total land surface (i.e. 157 025 ha in 2005; Statistikamt Nord 2010), and most of those 10% are managed forest for wood timber production.

In this context, four forest sites have been selected for the investigation of local forest and fire history, and for assessment of forest stand naturalness. Those sites are located along an edaphic transect, following the grain size increasing of the sandy moraine sediment from west to east (Fig. 2). At the eastern position are the two sites of the Riesewohld forest (Riesewohld North, RIEN, and Riesewohld South, RIES), presented in detail in Part 3, Chapter 5.1. More to the east, at the middle of the transect, is located the Westensee site (WES), presented in detail in Part 3, Chapter 5.2. At the eastern most position is the site of Stodthagener Wald (STO), presented in detail in Part 3, Chapter 5.3. Moreover, in the surrounding of each of those forests stand sites, peat lands have been selected for sampling of peat sequence providing additional material for the multiproxy analysis. In the Riesewohld forest, near the site RIES, the small fen SFM's have been sampled. In the surroundings of the site WES, the mire MDK's have been sampled. Finally, in the forest stand site STO, the small mire SHN has been cored. Only the material sampled from this last mire is presented in detail in this document (Part 3, Chapter 5.3). The main results of the two previously named peat lands are presented in the appendix and are used for the overall synthesis (Part 4).

3.2 Central Germany

The investigation sites selected in central Germany are located in the northernmost low - mountain range of central Europe, the Harz Mountains, and include mountain forest type vegetation (Fig. 3). The Harz Mountains are situated in the south of the northern European plain, and to the north of the European highlands. This is an “old” mountain area, formed during the Carboniferous Period, about 350 to 250 million years ago. The geological features of the overall Harz range are quite complex and made of an important diversity of substratum types, dominated by base-poor rocks (Gabriel *et al.* 1997). This contributes to form the current high heterogeneity of soil features, even at local scale.

The Harz range is oriented northwest and southeast, with a rapid elevation increase in the most northwestern part, the “Oberharz” (Upper Harz). The highest point of elevation, Broken Top, 1142 m a.s.l., is located more than 60 kilometers from the lowlands in the north. In the southeastern direction, elevation decreases more progressively along the “Unterharz” (Lower Harz), to reach the Elbe lowland alluvial plain (ca. 300 m a.s.l.), over 100 km. away. These large-scale relief features and orientation ensure that there is a highly marked climatic gradient from northwest to southeast, from a sub-oceanic to a continental climate. Such climatic gradient induces change in the currently dominating forest vegetation, from conifer dominated forest at higher elevation, to temperate, broadleaf dominated forest. However, looking back into the past over long temporal scale, the vegetation history is not so clear. The global trends of past vegetation change of the sub-continental part of the Harz range have been quite well investigated in palaeoecological investigations carried out in the national park area (Beug *et al.* 1999). However, some specific questioning, such as the past elevation of the transition area between *Fagus sylvatica* and *Picea abies* dominated forest, or detailed fire history, is missing (Kison, personal communication). On a shorter temporal scale, since the Harz National Park constitutes an important part of the sub-oceanic climatic area of the Harz, issues of biological conservation and naturalness purposes are of considerable interest. This is also the case for the most south-eastern part of the Harz Mountains, where an application for UNESCO recognition as Man and Biosphere Reserve is under consideration (UNESCO 2008; Piegert, personal communication).

Nevertheless, the entire natural system of the mountain range is being and has been dramatically impacted by forest resource management. Nowadays, forest systems are intensively managed for timber production throughout most of their areas, including large-scale, intensive, plantation-management of *Picea abies*. In long-term palaeo-research,

intensive use of wood resources for charcoal production and mining purposes has been demonstrated (Matschullat *et al.* 1997, von Kortzfleisch 2008). These human activities induced heavy deforestation during the Middle Ages. Vegetation history of the southeastern Harz range, however, has hardly been documented at any temporal or spatial scale, thus bestowing special interest upon the present investigation. Moreover, due to location, and to its topographical and soil characteristics, the Harz Mountains may have played an important role in the post-glacial and Holocene forest and tree species migrations and developments in central Europe. (Hewitt 1999, Petit *et al.* 2003, Magri 2008). This underscores the importance of the need for further documentation of the long-term vegetation history of the area.

Following the previously described gradient, five sites of investigation were selected, with also related mires for peat sequences sampling (Fig. 3). Two of the five sites are from the higher elevations area of the Harz Mountains, the Heinrichöhe (HEI) and Renneckenberg (REB), with their related respective mires, Brockenbettmoor (BBM) and Blumentopfmoor (BTM), the details of which are presented in Part 3, Chapter 6.1. Three more sites are situated at lower elevations, in the south-eastern part of the mountains range: the site of Rosentalskopf (ROS), the site of Siebengemeindewald (SIE), and, on the most south-eastern position, the site of Das Grosse Holz (DGH). Those three sites of investigation are presented in detail in the Part 3, Chapter 6.2. Additional data from small related mires ROM and OEB are presented in Appendix 2/a and 2/b. Their indications are used in the overall synthesis (Part 4).

4. Methods

General aspects of the methods used in this investigation are presented here. Specific aspects for each method and methodological “adaptations”, depending on the investigation site and aims, are detailed in chapters of Part 3.

Four approaches have been used, all in the broad conceptual frame of ecology, and, more specifically, in the frame of occurrences of changes in ecological systems structure (i.e. disturbance occurrences, see Chapter 2.4). For each of the approaches used, the accepted methods, described in literature, have been adapted from field to laboratory work, to the site and purposes of this investigation. The repeatability of each method, which is necessary in order to obtain comparable, relevant and reliable data sets (Poincaré 1908, Popper 1973), was maintained on the finally applied protocol.

The methods applied allow to obtain signals at the local scale (i.e. forest stand), constituting the basic spatial level of the investigation, allowing on-site multiproxy comparisons.

However, in some cases, supra-local signals have been obtained (i.e. landscape to regional signal), by comparing local scale signals within various investigation sites, over large spatial scale (see this part, Chapter 3) and identifying synchronies and/or asynchronies (see Part 3 Chapters 5.1 and 6.2).

The temporal relevance of the indicators and attributes used in this investigation allows continuity in the temporal scale of analysis. This temporal continuity is actually divided into two main clusters of investigation, providing data over (1) short-term scale and (2) long-term investigation (see Part 1, Chapter 2.1).

4.1 Long-term investigation of forest dynamics and fire history

4.1.1 Soil charcoal analysis

Soil charcoal analysis (i.e. pedoanthracology; Thinnon 1978) is a palaeoecological discipline allowing investigation of past occurrences of fire events (i.e. fire history; Fesenmyer and Christensen 2010) and identification of the correlated burnt woody vegetation (Talon 2010). This is based on the extraction of wood charcoal pieces assemblages from soil archives which are on-site-formed soils or sedimentary soil sequences (e.g. colluvial soil; Leopold and Völkel 2007). Those charcoal assemblages are quantitatively (charcoal concentration per weight unit of sampled earth) and qualitatively (taxonomical spectrum and radiocarbon dating) analyzed (Carcaillet and Thinnon 1996, Talon *et al.* 1998).

Charcoal records extracted from sediment soil sequences indicate past fire events and correlate burnt woody vegetation at the catchment scale. The presence of charcoal pieces in soil results from at least one occurrence of fire event producing the charcoal material, which is fragmented, buried and preserved in-situ over millennia (Fig. 8).

The resulting soil charcoal assemblage depends on complex taphonomical processes, like for all palaeo-signal recording and conservation (Behrensmeier *et al.* 2000, Ferguson 2005). For charcoal records, taphonomical processes include especially charcoal formation (correlated to fuel type, fire intensity, etc.), transport (correlated to weather condition during and after fire, to the size of the charcoal pieces, etc.), and deposition correlated to catchment area, topography, archive type, etc. (Gardner and Whitlock 2001, Scott and Damblon 2010). Concerning this last taphonomical aspect, several studies have shown that macro-charcoal pieces are deposited in-situ (Part 2, Chapter 4.1.2). Even more than macro-charcoal records (i.e. charcoal pieces bigger than 100/200 μm), soil charcoal analysis deals with “mega-charcoal”

records, since charcoal pieces must be bigger than 800 μm to 1 mm to be taxonomically identifiable. This size allows consideration of the soil charcoal palaeo-signal as locally relevant (i.e. ten-meter scale; Dutoit *et al.* 2009). However, the topographical context of the sampling site and the soil history aspect must be considered to pertinently interpret the analyzed soil charcoal record.

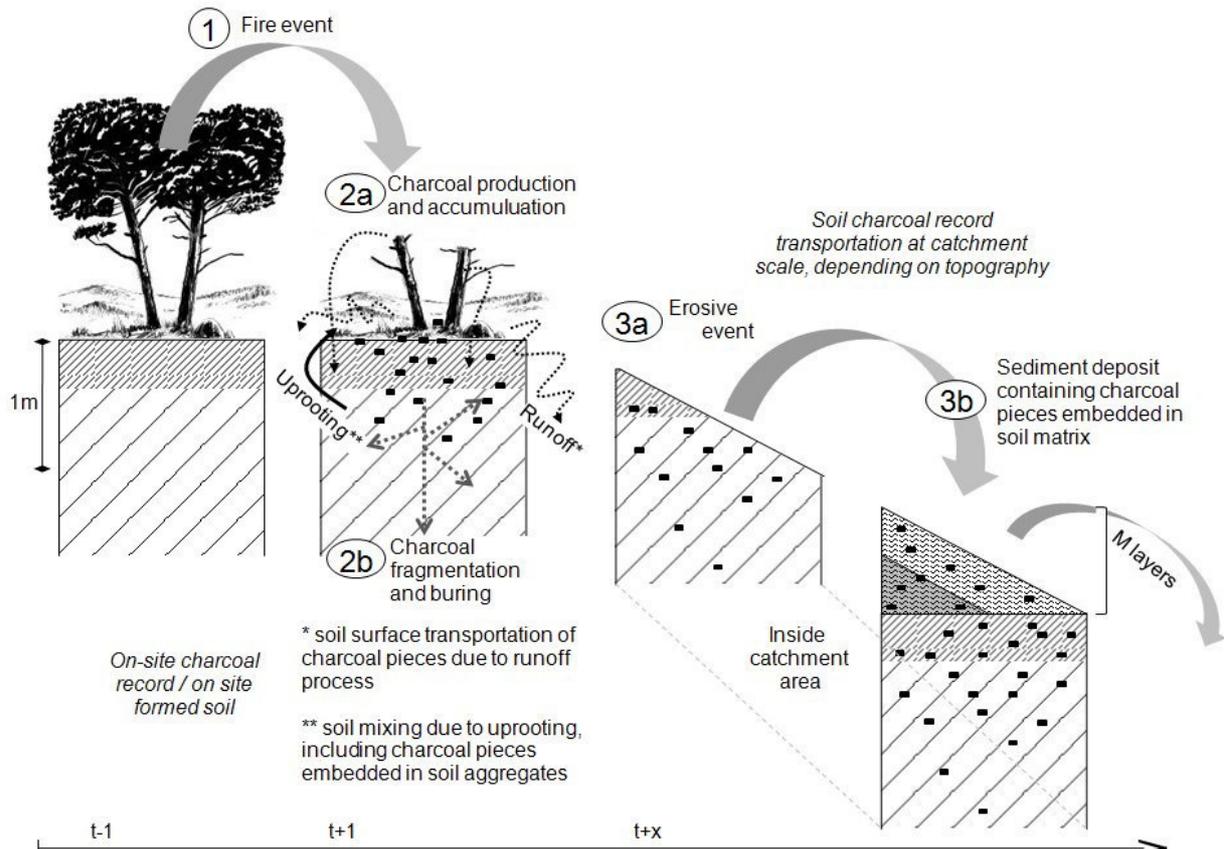


Figure 8. Main taphonomical steps of the soil charcoal records constitution. Steps 1 and 2: on-site burying of charcoal pieces; Step 3: soil erosion and charcoal assemblage transport (t = time; M layers=colluvial layers).

Indeed, post-fire erosion may have transported charcoal pieces, since earth matrix, eroded and deposited, might embed biotic indicators (Bork and Lang 2003, Pierce *et al.* 2004, Walther *et al.* 2009, Emadodin *et al.* 2010). This would extend the spatial resolution of the analyzed charcoal signal, compared to soil charcoal records extracted from soil that was formed on site (Fig. 8). At such local spatial scale, considering the high spatial resolution of soil charcoal signal, a multi-sampling strategy is needed (Touflan and Talon 2009, Touflan *et al.* 2010). Such strategy allows comparison of soil charcoal signals within the catchment scale in order to obtain representative data. This comparative reading of the soil charcoal assemblages is also very important for identifying anomalies in the soil charcoal signal (e.g. enrichment of soil in charcoal coming from fire places or charcoal production site; Knapp and Robin, in prep.). Indeed, charcoal in soil can derive from sources other than forest fire: fire

places or kilns, for example. Nevertheless, those types of soil charcoal records are relevant and interpretable palaeoecological data sources (e.g. Nelle 2003, Ludemann 2010), whereas those charcoal records passed through the “filter” of human activities/usage (Théry-Parisot *et al.* 2010).

To identify the burnt woody vegetation results of forest fire, charcoal assemblages extracted from soil samples are taxonomically analyzed. Using the microscopic anatomical characteristics of wood, taxa of the charcoal piece is identified. This is possible thanks to the fact that the anatomical structure of wood material is “fossilized” by carbonization (or even by partial charring), producing just a few small deformations and/or transformations (Théry-Parisot 2001, Braadbaart and Poole 2008). Identifications at both genus and species level are possible, using wood collection references (Institute of Ecosystem Research, Working group Palaeoecology, Christian-Albrecht University of Kiel) and wood anatomical atlases (e.g. Jacquot 1955, Jacquot *et al.* 1973, Schweingruber 1990a, Schweingruber 1990b). However, several parameters may influence the precision of the identification. In some cases, the taxonomical identification is not possible (i.e. indeterminable material), because of charcoal pieces being too dirty (e.g. cover of clay sediments) and/or overly transformed (e.g. vitrified charcoal; McParland *et al.* 2010). For some other cases, the anatomical characteristics of the wood itself, viewed as very small fragments of charred material, often allow taxonomical identification limited to the level of anatomical type group of taxa level, e.g. *Tilia/Prunus* or *Picea/Larix*. Concerning this last anatomical type group, since it was of primary relevance for the investigation done at the highest elevation of the Harz Mountains area (i.e. sites HEI and REB; Part 3, Chapter 6.1), microscope experimental analysis was performed. This is presented in Appendix 5.

Since soils are a dynamic archiving context, quantitative and qualitative analysis of soil charcoal assemblages must be interpreted delicately for chronology (Carcaillet 2001a, Carcaillet 2001b). Several processes may mix the charcoal assemblages within the soil archiving context, like uprooting (Gavin 2003, Šamonil *et al.* 2010), for instance, or bioturbation (e.g. earth worm activity; Darwin 1881, Jégou *et al.* 1998). Such aspects are discussed in depth in Chapters 5.3, 6.1, 6.2, of the Part 3. Nevertheless, when quantification of the soil charcoal record is combined with dating (i.e. by radiocarbon AMS-C¹⁴ measurement; Gavin 2001), soil charcoal analysis dealing with mega-charcoal pieces is the only palaeoecological approach which allows simultaneous investigation of both fire and forest history.

So far, based on the literature, charcoal pieces have been found in every type of natural soil, in every type of ecological system where this approach has been done. Of course, soils of fire-sensitive ecosystems, with easily inflammable vegetation, are particularly rich in charcoal pieces. Such ecosystems are found in Mediterranean areas (e.g. Bergaglio *et al.* 2006, Vernet 2006, Henry *et al.* 2010), boreal zones (e.g. Ohlson and Tryterud 2000, Talon *et al.* 2005), European alpine sites (e.g. Carcaillet and Thion 1996, Carnelli *et al.* 2004, Poschlod and Baumann 2010), and in the Andes mountain range (e.g. Pasquale *et al.* 2008, Pasquale *et al.* 2009). Moreover, soil charcoal records have been found also among areas where fire is supposed to have a less important role in the past ecosystems changed, like low mountain ranges of central Europe (e.g. Schwartz *et al.* 2005, Goepf 2007), and of North America (e.g. Hart *et al.* 2008, Fesenmyer and Christensen 2010), and even in tropical zones (e.g. Hammond *et al.* 2007, Titiz and Sanford 2007).

The work presented in this document illustrates that soil charcoal records are present in central Europe in conifer forests of low mountain ranges (Part 3, Chapter 6.1), in broad-leaf temperate forests (see Part 3, Chapter 6.2), and in the northern, oceanic climate lowlands of central Europe (see Part 2, Chapter 5.1 to 5.3).

4.1.2 Peat sequence macro-charcoal analysis

The accumulation of charcoal and/or charred material in natural “traps” such as lakes and mires constitutes a relevant archiving context for charcoal records (Conedera *et al.* 2009). Analysis of charcoal content of cores sampled from lake sediments and/ or peat bogs, correlated to time, provides insights into fire history (i.e. past fire regime; Scott *et al.* 2000, Whitlock and Larsen 2001, Olsson *et al.* 2009). Indeed, such archives are chronologically stratified, therefore, using a relevant number of radiocarbon dating, age/depth relations (i.e. age/depth modelling; Bronk-Ramsey 2008) are useful for determining the chronological framework of the charcoal content.

Aiming to get data with comparable spatial resolution with other data sets of the investigation, small peat bogs and mires, with relatively small catchment areas (i.e. from few 10 m² to ca. 1000 m²) were sampled. Such archiving context allows to get palaeo-signals at “local” scale (Higuera *et al.* 2005, Bjune *et al.* 2009), comparable to the local resolution of the soil charcoal record (this part, Chapter 4.1.1). However, it cannot be excluded that a part of the palaeo-signal is from regional input, even if the extracted material is from archives with small catchment areas and with reduced possibility of secondary deposits (i.e. no waterlogging

transportation in peat bogs; Nichols *et al.* 2000). Therefore, to minimize the part of the regional signal into the charcoal record, only the macro-charcoal record has been analyzed. Indeed, during the last three decades, many works have been undertaken, improving the methodology and the interpretation of charcoal signals from sediment sequences (Clark 1988a, Clark and Royall 1995, Whitlock and Millspaugh 1996, Gardner and Whitlock 2001, Tinner and Hu 2003, Carcaillet *et al.* 2007, Higuera *et al.* 2007). Several methods have been developed, e.g. “thin section” analysis (Clark 1988b), and “Oregon sieving method”, (Millspaugh and Whitlock 1995). Those increasing number of analyses determined important distinctions concerning the size of the charcoal and charred material constituting the fire signal. Micro- and macro-charcoal signals have been defined as having various relevances in terms of spatial resolution (Lynch *et al.* 2004, Duffin *et al.* 2008). As a general rule, it can be considered that: “The bigger the fragment, the closer it remains to its original locality”, even if this can be also discussed, depending on each study case (Tinner *et al.* 2006). The development of sieving methods (Millspaugh and Whitlock 1995, Carcaillet *et al.* 2001), allows extraction of charcoal records of various sizes, including relatively big charcoal pieces, and comparison to the size of the charcoal pieces found in pollen slides (Tinner and Hu 2003, Asselin and Payette 2005). The relevant distinction size between the micro- and macro-charcoal records is variable, over a range from 100 to 250 μm , depending on the authors and methods. Nevertheless, to use micro- and macro-charcoal records allows investigation of fire history at regional and local spatial scales, respectively (Laird and Campbell 2000, Briles *et al.* 2008).

To obtain the macro-charcoal records used in the investigation presented in this document, several peat sequences have been cored using the “Usinger piston corer”, providing 1 m long, 8 or 5.5 cm diameter undisturbed cores of peat or gyttja, which yield enough suitable material to do pollen and macro-charcoal analysis on the same cores (O'Connell *et al.* 2004, Mingram *et al.* 2007). From the sampled material, the macro-charcoal records have been extracted by sieving at a mesh size of 200 μm . The quantification of the macro-charcoal content was done following the “simple and fast” method developed by Mooney and collaborators (Mooney and Radford 2001, Mooney and Black 2003). The quantified amount of macro-charcoal was correlated to the age/depth model established for the corresponding peat sequences. This provides as main result the macro-charcoal accumulation rates per year. Based on this result, fire history may be reconstructed. Moreover, a statistical treatment of quantified macro-charcoal record was done, using the CharAnalysis program allowing to identify charcoal

accumulation background and to detect charcoal “peaks” interpretable as local fire events (Higuera 2009, Higuera *et al.* 2009, Higuera *et al.* 2010).

Moreover, the unit of measurement is a crucial aspect for the quantification of the charcoal content of peat sequences, and, more globally, for every type of sediment sequence. Indeed, the debate is still open as to whether it is more relevant and reliable to do quantification based on charcoal pieces per area or whether based on fragments per volume. Quantification of charcoal records from the same material but using various units of measurement may show variable results (Ali *et al.* 2009, Higuera *et al.* 2009). Such biases in measurement are the main explanation for this variability (e.g. charcoal piece fragmentation due to laboratory treatment, increasing the number of pieces but not the area). Therefore, for the macro-charcoal analysis of the peat sequence of this investigation, the correlation between the number of macro-charcoal pieces (no.) and the corresponding area (mm²) per samples of peat have been calculated (Appendix 2). A high correlation indicates that either the number or the area of macro-charcoal was reliable as a past fire signal, allowing to use both measurement units for the analysis. In contrast, a low correlation indicates variations in the macro-charcoal records in a number of pieces or areas. In such case, the area has been preferred for the macro-charcoal record quantification.

4.1.3 Complementary data

In order to obtain a larger, more detailed reconstruction of long-term ecosystem change, complementary data have been gained from the additive approach. Such data are supporting and contributing to the interpretation and the discussion of charcoal records analyzed, either from soil or from peat sequences.

In complement to soil charcoal, soil analysis was done. Field and laboratory methods for soil historical description and analysis, as described in several papers, were carried out (Bork and Lang 2003, Bork 2006, Reiss *et al.* 2009, Emadodin *et al.* 2010). Such data are of prime interest for the interpretation of soil charcoal records. Indeed, soil charcoal records are not bio-chronologically stratified, meaning that the interpretation of the soil charcoal assemblages strongly depends on the context of sampling, and especially on the soil history (also influencing the spatial resolution of the soil charcoal record). The identification of an in-situ soil horizon, and of one, or more, colluvial layer(s), may reveal interesting aspects that help to interpret the soil charcoal taxonomical and chronological data (from radiocarbon dating). The

methodological aspects are presented in greater detail in Chapters 5.1, 5.2, 6.1 and 6.2 of Part 3.

Moreover, using the same peat sequences than for the macro-charcoal analysis (see this Part, Chapter 4.1.2), pollen records were analyzed by collaborator of the Institute of Ecosystem Research (Working group Palaeoecology, Christian-Albrecht University of Kiel) and of the botanical platform of the Graduate School “Human Development in Landscapes” (Christian-Albrecht University of Kiel). This provided useful data, complementary to the macro-charcoal indication and to the taxonomical analysis of the soil charcoal. These data are presented in Part 3, Chapter 5.3, and in the Appendix 2a).

4.2 Short-term investigations of forest dynamics

4.2.1 Forest stand characterization

To assess the degree of naturalness of the forest sites of the investigation is it necessary to characterize the current state of those sites (Uotila *et al.* 2002, Gilg 2004, Laarmann *et al.* 2009). This has been based on the description and the measuring of several forest stand attributes.

The forest stand characterization provides insight concerning two main aspects:

(1) The intensity of forest human management, based on the data obtained from the considered forest stand attributes, provides data dealing with the influence of human management practices over the temporal scale of the on-site living tree population, at the stand spatial scale. These human management practices, possibly still active, create “marks” on the forest structure (Larsen 1995, Rouvinen and Kuuluvainen 2005, Sogachev *et al.* 2005), meaning anthropogenic influences on the biological systems which are the forest stand sites under consideration (Christensen and Emborg 1996, Liira *et al.* 2007). An attempt was made to identify and interpret such marks.

(2) Once the current state of the considered forest stand sites has been defined, it can be compared to data dealing with past change of the biological system, over long temporal scale (this Part, Chapter 4.1) and short-term as well (this part, Chapter 4.2.2). Such data about past changes of the biological system constitute reference states of the system (Gilg 2004, Winter *et al.* 2010). It is important here to highlight that, in this investigation, in contribution to the assessment of naturalness of the studied forest stands, recognizing the dynamism of ecosystems, not one but several states of reference have been defined (see Part 1, Chapter 2.1). These reference states are compared to the current state of the forest stands considered.

Allowing this comparative approach, the overall data set have comparative spatial resolution at local scale (i.e. forest stand; see Part 1, Chapter 2.3).

The forest stand attributes taken into consideration for the characterization of each forest site of the investigation have been selected to provide relevant and significant data for the two previously described aspects. Therefore, it is not an exhaustive forest stand characterization. The observed and measured parameters and indicators have been selected from the large range of existing forest attributes (Neumann and Starlinger 2001, Gilg 2004, McElhinny *et al.* 2005, Laar and Akça 2007). This selection has been made depending on the forest stand specifics and on local questioning, aiming to have a reliable protocol, repeatable and comparable site to site. An overview of those forest attributes is presented in Table 2, and they are presented in detail in some chapters of Part 3. Globally, the forest stand attributes taken into consideration provide data about the level of heterogeneity (i.e. complexity; McElhinny *et al.* 2005) of structure and the composition of the investigated forest sites. The total number of trees per measured dimension classes (i.e. diameter classes at breast height) and per species have been inventoried. Horizontal spatial distribution of the forest trees, vertical structuring in forest stands levels, and corresponding heights have been considered. The density of the forest stand regeneration in total and per species has been also inventoried.

Indicating of	Measure / Inventory (units)	Attribute
Stand horizontal structure	tree diameter (cm)	diameter distribution (d _{hb} *)
		number of large trees
		mean d _{hb}
	basal area (m ² /ha)	spatial biomass dominance
	tree x,y coordinates (m)	tree mapping
	Nearest Neighbor distance (m)	Clark Evans index**
	number of stems (n/ha)	tree density
Stand vertical structure	trees heights (m)	overstorey height
		understorey vegetation levels heights
	number of stems (n/ha)	tree density per vertical stand level
Stand composition	number of stems (n/ha)	tree density per species
		tree density per species, per vertical stand level
	stand species proportion (%)	relative abundance per species
		relative abundance per species, per vertical stand level
number of seedling and sapling (n/ha)	density of forest regeneration, per species	
Dead wood	volume (m ³ /ha)	total volume
		volume per decay classes***
		volume per type of piece***

Table 2. An overview of the forest attributes used for the forest stand characterization of the investigated sites (*d_{hb}: diameter at height of breast; ** Clark and Evans 1954; *** see Table 2).

Finally, the dead wood was inventoried (e.g. volume), since this is one of the most relevant indicators of forest naturalness (Siitonen et al. 2000, Christensen et al. 2005). To characterize the state of dead wood decay, whatever the type of piece or the species, there are several methods, all globally based on the dead wood characterization par decay classes (e.g. Travaglini and Chirici 2006, Aakala et al. 2007). The properties of the dead wood state per decay class vary from method to method and therefore provide various numbers of dead wood decay classes. In the research presented here for all of the investigated sites where dead wood has been assessed, the method used is based on five dead wood decay classes, ranging from class 1, which corresponds to fresh dead wood, to the class five, which corresponds to highly decomposed dead wood pieces. The assessment of the decay classes for each inventoried dead wood piece was done using the level of “penetrability” of a knife in the dead wood pieces, in parallel with, and perpendicular to, the wood fibre (Table 3).

Degree of decay	Classes of decay	Parallel to wood fibers	Perpendicular to wood fibers
- ↓ +	1	∅ (fresh dead wood)	∅ (fresh dead wood)
	2	The knife doesn't enter into dead wood (max. few mm)	The knife doesn't enter into dead wood (max. few mm)
	3	The knife enters easily into dead wood (about 1 cm)	The knife doesn't enter into dead wood (max. few mm)
	4	The knife enters easily into dead wood (about 1 cm)	The knife enters easily into dead wood (about 1 cm)
	5	The dead wood is in like powder	The dead wood is in like powder

Table 3. Dead wood decay assessment based on five decay classes of measurement. Methods of knife “penetrability” assessment.

The overall data set were gathered during various field campaigns, following standards of forest inventory and measurement (e.g. Saket *et al.* 2004, ForestBIOTA 2005). The detailed protocol has been adapted to each site, notably depending on current statutes of management (i.e. management system), while the general protocol stayed comparable from site to site. For some sites, the even aged, high mature forest structure makes senseless the measurement of some forest stand attributes. On each site, the sampling area was defined as the area separating the soil profiles of sampling of on each site (see this Part, Chapter 4.1.1). As much as possible, comparable sampling areas were used (i.e. in respect to shape and surface – ca. 3000/4000 m²), allowing comparable levels of data representativeness (Laar and Akça 2007). The collected data were converted to unit per hectare, and the measurement of steep forest stands were converted using a slope corrector coefficient, allowing comparison within and between the investigated forest stand (Saket *et al.* 2004).

4.2.2 Tree ring series analysis

The tree ring series analysis is a method that has been used in many scientific contexts for several decades, notably contributing to forest ecology sciences and vegetation history (Schweingruber 1996, Kipfmüller and Swetnam 2001, Eckstein and Schweingruber 2009). It constitutes in identified, counted, and measured growth-rings of sampled trees. By identifying the years of formation of one or a series of growth-rings, the chronological context of tree growth may be identified (i.e. dendrochronological principle; Fritts 1971). By counting and measuring series of growth-rings, growing patterns of trees over time may be identified (Stokes and Smiley 1996). By analyzing those growing patterns, comparing within and between sampled trees, variations can be detected. Variations indicate changes in tree growing conditions, especially in regard to environmental (Kipfmüller and Swetnam 2001) and/or climatic changes (Büntgen et al. 2011). The formation of each single growth-ring, representing radial growth during one vegetative season (Frankenstein et al. 2005), depends on many parameters at various temporal scales (Schweingruber 1996).

A simplified linear model represents radial growth (Modified from Lebourgeois 2002):

$$RgW = AgEf + CtEf + MiEn + MeEn + Hd$$

Where:

- ✓ **RgW**: Ring Width
- ✓ **AgEf**: Age Effect (width of rings decreases with age and then stabilizes)
- ✓ **CtEf**: macro- and/or micro-Climatic Effect
- ✓ **MiEn**: Micro-Environmental variation (i.e. intra-stand scale variability of biotic and abiotic parameters)
- ✓ **MeEn**: mMeso-Environmental variation (i.e. supra-stand scale variability of biotic and abiotic parameters)
- ✓ **Hd**: “Hazard” (random and no predictable variability of growing, e.g. genetic patterns of individual tree)

These parameters influence tree growth, affecting availability of resources needed for radial growth (i.e. change in resource “amount” and/or change in capacity of the tree to “catch” resources; Smith 2008). A drought period, for example, would limit water available for tree metabolism, and so would have consequences for tree growth (Nöjda and Hari 2001, Lebourgeois *et al.* 2005). Thus, one variation of at least one of those parameters will cause variation in ring formation, notably on ring width, the most visible variation. Successive variations, therefore, implicate successive growth variations over sequences of tree rings. Once correlated to a chronological frame (e.g. based on the known year of tree ring series sampling), the chronological frame of such variation can be identified at yearly to multi-century scales (e.g. Haneca *et al.* 2005).

Several methods can be employed to discriminate the various parameters influencing tree ring growth. Those methods consist principally in identifying the temporal scale of the variation occurrence (i.e. signal frequency). Variation in radial growth due to change in the tree metabolism profitability are correlated to the temporal scale of tree life (i.e. “tree age effect”, Schweingruber 1996). Such variation is observable in the long-term scale growing trends (i.e. low frequency signal). An abrupt ring width change from a year to the subsequent year, however, is often due to climate variability (i.e. high frequency signal; Fig. 9).

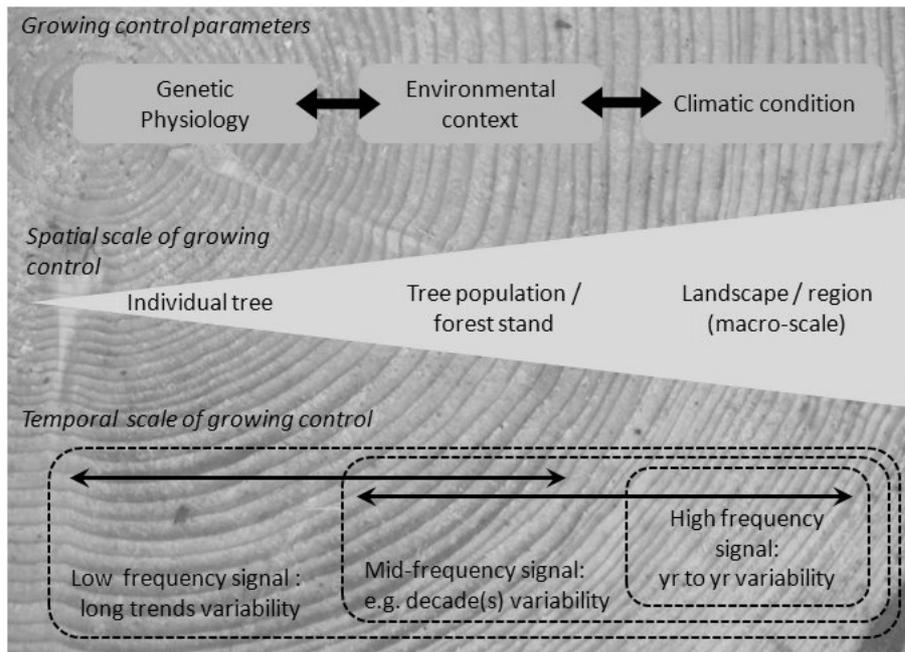


Figure 9. Illustration of tree ring series signals.

Intending to detect patterns of forest stand dynamic change (i.e. disturbance events), and to investigate the history of environmental conditions at local scale during the temporal scale of the living forest stand tree population, the tree ring series from the investigated sites have been analyzed. Therefore, 15 dominant trees per investigated forest stand were sampled (randomly selected from the canopy level of the sampling area for forest characterization; see this part, Chapter 3.2.1). In order to obtain robust tree ring series, each tree has been double cored at ca. 50 cm height, in a perpendicular position, using a Pressler drill (Fig. 10). Laboratory treatment of this sampled material is presented in detail in chapters of Part 3.

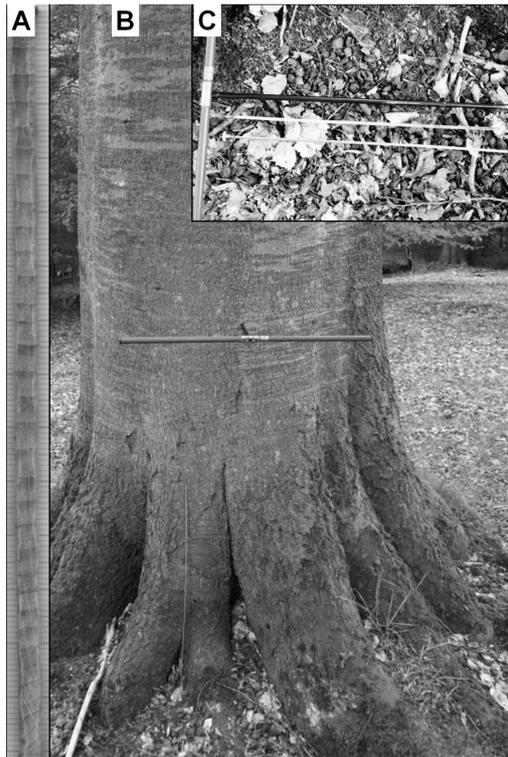


Figure 10. Pictures of the dendroecological coring. A: tree radial core (*Fagus sylvatica*); B: Pressler drill in a *Fagus sylvatica* trunk; C: Pressler drill Suunto (60 cm).

After having measured and cross-dated each tree ring series per site using a measuring table LINTAB 6 by RINNTECH and the TSAP-Win program version 0.59 (Rinn 2003) the mean site chronologies were obtained by averaging.

To get tree ring signal, the measured tree ring series have been standardized. It has been usage various type of standardization, aiming to get signal in various frequency resolutions allowing to postulate main determinism of growth patterns.

Tree ring series standardized on high frequency provide a signal that is related to climatic variability (e.g. Wigley *et al.* 1984, Saulnier *et al.* 2011). To obtain a high frequency signal, various methods have been used. When dealing with sites comparison, a high frequency standardization was made by detrending methods using an ARSTAN program (Cook and Holmes 1996, see Part 3, Chapter 5.2).

While dealing with a data set from a single sampling site, in order to increase the possibilities and the relevance of the interpretation of the on-site signals it was used comparable methods for the high-frequency standardization and the mid-frequency standardization. These methods of standardization are both based on the same method of calculation, on “running windows” of a previously-fixed duration (depending on the others; Bijak 2008, Black and Abrams 2003). The high frequency standardization by “running windows” constitutes a two-step calculation:

- (1) The signal ring width value is compared to the mean ring width value of temporal windows, along the complete duration of the ring series.
- (2) The obtained values are normalized for the complete tree ring series. The obtained values are indexed values.

From those indexed values, the years with ring width “anomalies” (i.e. “pointer years”) may be detected, depending on the level of variability of the yearly indexed values. Those pointer years are indicators of “weak”, “strong” and “extreme” ring width anomalies related to climate variations (Neuwirth *et al.* 2007; see Part 3, Chapter 5.1).

Moreover, statistical indicators such as mean sensitivity, correlation values, express population signal, etc., have also been used, depending on the case, to analyze and interpret the high frequency signal (e.g. assessing the year-to-year signal variations, Haneca *et al.* 2005). For every sites where tree ring series were done, the standardizations in mid-frequency have been done by quantify growth changes, by “running median” methods (Nowacki and Abrams 1997, Rubino and McCarthy 2004). The method of percentage of growth change calculations has been adapted to median values, instead of mean growth values (i.e. better fitting to biological data set distribution; Rubino and McCarthy 2004). Thus, the width of each of ring of the mean site chronologies, were compared to the ring width median value, over prior and subsequent temporal windows of variable duration depending on the species, to detect release events (Black and Abrams 2003). The detection of such release event(s) occurrence is related the identification of change in the on-site canopy structure (or crown; Schweingruber 1996, Nowacki and Abrams 1997), referring to change in light availability, and having consequences on growth patterns (Pickett and White 1985, Hart and Grissino-Mayer 2008).

The calculation was based on this formula:

$$pGC = [(medW^{ts} - MedW^{tp}) / MedW^{tp}] * 100$$

Where:

- ✓ **pGC**: proportion of growing change (%)
- ✓ **W**: measured ring width value
- ✓ **MedW_t**: median value of *W* over *t* temporal window
- ✓ **ts**: 10 subsequent rings from *W*
- ✓ **tp**: *W*, and 9 prior rings

Release events correspond to the growth change in percentages over threshold values. Those threshold values depend on variable parameters. The tree species autoecology seems to be of first importance in the detection and quantification of release events, especially because the capacity and the magnitude of the tree response to changes in light availability seem to be

directly correlated to the distinction of shade tolerant or light-demanding species (Black and Abrams 2003). Such parameters also change the duration of the temporal window in which growth change is calculated (i.e. resolution of the mid-frequency signal). For *Quercus* spp., for example, it has been determined that a growth change between 25 to 50 % indicates a minor release event, and that a growth change greater than 50 % indicates a major release event, calculated for 10 prior years and 10 subsequent years (Nowacki and Abrams 1997, Black and Abrams 2003, Rubino and McCarthy 2004).

Both previously described methods of tree ring series standardization are based on calculation on running windows of comparable duration, but differencing in that aspect the high frequency signal analysis compare annual ring values to “windows values” and mid-frequency signal analysis compare “windows values” to “windows values”. Therefore, by comparing growth patterns obtained from the two resolution of analysis it is attempt to identified environmental (i.e. mid-frequency) or climatic (i.e. high frequency) determinism for the detected growth change. Both high- and mid-frequency methods of tree ring series analysis are presented in detail in the Part 3, Chapters 5.1 and 5.2.

For detection of regional signal synchronies, the identified growth change patterns, detected release events and the high-frequency signal of each site chronology were compared to years with known specific climatic conditions inducing particular growing conditions (i.e. pointer years; Neuwirth *et al.* 2007), and to relevant “referenced” chronologies, available from online data bases (Schmatz 2011, World Data Center for Paleoclimatology 2011). This approach is especially developed in Part 3, Chapter 6.3.

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*RECONSTRUCTION OF FIRE AND FOREST HISTORY ON
SEVERAL INVESTIGATION SITES IN GERMANY, BASED ON
LONG AND SHORT-TERM INVESTIGATIONS - MULTIPROXY
APPROACHES CONTRIBUTING TO NATURALNESS ASSESSMENT
ON A LOCAL SCALE*

Part 3.

On-site Investigations

“Statue” of manuscript treatment

Chapter 5.1 / Paper 1: Multiproxy Assessment of the forest history and dynamic patterns of a beech forest in Northern Central Europe: a contribution to naturalness assessment. Vincent Robin and Oliver Nelle. Manuscript.

Chapter 5.2 / Paper 2: Characterization of forest stands features and history, on long- and short-term scales, contributing to the nature conservation/restoration planning: an illustration case in Northern Germany. Vincent Robin, Hans-Rudolf Bork and Oliver Nelle. Manuscript.

Chapter 5.3 / Paper 3: Assessing Holocene vegetation and fire history by a multiproxy approach: the case of Stodthagen Forest (Northern Germany). Vincent Robin, Björn-Henning Rickert, Marie-Josée Nadeau and Oliver Nelle. *The Holocene*, Accepted 2011.

Chapter 6.1 / Paper 4: Holocene fire history and forest composition in the Upper Harz Mountains (Central Germany), based on the analysis of charcoal records from peat and soil archives. Vincent Robin, Hannes Knapp, Hans-Rudolf Bork and Oliver Nelle. Submitted to *Journal of Quaternary Science*, June 2011.

Chapter 6.2 / Paper 5: Holocene Fire and Forest History of the Eastern Part of the Harz Mountains (Germany, Central Europe), Based on Soil Charcoal Analysis and the Recording of Non-linear Ecosystems Changes. Vincent Robin, Hans-Rudolf Bork, Marie-Josée Nadeau and Oliver Nelle. Submitted to *Quaternary Research*, June 2011.

Chapter 6.3 / Paper 6: Forest characterization and tree ring analysis of the Heinrichöhe investigation site (Harz Mountains, Central Germany). Vincent Robin and Oliver Nelle. Manuscript.

Chapter 6.4 / Paper 7: Forest characterization and tree ring analysis of two forest stands on the south-eastern parts of the Harz Mountains (Central Germany). Vincent Robin and Oliver Nelle. Manuscript.

5. Northern Germany

5.1 Multiproxy Assessment of the forest history and dynamic patterns of a beech forest in Northern Central Europe: a contribution to naturalness assessment

Introduction

The influences of human activities on ecosystems, like resource usage and management, have been identified as one of the main “drivers” of ecosystems dynamics (e.g. Larsen 1995, Messerli *et al.* 2000, Lefèvre 2004). Therefore, the naturalness is a crucial notion for conservation and/or restoration planning of ecological systems. This notion involves “measuring” how advanced the current state of an ecosystem is, compared to a hypothetical natural system of reference (Anderson 1991, Reif and Walentowski 2008). This measurement is based on several indicators providing multiproxy data set (Kotwal *et al.* 2008, Wallenius *et al.* 2010). The naturalness assessment is complementary to the hemeroby assessment, which measure the human impact on the current state of the system (Brentrup *et al.* 2002). Both notions deal with a natural system of reference (i.e. in the sense of pristine forest). Therefore, such natural systems are of first interest. However, in Central Europe, natural forest systems are rare and restricted to relatively small areas (Parviainen 2005). Moreover, it has been shown that insights from pristine forests are not necessarily usable as reference systems (Brang 2005). Proprieties of a pristine forest site are not necessary transposable to other sites, and such proprieties are not necessarily relevant to generalization, notably because of the local site features (i.e. micro/meso-environmental scale), influencing greatly the ecosystem structure, organization and functioning (Chapin III *et al.* 2002). Therefore, to describe what is natural (Willis and Birks 2006), the natural reference state of the considered ecosystem must be defined by assessing the state of the system before the human impact and the changing processes and consequences since. This requires an investigation of the ecosystem’s history. The human impact and the response of impacted ecosystems is not a linear relation. Instead, they present much complex variability due to many parameters and factors that influence the ecosystem dynamics. Therefore, the history of ecosystems should not be assessed by a “simple linear dichotomic approach” (i.e. human vs. natural impact). It seems much more relevant to investigate the history of the ecosystem by assessing the determinism and consequences of changes in the system’s dynamics (i.e. disturbances and resilience process; Gunderson 2000, Roxburgh *et al.* 2004), including both human and natural roles, as co-determinism factor. In central Europe, when considering the well-documented human influence on ecosystems on a long temporal scale (e.g. Berglund *et al.* 1996, Kalis *et al.*

2003, Berglund 2011), there is a need to investigate the ecosystem history over the long-term, meaning to deal with palaeoecological reconstruction (e.g. Foster *et al.* 1990, Valsecchi *et al.* 2010, Willis *et al.* 2010).

Regarding spatial scale, it is important for conservation and/or restoration, and/or general ecosystem management to assess naturalness on a fine spatial scale (i.e. stand scale). Indeed, forest management planning must be included in large spatial scale planning (i.e. from landscapes to regional scale), based on fine scale mosaic proprieties (i.e. stand scale; Spies *et al.* 2006, Pressey *et al.* 2010, Orsi *et al.* 2011). First because local scale is the resolution of the operational management action, meaning that local scale is relevant to identified current and past human impact. Secondly, the local scale is the scale of the process of patch dynamic, identified as an important natural process of forest systems dynamics (Pickett and White 1985, Roxburgh *et al.* 2004, Podlaski 2008). Therefore, it is important to define natural systems of reference at local scale, correlated to the current state of the considerate ecosystems.

In the range of disciplines potentially allowing to investigate vegetation history (Egan and Howell 2001), soil charcoal analysis and tree ring series analysis seems to be well complementary and suited to assess the naturalness of a forest stand. This is what we have sought to demonstrate in the case study presented here. Using those two approaches, an attempt has been made to analyse both the long- and short-term history of a forest stand in northern Germany. It has been aimed to define the reference state(s) and thus to contribute to the naturalness assessment of the investigated forest, in a perspective of forest conservation. Such an interdisciplinary approach has been rarely applied so far.

Study area

The investigation site is located in northern Central Europe, in the Westensee woodland. This woodland is situated in the northernmost federal state of Germany, Schleswig-Holstein, about 20 kilometres southwest of the city of Kiel (Fig. 1). This area, managed by a private owner, consists of a stand scale mosaic of broad-leaf forests, conifer plantations, lakes and mires, and presents a quite heterogeneous topography. The investigated forest stand (WES: 54°14'263N / 9°58'527E) presents a regular convex slope of about 40° on average, from a mire at 26 m a.s.l. the bottom of the slope, to 60 m a.s.l. at the top of the slope, reaching a plateau.

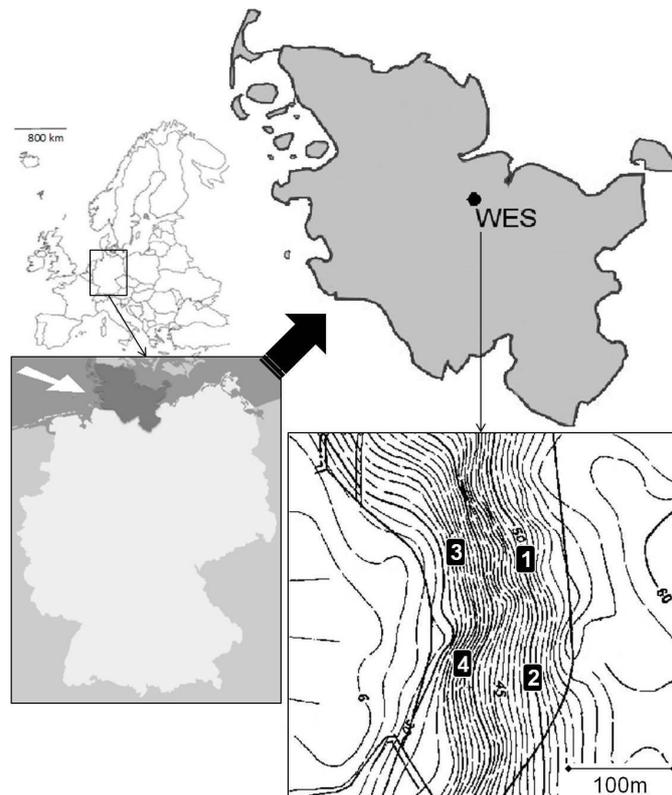


Figure 1. Map of localization of the investigated Westensee forest (WES) in Northern Central Europe, and of the four soil sampling spots (black rectangles containing numbers).

The on-site substratum consists of coarse morainic deposits from the last glacial phase. In the late maximum glacial period, the eastern part of the Schleswig-Holstein, along the Baltic Sea, was covered by ice-sheet, which shaped the current topography and deposited sandy sediments forming the current substratum material (Nelle and Dörfler 2008).

The investigation area is localized in the oceanic, temperate, broad-leaf forest domain, with an annual mean temperature of 8.5°C (warmest monthly mean temperature of 16.3°C in July; coldest monthly mean temperature of 0.7°C in January; Kiel-Holtenau meteorological station; mean period 1961-1990, Deutscher Wetterdienst 2011) and an annual mean rainfall of 807 mm (highest monthly mean rainfall of 85 mm in November; lowest monthly mean rainfall of 44 mm in February; Westensee meteorological station, mean period 1961-1990, Deutscher Wetterdienst 2011).

The main forest stand features are presented in Table 1. The investigated forest stand presents a very simple vertical and horizon structure, with a mature, high and homogeneous forest population of beech trees (*Fagus sylvatica* L.), and without any understory or scrub vegetation. Only a forest regeneration level is observable under the even-aged *Fagus sylvatica* dominant level. The trees have close stem dimensions (in diameter and height), are regularly spatially distributed.

► Stand structure	density (n/ha)	basal area (m ² /ha)	mean ddb (cm)	height (m)	CE
<i>Fagus sylvatica</i>	66	20	67	32	2.52
► Regeneration (n/ha)	seedling		sapling		
<i>Fagus sylvatica</i>	1600		94		
<i>Acer pseudoplatanus</i>	400		0		
<i>Sorbus aucuparia</i>	100		0		
tot	2100		94		
► Dead wood (m ³ /ha)					
Decay state	1	2	3	4	5
<i>Fagus sylvatica</i>	1.05	3.21	0.51	0	0
indet.	1.59	2.34	0.94	1.04	0
tot	2.64	5.55	1.45	1.04	0
Piece type	lying	standing	stumps	tot	
<i>Fagus sylvatica</i>	4.31	0	0.46	4.77	
indet.	1.13	0	4.78	5.91	
tot	5.44	0	5.24	10.68	

Table 1. Westensee features of forest stand investigated.

The area, at stand scale, will be subject to biological conservation. No more forest management activities will take place on-site in the future (Hedemann, personal communication). This makes the on-site assessment of naturalness even more important and justified. However, the influence of recent management is still visible (e.g. dead wood and stumps remaining from harvesting two to five years ago).

Methods

Soil charcoal analysis

The quantification and the taxonomical analysis of charcoal assemblages extracted from soil samples, combined with radiocarbon dating and soil characterization, allows to reconstruct the occurrences of past fire events and the correlated burnt wooden species composition, at local scale (Carcaillet and Thinon 1996, Robin *et al.* 2011). The local resolution of macro-charcoal records (i.e. charcoal pieces greater than 100/200 μm are deposited and buried in the soil at forest stand scale, ca. 10 to 100 m²) has been illustrated by several studies (Clark 1988, Scott *et al.* 2000, Whitlock and Larsen 2001). Moreover, in the case of soil charcoal records, the charcoal pieces analyzed as palaeo-signals must have a minimal size of ca. 1 mm, to allow charcoal taxonomical analysis. Therefore, soil charcoal records have a high spatial resolution. However, charcoals are possibly transported with eroded soil material, in which they might be embedded. Nevertheless, such transport occurs in the catchment area (Bork and

Lang 2003), meaning, for example, from the top to the bottom of a slope. Taking into account the high spatial resolution of charcoal records and the possible heterogeneity of charcoal recording within the catchment area, a multi-sampling strategy was applied (Touflan *et al.* 2010). Four soil profiles were dug at equivalent distance of ca. 100 m (Fig. 1). Soil samples of ca. 10 l were taken from the bottom to the soil surface, per sampling layer at a maximum depth of 10 cm each, allowing a relatively fine resolution of sampling along the depth to be maintained, no matter what the height of the soil horizon. The soil samples were named from the surface to the profile bottom using upper case letters in alphabetic order, from A.

In the laboratory, charcoal assemblages were extracted from soil samples by floating, sieving and sorting (Carcaillet and Thinon 1996, Talon *et al.* 1998). The soil charcoal richness is expressed in soil charcoal concentration (i.e. dry weight of charcoal in mg, per dry weight of sampled earth in kg; mg.kg^{-1} ; Talon 2010), per profile and layer of sampling. The taxonomical analysis was done for a maximum of 90 charcoal pieces (indeterminate charcoal pieces not included) per layer of sampling. To avoid bias due to possible viability in the fragmentation of the charcoal pieces, depending on the type of anatomical structure and/or state of conservation, those 90 analyzed pieces were randomly selected and equitably shared in three classes of size: 1-2, 2-5, >5mm. Taxonomic identification was done with a stereo lens (x7,5 – 112,5) and an incident light microscope (x100, x200, x500), according to the wood anatomical features based on a charcoal reference collection (Palaeoecology working group, Institute for Ecosystem Research, University of Kiel) and wood anatomical atlases (Jacquot *et al.* 1973, Schweingruber 1990a, Schweingruber 1990b). The quantification of the identified wood taxa was done by relating the total taxon charcoal amount to the sample weight, which gives the charcoal concentration in mg.kg^{-1} (Talon 2010).

To characterize the sampled soil profiles, field soil profile description (i.e. skeleton pattern, roots distribution, identification of obvious soil stratigraphic disturbance, etc.), and laboratory analysis of soil samples of ca. 500 g were done (Reiss *et al.* 2006, Emadodin *et al.* 2010). For each sampled soil horizon, the pH value and organic matter content was measured. Grain size proportion for the coarse (i.e. > 2 mm) and fine (i.e. < 2 mm) soil fraction was done by particle laser scanning (Malvern Instruments Limited 2005). The soil description follows the “German soil nomenclature” (Sponagel *et al.* 2005).

Tree ring series analysis

The assessment of growing patterns of the living tree population permits one to identify dynamic trends of the forest stand, especially canopy structure changes events, which

constitute a change in the competition (Schweingruber 1996, Kipfmueller and Swetnam 2001). Tree ring series from 15 dominant trees, randomly selected at the site, were analyzed. The set of tree ring series provides a sufficiently robust data set since changes in canopy structure are well recorded in dominant trees (Nowacki and Abrams 1997). To obtain a robust chronology per individual tree, two ring series were analyzed for each tree.

Two radii per each selected tree were cored with a Pressler drill, in a perpendicular position at ca. 50 cm high. After drying under a press, each single radius was polished with sand paper in the laboratory to make the rings boundaries clearly visible. The counting and width measurement of the ring series was done using a LINTAB 6 measurement table (Rinntech), at 1/100 mm units under a stereo lens (magnification x32 to x63).

To build the trees' chronology, the radii couple per tree were cross-dated to identify the best matching position. This was done by eyes using the Cross-Dating-Index (i.e. CDI) of the Time Series Analysis and Presentation program (TSAPwin 0.53, Rinn 2003). Once the best matching position of the ring couple series for each tree had been identified, the series were averaged, providing the individual tree chronology. To obtain the site chronology, the tree chronologies were averaged by the same methods, after cross-dating the tree chronologies.

The growing patterns in high frequency were obtained by identifying annual growth anomalies, such as "pointer years", after standardization of the tree ring series, which permits one to skip the physiological "age tree effect" on the annual radial increment (Schweingruber 1996, Frankenstein *et al.* 2005). By averaging those standardized tree ring series, the standardized site chronology was obtained. Those standardizations were made following a two-step process (Cropper 1979, Bijak 2007, Neuwirth *et al.* 2007). First, every measured ring width is transformed into the ratio value between each annual ring width and the growth mean on a temporal window of 11 years (i.e. five years before and five years after the annual ring). Secondly, the transformed value of every ring is normalized. Then, by comparing the standardized annual ring values to threshold values, "pointer years" could be identified that correspond to years with a radial growth signal response to an abrupt change in growing condition, and especially to climatic variability. The latter factor greatly contributes to annual growth variations (i.e. high frequency signal; Schweingruber 1996, Tardif and Conciatori 2006). Following Neuwirth *et al.* (2007), if the annual ring values are more than the threshold value of 1, 1.28 and 1.64, the annual ring values can be defined as receptively "weak", "strong" or "extreme" pointer years. Such method of standardization and change detection in the growing pattern, in high frequency, enables to obtain results comparable (e.g. pointer years) to the growth change calculation in the mid-frequency resolution, presented below.

Additional statistical indicators, like autocorrelation and mean sensitivity, were used to assess the stand's growing sensitivity to climate variability in high frequency (Schweingruber 1996, Haneca *et al.* 2005).

The identification of growing pattern and the quantification of growth change on mid-frequency, to detect release event(s), was done based on running mean methods (Nowacki and Abrams 1997). However, it used median values of ring width, instead of mean values, since the median parameter is more relevant when dealing with biological data distribution (Rubino and McCarthy 2004). Nevertheless, the same calculation setting has been used as with running mean methods (Nowacki and Abrams 1997, Black and Abrams 2003, Black and Abrams 2005). The growth change proportions were calculated on 10-year windows (i.e. prior and subsequent). This is the duration that is most commonly used in the literature for *Fagus* trees (Rubino and McCarthy 2004). The release event(s) correspond to the growth changes with a proportion in excess of certain threshold values, depending on the variable parameters, and especially on the autecology of the investigated tree species (Nowacki and Abrams 1997, Black and Abrams 2003). Based on literature and on the fact that *Fagus sylvatica* is a shade-tolerant species, therefore reacting vigorously to canopy change (Black and Abrams 2003), it is assumed that the trees' growth reaction to the occurrence(s) of release event(s) would be sufficiently intensive to be detected with quartile proportion as threshold values.

Both previously described methods of tree ring series analysis are based on values calculated by running windows of comparable duration, but differing on this following aspect: the high frequency signal analysis compare annual ring values to "windows values", while and mid-frequency signal analysis compare "windows values" to "windows values". Therefore, by comparing growth patterns obtained from the two resolution of analysis, an attempt has been made to identify environmental (i.e. mid-frequency) or climatic (i.e. high frequency) determinism for the detected growth change.

Results

Soil charcoal analysis

168 kg of soil were sampled in four profiles from which a total of 15.1 g of charcoal (greater than 1 mm) were extracted. Charcoal pieces have been found in all of the layers of sampling in the four sampled soil profiles. The total soil charcoal concentration shows a considerable variation between the profiles (Fig 2.). WES2 presents the largest soil charcoal concentration, while WES3 presents the smallest, with about one sixth as much charcoal per kg of soil.

Regarding the vertical distribution of the charcoal records, no common patterns are identifiable within and between soil profiles. However, it can be noted that there is a smaller soil charcoal concentration in the deepest soil horizon identified in all the soil profiles.

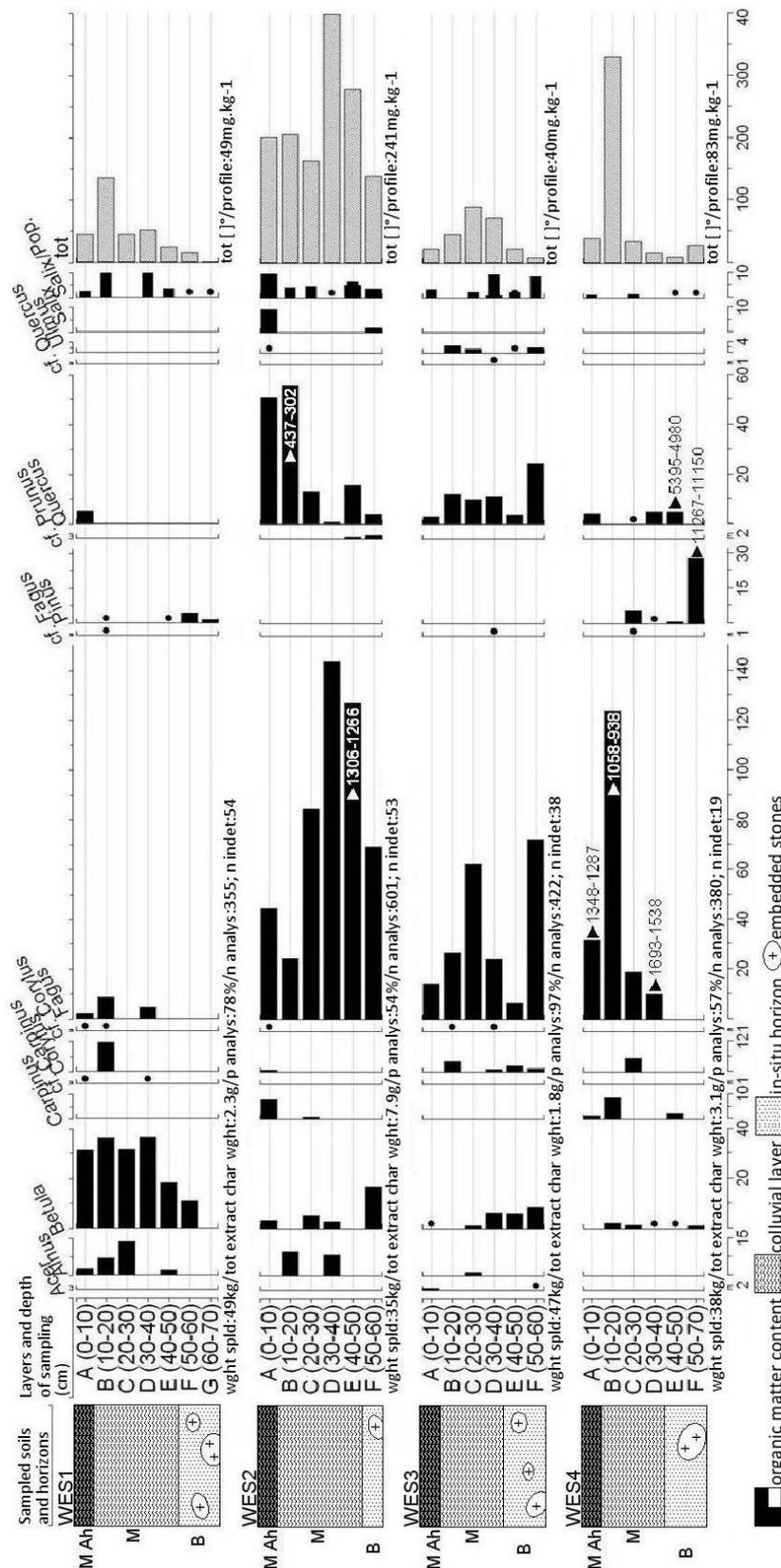


Figure 2. Westensee soil charcoal concentration (in mg.kg⁻¹; x-axis below) per identified taxa (x-axis above) in soil charcoal assemblages of the soil profiles WES1 to WES4. Soil horizons, layers of sampling and analyzed charcoal assemblages are described on the y-axis. wght spld: weight of soil sample / tot extract char wght: weight of the total amount of extracted charcoal pieces from the profile/p analys: weight proportion of the total amount of extracted charcoal pieces per profiles / n analys: number of charcoal pieces analyzed per profiles; n indet: number of indeterminate charcoal pieces analyzed per profiles. ● : charcoal concentration < 1 mg.kg⁻¹; ▲ : radiocarbon dates in calibrated BP (2σ interval); right column, grey stripes: total soil charcoal concentration per layer of sampling.

From the bottoms of the profiles to ca. 50/40 cm, an in-situ formed mineral soil horizon developed (i.e. B horizon). This horizon presents a more compact structure and yellowish aspect than the upper horizon, which presents a more brownish color, a less compact structure, a particular aggregate shape, and more organic matter (Table 2). This soil horizon corresponds to a colluvial layer (i.e. M horizon) on each soil profile, up to ca. 40/50 cm. In the upper ca. 10 cm of this colluvial layer, an organic layer that is rich in humic matter developed (i.e. Ah horizon). The sampling layers of the colluvial horizon present a globally higher soil charcoal concentration. Nevertheless, according to the overall charcoal concentration of the layer of sampling, the charcoal vertical distribution is variable within the colluvisol (Fig. 2). The texture of the soil profiles is dominated by sandy material, corresponding to the sediment from Weichselian glaciation's morainic deposits (Table 2).

profile	soil layer	depth (cm)	ph H ₂ O	grain size %					OM %
				> 5 mm	5-2 mm	sand	slit	clay	
WES1	M Ah	A 0-10	3,9	3,2	5,3	66,2	24,3	1	1,2
	M	B 10-20	4,6	1,4	4,9	52	39,1	2,7	0,6
		C 20-30							
		D 30-40							
		E 40-50							
	B	F 50-60	4,3	6,4	4,6	67,4	19,1	2,5	0,5
		G 60-70							
WES2	M Ah	A 0-10	4,5	2,2	3,6	43,6	46,4	4,1	2,8
	M	B 10-20	4,3	1,6	9,7	41	38,6	9,1	0,7
		C 20-30							
		D 30-40							
		E 40-50							
	B	F 50-60	4,7	6,5	19,7	23,2	43,3	7,4	0,5
WES3	M Ah	A 0-10	3,2	2,6	3,1	55	34,7	4,6	3,4
	M	B 10-20	4,1	9,6	3,1	33,5	47,4	6,4	0,9
		C 20-30							
		D 30-40							
	B	E 40-50	4,3	5,6	5	55,5	30,3	3,5	0,7
F 50-70									
WES4	M Ah	A 0-10	3,9	2,9	7,5	48,9	34,6	6,1	1,7
	M	B 10-20	4,3	2,4	10,1	42,4	38,3	6,8	1,8
		C 20-30							
		D 30-40							
	B	E 40-50	4,5	1,5	18,4	31,2	42,5	6,4	0,6
F 50-70									

Table 2. Westensee soil features of the sampled soil profiles.

To obtain taxonomical information, a total of 1758 charcoal pieces were analyzed. From this charcoal amount, a total of 164 pieces were not taxonomically identifiable, because they were too dirty or too distorted (Théry-Parisot 2001, McParland *et al.* 2010). Since those indeterminate charcoal pieces are providing no information for the past forest reconstruction, they were not included in the presentation of the taxonomical results (Fig. 2). However, these charcoal pieces are included in the analysis of the total charcoal amount.

Overall, 10 different taxa were identified. Additionally, groups of uncertain anatomical identification, like cf. *Prunus*, and *Salix/Populus*, were used.

Fagus is the most common and regularly identified taxon in the soil charcoal assemblage, except in the soil profiles WES1, where the dominant taxon is *Betula*. Birch is also regularly identified in various amounts in the assemblages of the other soil profiles. *Quercus* is also regularly present, especially in WES2 and WES3. *Salix* and *Salix/Populus* occur regularly, but in small concentrations. Other taxa are present infrequently and in small amounts (e.g. *Ulmus*). Among those, it is especially interesting to notice the presence of *Pinus* charcoal pieces, which are especially important in the four deepest layers of WES4. Above these layers, *Fagus* is clearly predominant (Fig. 2). Radiocarbon dating of single charcoals from WES4 indicates a Preboreal date for a *Pinus* charcoal (i.e. 11267-11150 yrs cal BP; Table 3), a mid-Holocene date for a *Quercus* charcoal (i.e. 5395-4980 yrs cal BP), and three late Holocene dates for *Fagus* charcoal pieces (i.e. 1693-1538, 1348-1287, and 1058-938 yrs cal BP). Two more late Holocene dates have been obtained from the soil charcoal assemblages of the soil profile WES2 with one date of *Fagus* at 1306-1266 yrs cal BP and one date of *Quercus* at 437-302 yrs cal BP.

Reference	Site / Layer of sampling	Depth (cm)	Taxa	Age conv BP	Age cal BP	Age cal AD
KIA43761	WES2/B	15	<i>Quercus</i>	305 ± 20	437-302	1513-1648 AD
KIA43760	WES2/E	45	<i>Fagus</i>	1355 ± 20	1306-1266	645-685 AD
KIA42905	WES4/A	5	<i>Fagus</i>	1405 ± 25	1348-1287	603-663 AD
KIA42906	WES4/B	15	<i>Fagus</i>	1090 ± 25	1058-938	893-1013 AD
KIA42907	WES4/D	35	<i>Fagus</i>	1695 ± 25	1693-1538	257-413 AD
KIA42908	WES4/E	45	<i>Quercus</i>	4485 ± 35	5395-4980	BC 3346-3031
KIA42909	WES4/F	55	<i>Pinus</i>	9790 ± 45	11267-11150	BC 9318-9201

Table 3. AMS-14C dates from single charcoal pieces soil charcoal assemblages of WES. Dated by the Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research - University of Kiel, Germany. Calibration in BP and BC/AC done at 2 σ confidence interval, based on the IntCal09 dataset.

Tree ring series analysis

The site chronology, based on the averaging of the 15 tree ring series, provides a span of 216 years, from 2010 back to 1795 (Fig. 3). The period of the site chronology which is covered by all the 15 cored trees is of 140 years. The oldest 12 years (1795-1807) are only covered by one series. The mean ring width size is of 1.49 mm. The cross-dating of trees, and at the site scale, presented satisfying results visually and based and the cross-dating-index (Rinn 2003).

Due to the window duration used for the high frequency standardization, the signal at that resolution of analysis, spans a period from 1800 to 2005 (i.e. 205 years). Overall, 43 pointer years were identified: 12 weak, 11 strong, and 20 extreme pointer years (Fig. 4). The standardization in high frequency allows to observe the initial phases with relatively small and homogenous ring width variations, compared to the following phase, from 1832 to 1853, which presents larger amplitude of ring width (Fig. 3).

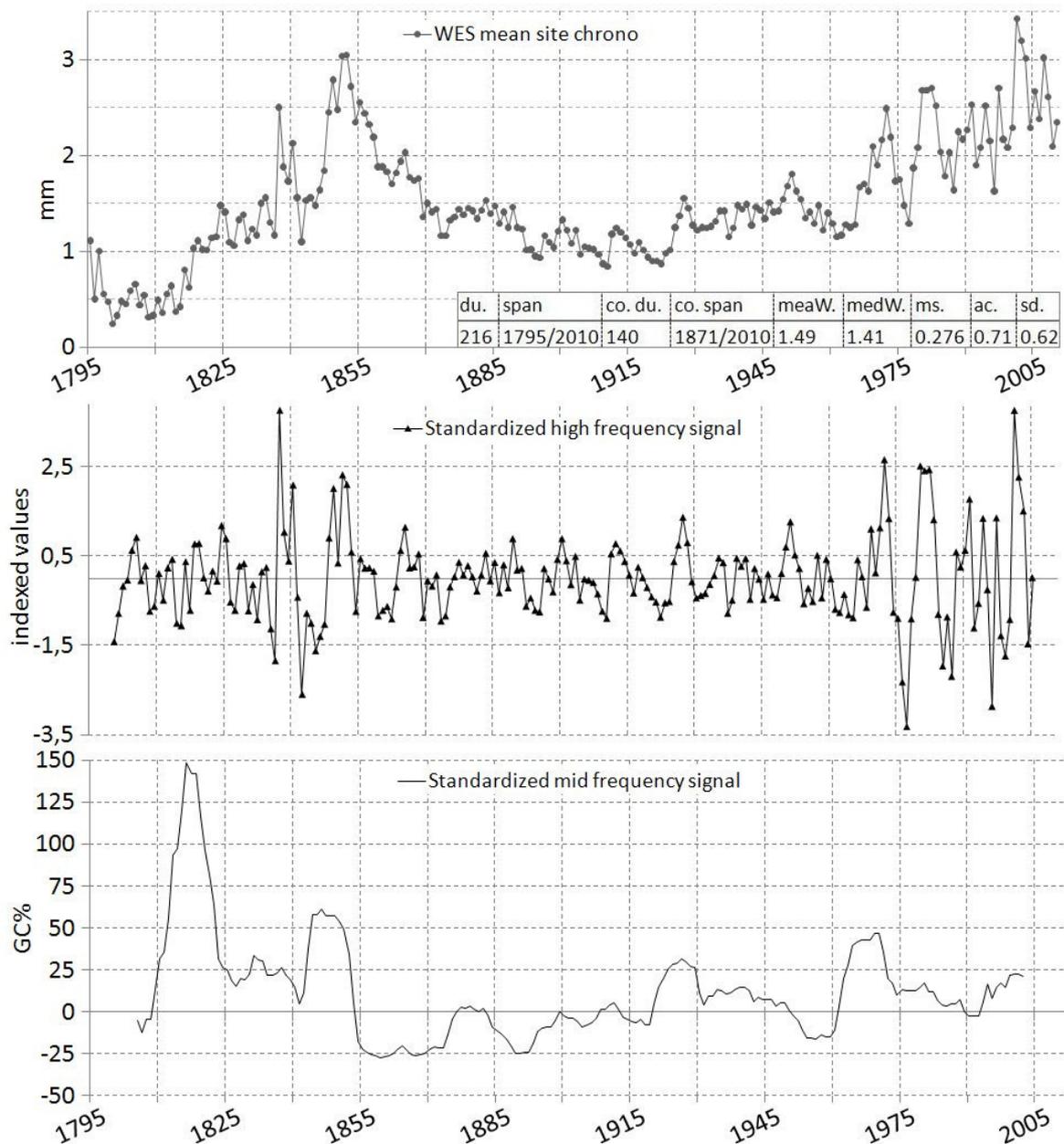


Figure 3. Westensee forest stand measured (in mm) and standardized (no unit) chronologies. Statically indicator of the measured chronology on the central table [du.: duration; co. cu.: common duration; co. span: common span; meaW: mean ring width; medW.: median ring width; ms.: mean sensitivity; sd.: standard deviation; ac.: autocorrelation order 1].

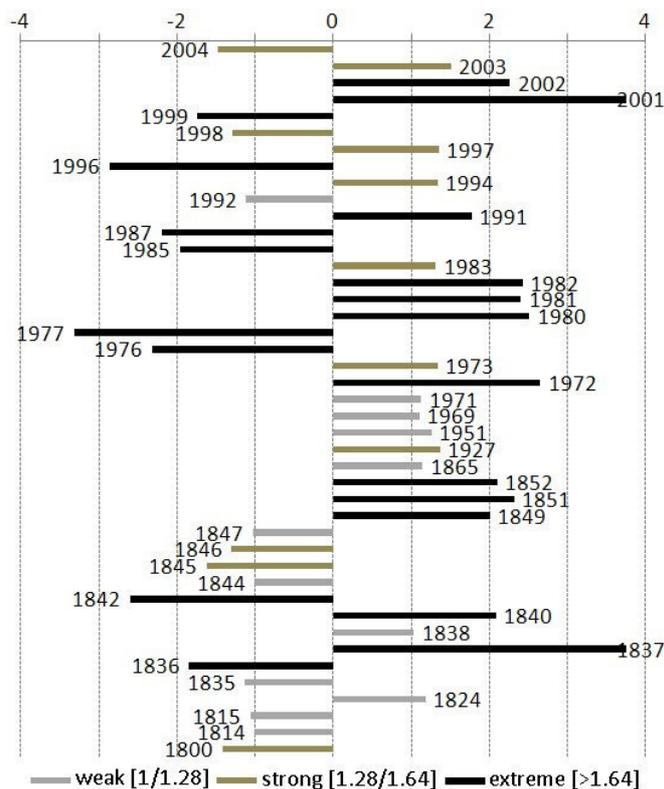


Figure 4. Westensee pointer years detected.

This second phase presents several identified pointer years, with “weak,” “strong” or “extreme” intensities (Fig. 4). Since 1855, the high frequency signal shows globally a more homogenous and stable pattern, with less amplitude in the year-to-year variations of ring width, equivalent to the first phase of the tree ring signal. During this phase, only two “weak” pointer years (1865 and 1951) and only one “strong” pointer years were detected (1927; Fig. 4). Then, from 1969 to the end of the chronology (i.e. 2005), the high frequency signal again presents large amplitudes of ring width yearly variation, equivalent to the second phase of the growth patterns previously described. This more recent growth phase presents many pointer years, with “weak”, “strong” or “extreme” intensities. Moreover, both, autocorrelation of 1st order and mean sensitivities present relatively high values (Fig. 3).

The mid frequency signal shows a variable growth change pattern. The period covered by this signal resolution of analysis spans from 1804 to 2001 (i.e. 197 years). On that period it has been identified 45 release events: 27 in the second quartile (25 to 50% of growth change), 9 in the third quartile (50 to 75% of GC), 4 in the fourth quartile (75 to 50% of GC), and 5 in excess of 100 % of GC (Fig. 5). The first phases of growth change, presenting intensive release events (i.e., over “five quartiles”), occurred from 1809 to 1824. From 1842 to 1851, a second phase of growth change occurred, with weaker release events, but still significant. Then, from 1992, the growth change pattern in mid-frequency indicates very small (or negative) proportion of change. Only two more phases with significant release events are

observable. One spans 1922 to 1928, and a second one spans 1962 to 1970. Those phases present relatively small proportion of growth change (i.e. no more than the second quartile of growing change proportion), in a relatively short span.

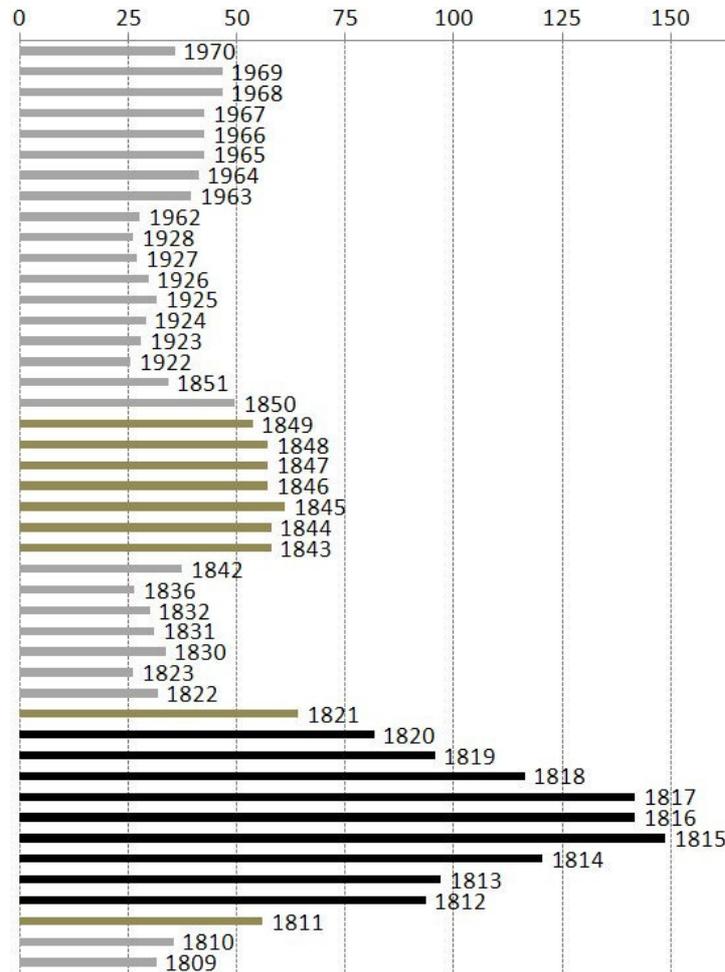


Figure 5. Westensee release event detected, based on the proportion of growth changes in 10 year-temporal windows.

Discussion

Important amounts of charcoal have been extracted from each layer of sampling of each soil profile, in comparison to investigations in others areas (e.g. Touflan et al. 2010; Robin et al. 2011). Considering, moreover, the old radiocarbon dates obtained from the few charcoal pieces and the absence of topographical feature that correspond to the site of charcoal production (i.e. kilns), it is assumed that these on-site charcoal records indicate the past occurrences of forest fire.

The taxonomical analysis provides information about the burnt forest trees. Even if *Fagus* charcoals dominate the assemblages, the taxa diversity provides a species spectrum that is comparable to other palaeoecological records concerning northern Germany (Wiethold 1998,

Rickert 2006, Nelle and Dörfler 2008, Bos 2010). *Pinus*, *Salix*, and *Betula*, species that dominated the late Pleistocene – early Holocene woodland composition, are present and are dated in the on-site formed B soil horizon of WES4 (Fig. 2, Table 3). A comparable taxonomic indication can be observed in all soil profiles. There is a shift in charcoal amount and taxonomical spectrum from the B soil horizon, at the bottom of the soil profiles, to the colluvial layer, above the B horizon, to the soil surface in the four soil profiles. Based on these observations, the radiocarbon date from WES4F (Fig. 2), and soil horizon properties (Table 2), one can postulate that the soil horizon B is an on-site formed horizon from, at least, the late Pleistocene – early Holocene period. Therefore, it is assumed that the forest recorded in the soil charcoal assemblages from soil horizon B corresponds to the pioneer stages of the forest established during postglacial times. During this period, it is assumed that human impact on the natural forest dynamic, if existing, was weak. In the area of investigation, no evidence for human presence older than the Neolithic has been found. The occurrence of a fire event during this period has been discussed in macro-scale synthesis about long-term fire history, indicating fire activity during the early Holocene (Carcaillet *et al.* 2002, Power *et al.* 2008), even if long-term fire regime and determinism in Central Europe is not well documented (Tinner *et al.* 2005). The occurrence of such fire event(s) in that period and for such type of “flammable” forest is usually interpreted as being under natural control (i.e. climatic forcing; Carcaillet *et al.* 2007, Olsson *et al.* 2009). However, occurrences of fire under human control have been illustrated also involving the early Holocene period (Mason 2000, Moore 2000). Therefore, man-made fire also in that period cannot be entirely excluded. According to the previous hypothesis, the presence of *Fagus* charcoal pieces in the on-site formed B soil horizon is difficult to interpret since this species became established much later during the Holocene period than the age postulated for this soil horizon (Magri *et al.* 2006, Tinner and Lotter 2006). The disturbance of the soil stratigraphy, mixing charcoal pieces assemblages from upper layers (i.e. from the colluvial layer) may explain such a charcoal taxonomical record (Jégou *et al.* 1998, Carcaillet 2001, Šamonil *et al.* 2010).

Nevertheless, the “late Pleistocene – early Holocene phase” of natural forest dynamics seems to last at least to the Subboreal, as the increasing occurrences of *Quercus* charcoal, also with *Ulmus*, *Salix*, etc., indicate. Such forest composition fits the “*Quercus* forest type” of the Atlantic period (Behre *et al.* 1996, Wiethold 1998, Nelle and Dörfler 2008), with moreover, one *Quercus* charcoal piece dated from 5,395-4,980 yr cal BP (Fig. 2). Similar taxonomical assemblages have been identified from the colluvial layer, just above the B soil horizon. This indicates that the erosion and sediment accumulation probably started on site at the end of the

Neolithic. This is supported by the important soil charcoal concentration of the “*Quercus* and *Fagus* forest type” in the colluvial layer charcoal assemblages (Fig. 2). Chronological information indicates that such forest type was burned during the late Holocene (Table 2), and the forest cover removed, at least at the stand scale, inducing post fire erosive process (Leopold and Völkel 2007, Emadodin *et al.* 2010). It is postulated that this last Holocene erosion and fire phase occurred under human control. Indeed, the identified burned temperate broadleaf forest is supposed to be less flammable than the “Pleistocene - early Holocene forest type,” presenting a less moist condition that would not burn without human ignition. Consequently, it is assumed that those late Holocene fire occurrences are due to human activities, as has been discussed concerning Central Europe for this period (e.g. Goldammer and Page 2000).

So, the naturalness level of the investigated site decreased significantly during late Holocene, with a forest dynamic that was probably strongly influenced by human activities. However, such human impact seems to have occurred through successive phases of deforestation/forestation, as indicated by the charcoal records that indicate light-demanding species, like *Acer*, *Betula*, *Salix*, and *Corylus*, but also shade-tolerant species like *Carpinus* and *Fagus* (Fig. 2). The last, *Fagus*, is currently the only on-site, dominating, species.

Looking at the vegetation history on the relatively short temporal scale of the two last centuries that are provided by the tree ring series, different phases of growth change have been identified from the various resolution of signal analysis. Both high and mid-frequency signals present various patterns of growth changes (Fig. 3). Based on the assumption that the high-frequency signal is more related to climatic variability, and the mid-frequency signal is more related to environmental variability (Schweingruber 1996). To compare synchronies and asynchronies of the growth patterns in high and mid-frequency would provides an indication of the occurrences of growth condition changes and related determinism.

From 1800 to 1832, only a few events of weak growth change have been recorded in the high frequency signal, indicating relatively a “stable” condition in terms of climatic variability. While, the mid-frequency signal indicates growth change phases, beginning in 1809, with several significant release events, until 1824 (Fig. 5). This could be the recording of changes in the canopy structure, increasing the light availability due to canopy opening, or inducing a fast and vigorous “growth response” of the on-site *Fagus* stems. Indeed, *Fagus sylvatica*, as a shade tolerant species, reacts much vigorously to canopy opening (Black and Abrams 2003). Before this environmental change, those *Fagus sylvatica* stems were probably understory on-site, as in a juvenile growth phase. This is supported by the regular increase in the ring width

on the mean site chronology during this phase (Fig. 3). The identified canopy opening might be due to various parameters, including influences of climatic control on the growth variation, as the high-frequency signal seems to indicate. This is supported by the values of the autocorrelation of 1st order and the mean sensitivity, from the overall temporal span of the analysed tree ring series (i.e. Fig. 3).

From 1832 to 1853, a phase of large amplitude, high-frequency signal variability starts, with the identification of several extreme pointer years (Fig. 4). This important year-to-year variability is probably due to micro-climatic condition change that is related to the previously identified canopy opening. Indeed, a change of the forest cover induces change of the on-site environment features and the micro-climatic parameters as well (e.g. stand temperature, moisture, etc.). In parallel with this phase of climatic susceptibility, a phase of significant growth change, which is indicated by the mid frequency signal, occurred from 1842 to 1851. This could correspond to a phase with high level of stems competition, when juvenile stems reach to the dominating level. From about 1854 on, the tree ring series analysis show a more homogenous, “stable” condition of growth, probably indicating a more “mature” state of the forest history. This phase seems to correspond to the biostatic phase, the “optimal” growth phase (Gilg 2004). While few and relatively weak, but significant, growth changes were detected. A strong pointer year was identified in 1927. This is synchronous to a release phase. Therefore, this phase is probably related to an abrupt climatic variation. Other, asynchronous, growth changes may be indications of the occurrence of sporadic disturbances, inducing weak, fine scale, canopy opening and severe abrupt climatic variability. The determinism of those small growth changes cannot precisely assess, either human impact (e.g. thinning) or natural factors (e.g. insect attack) can be explicative parameters. From 1962, a new phase of growth change began. It was indicated by a mid-frequency signal, therefore probably indicating environmental change (Fig. 3), like a new phase of canopy opening. This phase was followed from 1969 on by a phase with a large amplitude variability of the high-frequency signal, correlated to an increase in the width of the rings width of the mean site chronology. Those observations seem to indicate that the forest stand tree population reached the “aging or “degradation” phase (Gilg 2004). Indeed, it seems that competition processes in a mature forest stand are less intensive that during younger stages. Therefore, the mature *Fagus* stems on the forest stand are slowly reacting somewhat to the environmental changes, indicated first by the mid-frequency signal, while climatic variation began as an important growth-influencing event. With regards to these last growth change phases, it is postulates that human impact was the main determinant. Indeed, in regarding the overall two-century

growth patterns of the *Fagus* stems population, human management of the area to produce, in the end, large dimension *Fagus* stems seems to were the main environmental dynamic driving factor. This is supported by the field observation of freshly harvested trees stems of large dimensions.

Therefore, despite the fact that natural competition has been postulated for a growth changes phase, with also influences of climate variability, it is assumed that the growth history of the stand *Fagus* stems was mainly under human control and that the current state of the forest stand therefore presents a low naturalness level. Such a history of forest dynamic under human control also explains the simple present state of the structure and composition. While compared to long-term species composition, soil charcoal records have been identified a much diverse species composition than currently. However, even on a long temporal scale (since the late Holocene), on-site human impact has been also indentified. It has been postulated that man-made fire, inducing soil erosion, was responsible for the forest stand opening.

Conclusions

The combination of long-term and short-term vegetation history, on a comparable spatial scale, provides an interesting insight to the naturalness assessment. The ancient and natural stage of dynamic pioneer forest has been identified based on soil charcoal analysis. Then, a phase of strong forest opening, inducing soil erosion, probably related to man-made fire, occurred since, at least, the late Holocene period. During the two last centuries, the established and dominated *Fagus* forest seems to have been driven by human management, for wood usage purposes. Based on these observations, the low naturalness level of the investigated forest stand, from a vegetation history point of view, was revealed.

Aiming to conserve, and even to restore, the natural state of the forest stand, would involve a plan to promote and, at least, protect factors of heterogeneity of the forest stand. Forest management should favour the establishment and growth of the current, on-site, forest regeneration with light-demanding species, such as *Acer* and *Sorbus* seedlings (Table 1). This would increase the diversity of tree species and vertical heterogeneity of the stand. This intervention can be managed by first increasing progressively the opening of the stand forest canopy. Few stems with large crown would be harvested. Moreover, the harvested stems should be left on-site, to increase the dead wood volume, increasing the micro-habitat for adapted organisms.

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5.2 Characterization of forest stands features and history, on long- and short-term scales, contributing to the nature conservation/restoration planning: an illustration case in Northern Germany

Introduction

In Central Europe the current forest areas are in a considerably “degraded” stage compared to pristine forest areas (Larsen 1995), which are rare nowadays and restricted in area (Parviainen 2005, Reif and Walentowski 2008). Therefore, for patrimonial and biological conservation purposes, protected forest areas are of important interest (Ehrlich 1996, Keulartz 2009, Pressey *et al.* 2010). The human impact has been identified as one of the major factor of “degradation”, notably because of use of forest resources. Such human impact has been documented on a long temporal scale, since at least the Neolithic period, and has increased in intensity with human cultural development (Kalis *et al.* 2003, Berglund 2011). Therefore, for conservation and/or restoration planning, it is necessary to take into consideration the long-term historical perspective of the ecosystems (Egan and Howell 2001). It is crucial to define “reference states” to assess the current state of ecosystems (White and Walker 1997). To do this, it is necessary to combine long-term, dealing with previous trees population (i.e. millennium scale), and short-term investigation, dealing with living forest tree population (i.e. centuries scale), in regards to the current state of the forest stand, and in comparable spatial scales (i.e. stand scale). Within the range of approaches regarding vegetation history, or palaeoecological approaches, the combination of tree ring series analysis and soil charcoal analysis seems to be quite relevant and reliable for investigation of short- and long-term forest history connected to the forest stand characterization, thanks notably to comparable spatial resolution of their data (Carcaillet and Thimon 1996, Kipfmüller and Swetnam 2001). This is what we illustrate in this paper.

Using those approaches, we investigated both long- and short-term forest history on two forest stand plots in the protected forest area of the Riesewohld forest, in northern Central Europe. This forest area presents the benefit of having a rich patrimonial and biological value, notably due to a continued forest presence for several centuries (Arnold and Denker 2007).

We compiled and compared data sets from forest stand characterization, tree ring series measurement and soil charcoal analysis to assess the current state of the forest stand, in regards to the occurrences of changes, and consequences, in short- and long-term, at comparable spatial scale. Moreover, this work illustrates how such interdisciplinary approach

might be relevant and useful in defining a reference forest state and how that might contribute to conservation and/or restoration planning.

Material and Methods

Study area

The Riesewohld forest is situated the western part of the northernmost federal state of Germany, Schleswig-Holstein, in the northern European lowlands (Fig. 1). This investigation area is localized in the temperate broadleaf forest domain, under oceanic climate, with a mean annual rainfall of 930 mm (maximum mean month rainfall of 98 mm in November and a minimum of 46 mm in February) and a mean annual temperature of 8.3°C (a mean warmest monthly temperature of 16.1°C in July and a mean coldest monthly temperature of 0.4°C on January; Albersdorf meteorological station; Deutscher Wetterdienst 2011). The natural vegetation of the area is defined as the Atlantic/Subatlantic *Deschampsia flexuosa*-(*Quercus* spp.-) *Fagus sylvatica* forests, with transitions and combination with *Betula-Quercus* forests (Bohn *et al.* 2000, Dierssen 2004). The substratum consists of Pleistocene sand deposits (i.e. old moraine deposit during the Saalian, 130 – 200 ka yrs), and consequently the soils are basically sandy soils.

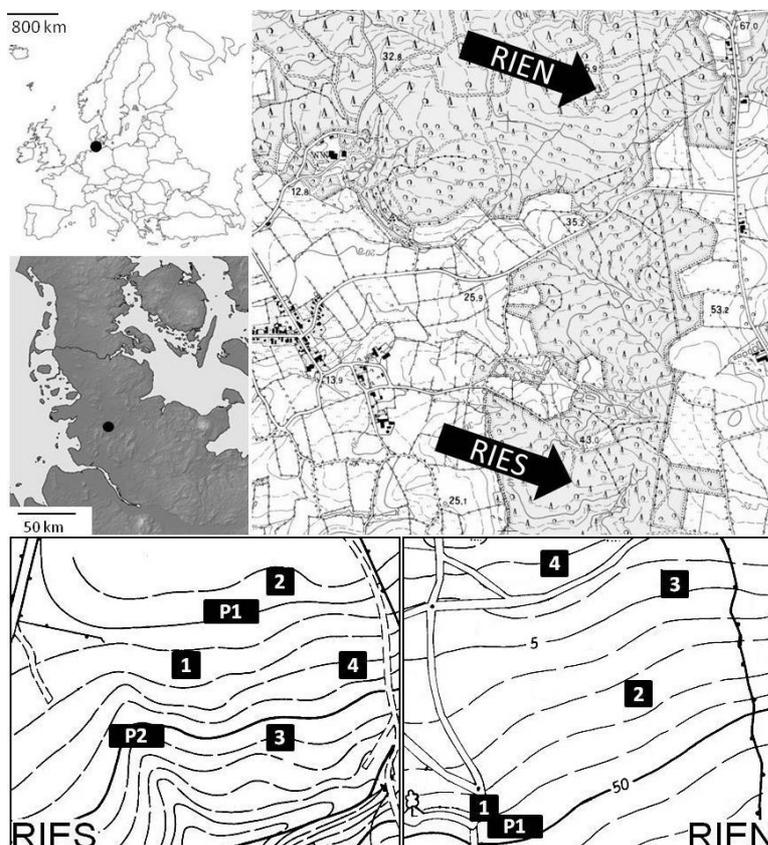


Figure 1. Riesewohld forest localization maps at the European, federal state scales (Schleswig-Holstein), map of localization of the two investigation sites, RIEN and RIES, in the Riesewohld forest, and topographical maps of the investigation sites, with the localization of the soil samples (black squares).

In the federal state of Schleswig-Holstein, the total forested surface represents about 10 % of the total land surface (Statistikamt Nord 2010) and, whatever the statue of protection, only few forest areas are nature conservation areas. The Riesewohld forest includes protected areas that are owned by the “Stiftung Naturschutz”. The latter is a foundation that manages wetlands and woodlands for nature conservation and restoration purposes. Two investigations plots were selected, at forest stand scale, in this forest owned by the “Stiftung Naturschutz”. The plot Riesewohld North (i.e. RIEN: N54°09’01/E9°13’27, ca. 50 m a.s.l.) is situated about two km north of the plot Riesewohld South (i.e. RIES: N54°07’94/E9°13’2, from ca. 65 to ca. 49 m a.s.l.). RIEN has a homogenously flat topography, while RIES exhibits a more heterogeneous topography, with an increasing slope from north to south (ca. 8° at maximum), from a flat top slope area to an east-west oriented stream “valley” (Fig. 1).

Forest stand characterization

The measurement and sampling was done on two plots of ca. 3000 m² each (50m*60m). The data have been rounded per hectare to allow site comparison. To assess the stand structure and composition, several forest attributes have been inventoried and measured, out of the large range of existing indicators (McElhinny *et al.* 2005), following methods used by Black and Abrams (2005), and Hart and Grissino-Mayer (2008), and adapted from the ForestBIOTA protocols (2005).

The diameter distribution of the two study plots has been measured at breast height (dbh), per 5 cm class size on all living trees that were greater in diameter than 5 cm at breast height. The vertical stand structure has been characterized by inventory of stems per species and per dbh classes, in three vertical levels: (1) canopy trees (i.e. overstore trees), (2) understory trees, and (3) scrub vegetation. The stand alive trees composition (dbh > 5 cm) has been estimated based on the number of stems (abundance n/ha) and the basal area (in m²/ha).

The horizontal spatial structure of the forest trees have been assessed by calculating the Clark-Evans index (CE), derived from the measurement of the nearest-neighbour distance of forest trees (Clark and Evans 1954; Laar and Akça 2007). This index describes the tendency of forest trees to aggregate in a considered study area. A CE value below 1 indicates a clustered distribution, values around 1 indicate a random distribution, and a values greater than 1 indicates a tendency to regular spatial distribution (Pretzsch 1997, Laar and Akça 2007). Moreover, for each study plot a mapping of the horizontal tree distribution was made by diameter (dbh > 5 cm), and by species, based on the x/y coordinates along straight lines on

the ground, marking the border of the sampling plot (measured distances are rounded to the nearest 10 cm).

The forest regeneration abundance of each plot was inventoried on sub-samples of 100 m² (i.e. four circular sub-sampling plots of 25 m² each, randomly localized in the sampling plot, but distant from each other of at least the diameter of one circular sub-sampling plot) for the sapling (i.e. stems from 1 cm diameter at ground to 5 cm at breast height and the seeding (i.e. stems < 1 cm in diameter at ground level).

The dead wood is an important indicator for the assessment of the state of the forest. Therefore, its volume was inventoried at each plot (Green and Peterken 1997, Wallenius *et al.* 2010). The diameter and the length of every piece that had a diameter greater than 5 cm, including pieces lying on the ground, standing, and stumps, were measured. The degree of decay of every dead wood pieces was estimated based on five levels of wood decomposition, decreasing from 1 (i.e. “fresh dead wood”) to 5 (i.e. “powder”; Christensen *et al.* 2005, Aakala *et al.* 2008), along with the species, if determinable.

Tree ring series analysis

To investigate the vegetation history based on the growth patterns of the forest tree population of the two study plots, tree ring series were analyzed (Kipfmüller and Swetnam 2001). Those tree ring series were obtained from the 15 living dominant long lifespan trees, randomly selected. Using a Pressler drill, two radial cores per trees were sampled in the autumn of 2009, in a position perpendicular to the stem at a height of about 50 cm above the ground,. Such a sample provides a suitable data set, since the dominant trees respond significantly to a canopy opening (i.e. to changes in the competitive situation), recording those changes more visibly in rings series than understory trees (Nowacki and Abrams 1997). In the laboratory, each radius was dried under a press, and then cleaned and polished using sand-paper of 320 grain particle size (using a Metabo-Tba 1018D sanding belt machine), making the ring borders clearly visible. To obtain the growing chronology of the 15 cored trees per plot, every radial ring series was digitally measured at 1/100 mm, using the LINTAB 6 measurement table (Rinntech), and the two radii of each tree were cross-dated, by eye using a stereo lens (magnification x32 to x63) and the Cross-Dating-Index (i.e. CDI) mathematic tools of the Time Series Analysis and Presentation program (TSAPwin 0.53; Rinn 2003). This index combines two major indicators for tree ring series matching and concordance with time (i.e. the “Gleichläufigkeit” and the “t-value”; Rinn 2003). Taking into account possible missing rings and/or the presence of false rings, especially for *Fagus*

sylvatica rings series (Frankenstein *et al.* 2005, Grundmann *et al.* 2008), the tree ring series was obtained by averaging the two radii to the best identified matching position. The mean chronologies per plot were obtained by averaging the 15 tree ring series per plot, after the same cross-dating method as used for the tree ring series. To identify low and high (removing the age-related growth trend) signal frequency, the mean plot chronologies were standardized by detrending methods, using the trend/regression of the math operation of TSAPwin 0.53 (Rinn 2003, Rubino and McCarthy 2004). Simple correlation values were used to compare the mean chronology per plot, and statistical indicators (i.e. mean sensitivity and 1st order autocorrelation coefficient; Haneca *et al.* 2005), to assess the level of variability of the width of rings from year-to-year, providing information on the forest stand growth response to climatic variability in high temporal frequency (Lebourgeois *et al.* 2005). Moreover, the growth change proportion in temporal windows of 10 years was calculated, based on the measured tree ring series, providing the mid-frequency signal. The median value of ring width in the five years prior and that of the subsequent measured rings were compared to calculate the proportion of growth change (Nowacki and Abrams 1997, Rubino and McCarthy 2004).

Long-term investigation

The forest history was investigated using soil charcoal analysis. This consists of taxonomical analysis and the quantification of charcoal pieces contained in earth sample from natural soil (charcoal pieces larger than 1 mm). By combining the radiocarbon dating of some charcoal pieces with charcoal pieces taxonomical identification, based on the anatomy of the structure which was conserved by carbonization, it was possible to reconstruct the past forest composition and identify events of change correlated to the occurrences of fire (Carcaillet and Thion 1996, Fesenmyer and Christensen 2010).

Taking into consideration the fine spatial resolution of soil charcoal data (Scott *et al.* 2000, Dutoit *et al.* 2009), a multisampling strategy was applied on both plots (Touflan *et al.* 2010). Soil samples were taken on four small soil trenches, noted from RIEN/S 1 to 4, about 50 m apart (Fig. 1). In addition, one longer soil trench, with a length of 15 m and a depth of 2 m (noted RIEN/S P) was excavated on RIEN, and two on RIES, because of the particular interest which represented the in-situ gully system. Soil stratigraphy description was done in the field, after cleaning, measuring, and drawing the profiles, by identifying layers, describe structure, etc. (Bork and Lang 2003, Bork 2006). About 10 l of earth were sampled following

soil layers, with a maximum thickness per layer of sampling of 10 cm to obtain a fine resolution of the vertical distribution of the charcoal assemblages.

Wood charcoal pieces were extracted from earth samples in the laboratory by sieving and manual sorting under a stereo lens (magnification x7.5 to x112.5). The taxonomical analysis was done for a total of 90 charcoal pieces per layer of sampling, equitably balanced in the different size classes of charcoal pieces (i.e. 30 pieces from three classes: 1-2, 2-5, >5 mm). For the taxonomical identification, a microscope view of from x200 to x500 magnification was used, with comparison to a reference collection of carbonized wood and anatomical atlases (Jacquiot 1955, Schweingruber 1990). The quantification of the charcoal was based on the weight concentration of the charcoal amount in mg per kg of sediment (i.e. specific anthracomass in mg.kg^{-1}). This way of quantification allows to compare charcoal quantities within and between study from site, for different soil profile, layer, etc.

Moreover, in addition to the field soil description, a part of the sampled earth (i.e. about 500 g) was retained for soil characteristic lab analysis. For each soil horizon, the ph value and the grain size proportions (Mastersizer 2000 laser scanning; Malvern Instruments Limited 2005) were measured, as well as the organic matter content (by loss in ignition; Reeuwijk 2002). The soil horizon identification follows the last “AG Boden” classification (Sponagel *et al.* 2005).

To obtain chronological data from soil charcoal assemblages, 16 charcoal pieces (6 from RIES, 8 from RIEN and 2 others from preliminary soil charcoal analysis for the investigation survey; noted RiW), previously formally identified, were dated by AMS-¹⁴C (Leibniz labor; Grootes *et al.* 2004). Those charcoal pieces were selected based on their position in the soil profiles, their taxonomical significance and the general charcoal amount distribution in the charcoal assemblages of the soil layers and profiles of the two study plot. The radiocarbon ages were calibrated with a 2σ confidence interval, using the IntCal09 dataset (Reimer *et al.* 2009), on Oxcal 4.1.56 program (Bronk-Ramsey 2001).

Results

Forest stand characterization and short-term investigation

Forest stand characterization

Three vegetation levels were identified on each plot. The scrub vegetation level presents stems of *Corylus avellana* on both plots (28 stems/ha on RIEN and 23 stems/ha on RIES) and *Crataegus* sp., only on RIEN (4 stems/ha). The understory level includes seven tree species on RIEN, but only three on RIES. The canopy level includes six tree species on both plots.

Both understory and canopy levels include light-demanding and shade-tolerant species (Table 1). In total, the plot RIEN presents more than the double the stem density of RIES. This tree density difference is especially significant for the understory stems, with 77 stems/ha on RIES, while RIEN presents 327 stems/ha. There is a greater density of *Alnus glutinosa* and *Carpinus betulus* in RIEN and *Tilia cordata* is present on that site, while it is not in RIES. However, on both plots *Fagus sylvatica* is the most represented tree species, in stems/ha. *Fraxinus excelsior* is the second most common. However, according the basal area measurement *Fraxinus* is the dominant species. While *Fagus* presents the second largest basal area in RIES, it is *Quercus* spp. in RIEN, which presents the second largest basal area with, however, a value very comparable to that of *Fagus*. In RIES, *Quercus* spp. is the third species in terms of basal area, and *Fagus* presents a much larger basal area (Table 1).

RIEN presents a continuous Gaussian canopy trees dbh distribution from 20/24 cm to 50/54 cm, with a few larger stems of 60/64 cm. RIES presents a large range and continuous bimodal canopy trees dbh distribution from 15/19 cm to 80/84 cm. For both plots, the dbh class presenting the greatest number of trees is the 35/39 cm class, while the mean dbh class differs on the two plots (including understory and canopy trees; Fig. 2).

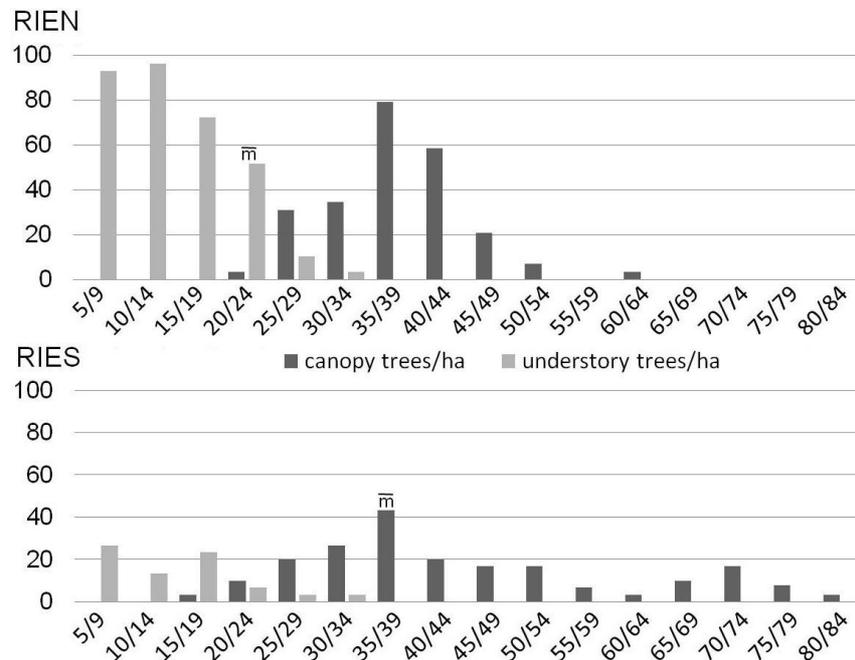


Figure 2. Diameter distribution of the study plots, RIEN and RIES, of the Riesewohld forest: number of stems per class of diameter (in cm), at breast height (dbh) of living tree > 5 cm dbh, for the understory and canopy vertical forest levels; \bar{m} : mean dbh class.

The regeneration inventory indicates an important and diversified sapling and seedling density/ha. On both plots, the regeneration includes light-demanding and shade-tolerant species with, however, a much more important density/ha of light-demanding species, with the especially important seedling of *Acer* sp. (Table 1).

Species	Trees density (n/ha)	Relative tree density (%)	Basal area (m ² /ha)	Understory basal area proportion (%)	Regeneration density (n/ha)*
RIEN					
<i>Acer platanoides</i>	3	1	0,01	100	134000 (<i>Acer</i> sp.)
<i>Alnus glutinosa</i>	76	13	2,88	21	.
<i>Betula pendula</i>	17	3	0,98	6	.
<i>Carpinus betulus</i>	62	11	2,35	23	12000
<i>Fagus sylvatica</i>	162	29	3,67	17	8000
<i>Fraxinus excelsior</i>	117	21	12,58	6	2000
<i>Quercus</i> spp.	34	6	3,70	0	4000
<i>Tilia cordata</i>	93	16	1,05	100	.
Totals	564	100	13,51	17	160000
RIES					
<i>Acer platanoides</i>	27	10	0,30	100	205800 (<i>Acer</i> sp.)
<i>Alnus glutinosa</i>	3	1	0,36	0	.
<i>Betula pendula</i>	3	1	0,19	0	.
<i>Carpinus betulus</i>	23	8	1,34	10	6200
<i>Fagus sylvatica</i>	140	50	5,97	3	600
<i>Fraxinus excelsior</i>	67	24	10,19	0	55400
<i>Quercus</i> spp.	17	6	2,04	0	200
Totals	280	100	30,43	2	62400

Table 1.

Forest features of the study plots RIEN and RIES, of the Riesewohld forest, based on the forest characterization plots inventory (3000 m² each). *regeneration includes seedlings and saplings (<5 cm dbh).

With regard to the mapping of trees, no specific pattern of tree distribution was observed, either per dbh (Fig. 3A and B) or per tree species, at least on RIES (Fig. 3C). RIEN presents a variation in the trees species spatial distribution. *Tilia*, *Fagus*, and *Quercus* are absent in the south-eastern part of the plot, but present overall in the other parts of the plot (Fig. 3D). There is a fine spatial stems mixing with a mean nearest-neighbour distance per plot of 3.3 m on RIEN and 4.7 m on RIES. The values of the CE index indicate a marked tendency to aggregates the tree spatial distribution for both plots (Fig. 3).

In regards to the types of dead wood pieces (Fig. 4a), there was a considerable volume of pieces of stumps on both plots. However, the proportion of total dead volume per plot varied. This difference is particularly important to the volume of dead wood pieces lying on the ground or standing, which represent respectively ca. 59 % and ca. 26 % of the total dead wood volume on RIES. In contrast, the stumps' dead wood volume on RIEN represents more than 85 % of the total dead wood volume. Moreover, it is interesting to note that most of the inventoried stumps presented marks of human harvesting that were clearly visible in the field. The dead wood inventory per decay class provides volume in the five classes of decay, with however considerable variation (Fig. 4b and 4c).

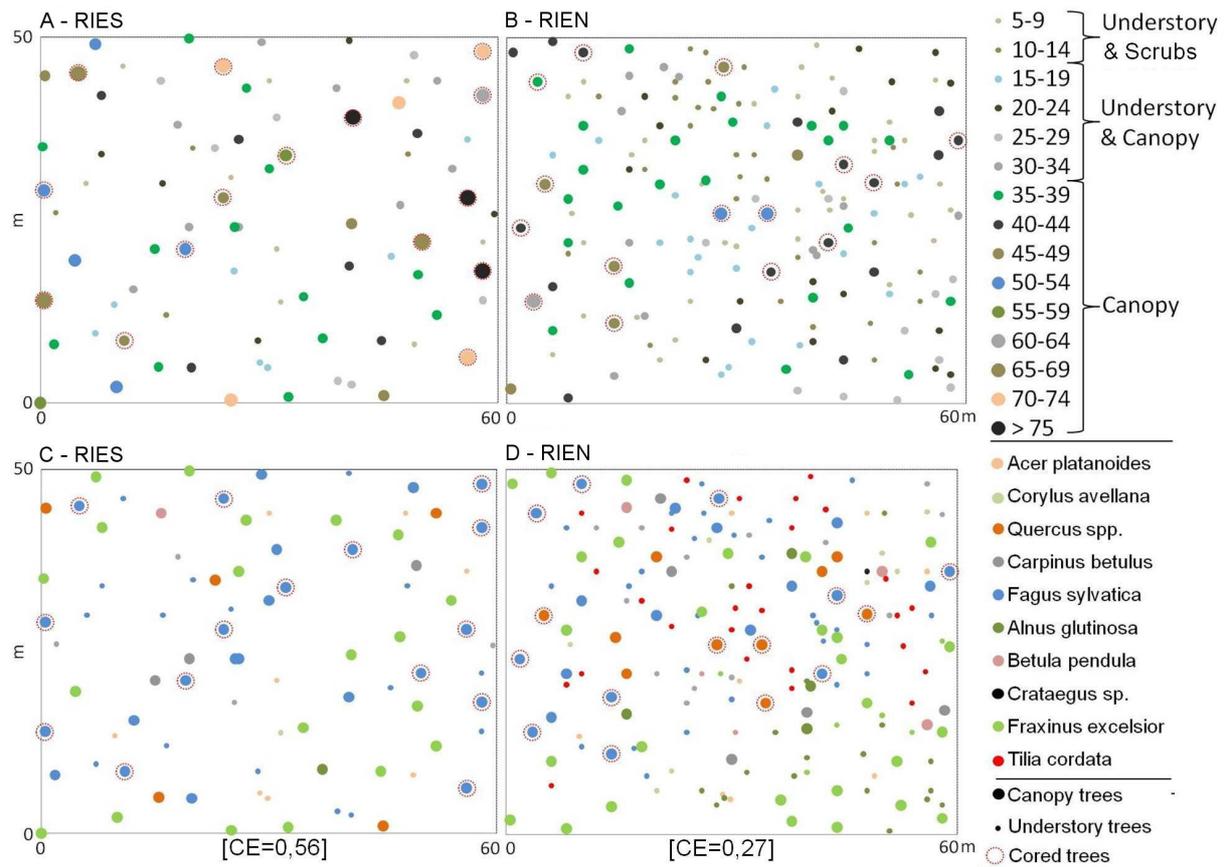


Figure 3. Spatial mapping of the trees' stems on the two investigation sites of the Riesewohld forest, RIEN and RIES. A and B: per diameter classes at breast height (dbh); C and D: per species. CE = values of the Clark-Evans index.

The volume in class 5 on RIES is much smaller than in the other classes, and is a volume comparable to that of class 5 on RIEN, where this dead wood decay class presents a greater bigger proportion than in the other classes. In regards to the species identified in the dead wood inventory, it is particularly interesting to observe the important proportion of *Betula* sp. and *Fraxinus* sp., two light-demanding and short lifespan species and, also, the presence of *Picea abies* in decay class 4 of RIES, and *Fagus* dead wood in the first three decay classes of RIEN.

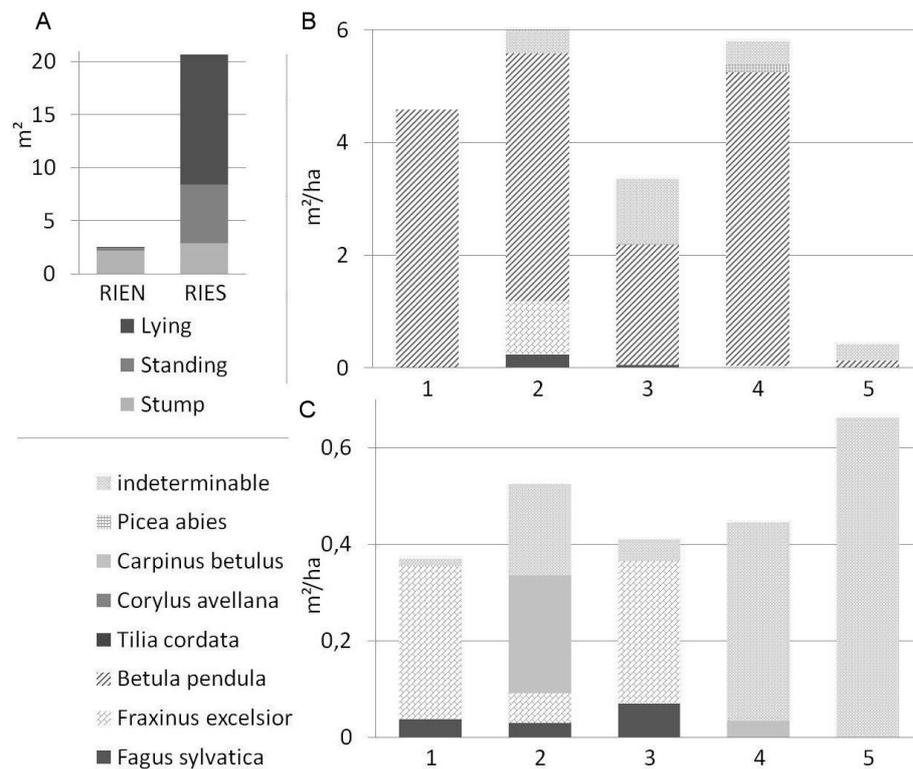


Figure 4. Dead wood inventory of the two investigation sites of the Riesewohld forest, RIEN and RIES. A: total volume per site and per type of dead wood piece; and volume per hectare per class of wood decay for B: RIEN and C: RIES.

Tree ring series analysis

On RIES, 15 tree chronologies of *Fagus sylvatica* stems have been obtained, providing an overall span of 124 years, from 2009 to, at a maximum, 1886 (Table 5A). The common span presents 64 rings (i.e. the shortest tree chronology), from 1946 to 2009.

On RIEN, 10 tree chronologies of *Fagus sylvatica* were obtained, reaching at a maximum 1918 (i.e. 92 rings). The common span was from 2009 to 1930. The shortest measured tree ring series contained 80 rings. Five tree chronologies of *Quercus* spp. were measured, spanning from 2009 to 1900 (i.e. 110 rings). The common span is 97 years, from 2009 to 1913, corresponding to the shortest measured tree ring series.

The values of the Cross-Dating-Index (i.e. CDI) are significantly low for all tree ring series compared to each other, per site, even in the best matching position of the tree ring series (Table 2A and 2C). Despite these low CDI values, the mean site chronologies have been prepared, based on the finally selected, best matching position of the tree ring series (i.e. the position presenting the highest CDI values, fitting with reliable cross-dating by eye). The simple correlation of those mean site chronologies presents weak values. Moreover, those mean site chronologies present relatively high values of autocorrelation of 1st order, low mean sensitivity values, and high standard deviation values (Table 2C).

A - tree series	RIES (<i>Fagus</i>)														
	t01	t02	t03	t04	t05	t06	t07	t08	t09	t10	t11	t12	t13	t14	t15
t01	—	4/	5/	2/	46/	29/	17/	12/	22/	28/	4/	2/	16/	1/	5/
t02	4/	—	17/	12/	2/	7/	3/	1/	4/	5/	2/	10/	2/	29/	9/
t03	5/	17/	—	11/	1/	3/	3/	4/	2/	7/	2/	6/	3/	20/	1/
t04	2/	12/	11/	—	7/	4/	10/	10/	1/	6/	1/	6/	11/	3/	3/
t05	46/	2/	1/	7/	—	15/	19/	14/	20/	13/	10/	5/	31/	5/	5/
t06	29/	7/	3/	4/	15/	—	12/	6/	22/	31/	5/	2/	7/	2/	5/
t07	17/	3/	3/	10/	19/	12/	—	3/	4/	5/	10/	3/	36/	1/	2/
t08	12/	1/	4/	10/	14/	6/	3/	—	8/	1/	8/	8/	12/	1/	10/
t09	22/	4/	2/	1/	20/	22/	4/	8/	—	29/	5/	4/	9/	9/	13/
t10	28/	5/	7/	6/	13/	31/	5/	1/	29/	—	8/	11/	9/	9/	4/
t11	4/	2/	2/	1/	10/	5/	10/	8/	5/	8/	—	2/	14/	9/	4/
t12	2/	10/	6/	6/	5/	2/	3/	8/	4/	11/	2/	—	4/	17/	2/
t13	16/	2/	3/	11/	31/	7/	36/	12/	9/	9/	14/	4/	—	2/	0/
t14	1/	29/	20/	3/	5/	2/	1/	1/	9/	9/	9/	17/	2/	—	7/
t15	5/	9/	1/	3/	5/	5/	2/	10/	13/	4/	4/	2/	0/	7/	—
B - tree series	RIEN (<i>Fagus</i> ^F and <i>Quercus</i> ^Q)														
	t01 ^F	t02 ^F	t03 ^F	t04 ^F	t05 ^F	t06 ^F	t07 ^Q	t08 ^Q	t09 ^Q	t10 ^Q	t11 ^Q	t12 ^Q	t13 ^F	t14 ^F	t15 ^F
t01 ^F	—	4/	18/	2/	17/	5/	14/	7/	4/	9/	2/	57/	38/	8/	31/
t02 ^F	4/	—	13/	16/	2/	2/	10/	3/	1/	1/	6/	27/	6/	11/	1/
t03 ^F	18/	13/	—	2/	12/	4/	9/	7/	1/	9/	7/	42/	24/	11/	7/
t04 ^F	2/	16/	2/	—	1/	1/	4/	14/	21/	4/	26/	10/	7/	10/	2/
t05 ^F	17/	2/	12/	1/	—	11/	2/	3/	6/	3/	1/	43/	16/	2/	19/
t06 ^F	5/	2/	4/	1/	11/	—	4/	7/	10/	1/	2/	22/	3/	5/	8/
t07 ^Q	14/	10/	9/	4/	2/	4/	—	2/	3/	10/	2/	13/	4/	1/	8/
t08 ^Q	7/	3/	7/	14/	3/	7/	2/	—	47/	2/	2/	13/	4/	19/	3/
t09 ^Q	4/	1/	1/	21/	6/	10/	3/	47/	—	2/	7/	5/	3/	15/	2/
t10 ^Q	9/	1/	9/	4/	3/	1/	10/	2/	2/	—	4/	9/	4/	2/	5/
t11 ^Q	2/	6/	7/	26/	1/	2/	2/	2/	7/	4/	—	1/	5/	9/	1/
t12 ^Q	57/	27/	42/	10/	43/	22/	13/	13/	5/	9/	1/	—	30/	24/	39/
t13 ^F	38/	6/	24/	7/	16/	3/	4/	4/	3/	4/	5/	30/	—	13/	7/
t14 ^F	8/	11/	11/	10/	2/	5/	1/	19/	15/	2/	9/	24/	13/	—	3/
t15 ^F	31/	1/	7/	2/	19/	8/	8/	3/	2/	5/	1/	39/	7/	3/	—
C - mean chrono	n rings	Rings width (mm)			sd	ac	ms	Simple correlation							
		min	mean	max				RIEN ^F	RIEN ^Q	RIES					
	RIEN ^F	92	1.03	2.21	3.45	51	0.8	0.147	—	0.62	0.58				
RIEN ^Q	110	0.76	2.23	4.37	62	0.7	0.153	0.62	—	0.55					
RIES	124	0.23	2.52	4.02	72	0.9	0.158	0.58	0.55	—					

Table 2.

Main quantitative feature of the tree ring series analyzed in the study plots RIEN and RIES of the Riesewohld forest. A: correlation table of the Cross Dating Index (CDI) of the 15 tree ring series correlated one/one for the plot RIES, and B: for the plot RIEN; C: mean site chronologies per plots and species (RIES, and RIEN^Q / RIEN^F); n rings = number of rings; ring size min/mean/max= minimum, mean and maximum, ring size measurement in 1/100; sd= % of standard deviation ; ac= autocorrelation of first order; ms = mean sensitivity.

The low frequency signal of RIEN varies slightly over the average window of ca. 10 years for *Quercus* spp., while *Fagus sylvatica* presents a more stable low-frequency signal (Fig. 5A). The *Fagus sylvatica* low-frequency chronology from RIES presents a variation of trends over the average window of ca. 20 years (Fig. 5B). The high-frequency signal of all the site chronologies presents a quite high temporal resolution of growing pattern change. No growth tendency was apparent in more than three successive rings. In a comparison of the signal

indication of both species on RIEN and the signal indication of RIES, any similarities were barely identifiable, except for a few years (Fig. 5C and 5D).

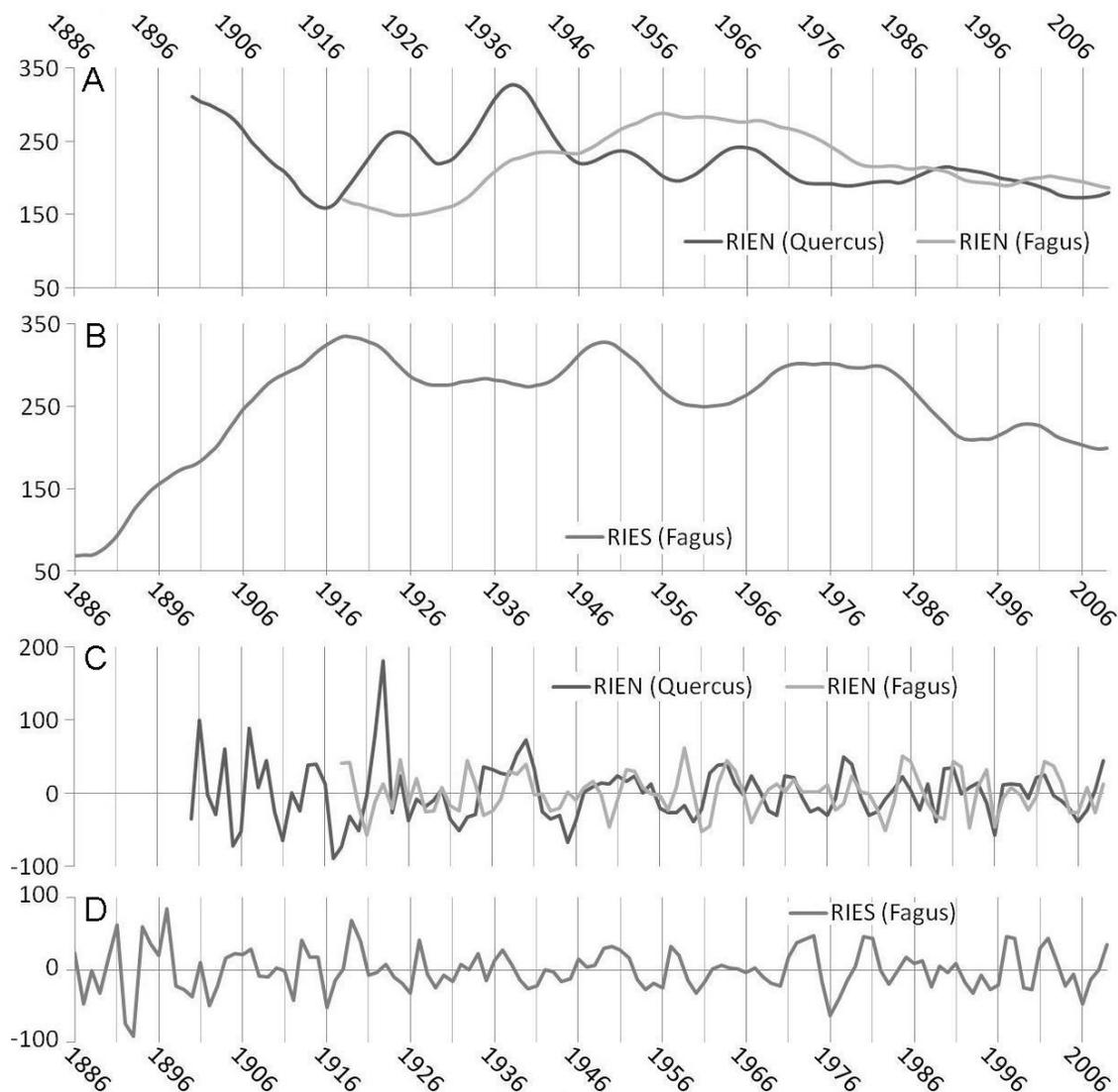


Figure 5. Rieseowhld forest stand mean chronologies; Low frequency signal: A- mean chronology trends of RIEN *Quercus* and *Fagus* tree ring series; B- mean chronology trends of RIES tree ring series; High frequency signal: C- standardized mean chronology of RIEN *Quercus* and *Fagus* tree ring series; D- standardized mean chronology of RIES tree ring series.

The calculation of growth change proportion in 10-year temporal windows (i.e. mid-frequency signal) indicated a certain cycling tendency, with a regular increase and a decrease of growth change (Fig. 6). Those growth change patterns occurred on ca. of 20 to 30 years on both sites, and for both species on RIEN. Those growth changes present comparable and regular amplitudes, except for the older phase of the RIES site chronology. On this phase, growth changes with large amplitudes were identified.

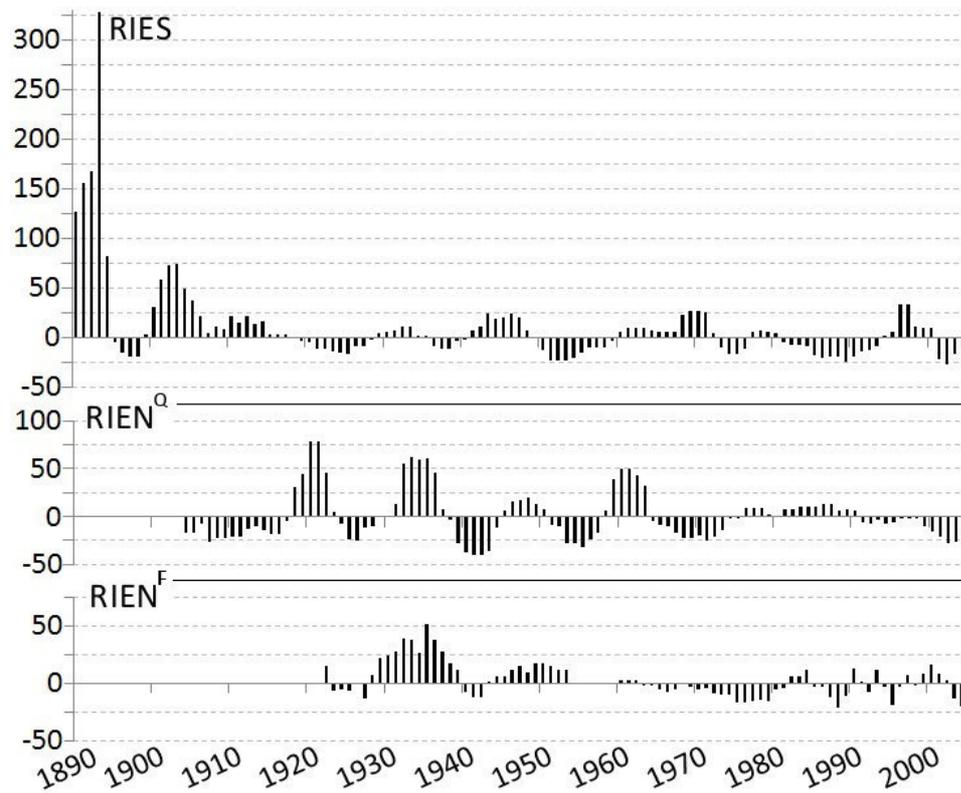


Figure 6. Riesewohld forest stand growth change (%) of the tree ring series measured, calculated on 5-year temporal windows.

Long-term investigation

Soil field description and laboratory analysis allowed general common soil characteristics and soil historical processes to be identified on both study plots. RIES and RIEN are sandy soil, with a soil surface layer rich in organic matter (Tables 3 and 4). Soil formation began to develop during the early-Holocene period over the post-glacial sand deposits reached at the soil profiles bottom. This resulted in the formation of a Luvisol (i.e., Bt – Bs/Al), with a gley layer in RIEN2; Go/r. This soil formed on-site is now partly eroded, and overcome by colluvial layers of various thicknesses: layers M1 and M2 on RIENP1 and on RIESP2, five M layers on RIESP1. However, with regard to this last soil profile, it must be noted that it is situated in a particular location of the study site in a gully system, making it unrepresentative of the soil at the stand scale. In the 50 to 30 upper cm range, we observed the in-situ formation of a Cambisol (i.e. B-Bv-A/Ae). Moreover, on the upper part of the colluvial layer M2, on RIES, we identified marks of ploughing (i.e. M2 Ap).

profiles	soil horizon	layer of sampling	depth of sampling (cm)	ph (H ² O)	grain size % (mm)					OM %
					pebble (> 5)	gravel (5-2)	sand	silt	clay	
RIEN1	M2	A	0-10	3.5	1.7	0.6	76.9	16.3	6.2	6.8
	Bs	B	10-20	4.6	1.0	0.0	86.5	8.2	4.8	2.8
		C	20-30							
	Bt	D	30-40	5.1	2.2	1.2	82.5	8.7	8.5	1.7
		E	40-50							
		F	50-60							
		G	60-70	5.2	0.0	1.0	73.8	17.9	8.0	0.9
		H	70-80							
		I	80-90							
RIEN2	M2Ah	A	0-5	3.2	2.7	1.0	81.7	11.0	6.4	9.7
	M2Ae	B	5-15	3.8	3.0	4.2	62.5	32.8	4.4	10.3
	Bs	C	15-25	4.4	4.3	5.3	70.9	21.1	7.9	17.6
		D	25-35							
	Bt (Go/r)	E	35-45	4.4	1.7	3.4	74.9	17.9	6.8	2.4
		F	45-55							
RIEN3	M2Ah	A	0-10	4.9	2.6	1.5	79.7	17.2	3.0	6.7
	Bs	B	10-20	5.4	3.1	1.6	80.6	12.5	6.4	2.8
		C	20-30							
	Bt	D	30-40	5.1	1.3	3.4	79.7	12.4	7.8	1.6
		E	40-50							
Cv	F	50-60	5.4	0.9	2.7	82.5	8.5	8.7	0.9	
RIEN4	M2Ah	A	0-10	4.8	1.1	0.7	78.3	12.3	9.2	12.3
	M2Ae	B	10-20	5.2	1.2	0.9	83.2	10.9	5.3	1.3
	C	20-30								
	Bs	D	30-40	5.2	2.7	1.8	89.5	5.5	4.2	2.5
		E	40-50							
	Bt	F	50-60	5.2	1.2	0.8	92.6	3.4	3.6	0.4
G		60-70								
H	70-80									
RIENP1	M2Ae	A	5-25	3.9	3.3	1.3	84.8	9.8	5.4	3.2
	Bs	B	35-55	5.2	2.0	1.7	82.9	10.2	6.4	3.7

Table 3. Riesewohld forest investigation site of RIEN: soil horizon features for the five soil profiles sampled.

profiles	soil horizon	layer of sampling	depth of sampling (cm)	ph (H ² O)	Grain size % (mm)					OM %
					pebble (> 5)	gravel (5-2)	sand	silt	clay	
RIES1	(M2) Ah	A	0-10	4.1	9.8	9.1	73.6	18.0	8.3	5.6
		B	10-20							
	M2 Bv	C	20-30	5.0	4.2	13.7	76.0	15.4	7.9	2.0
		D	30-40							
	Al	E	40-50	5.7	3.5	0.0	78.3	17.1	3.7	1.6
		F	50-60							
RIES2	(M2) Ah	A	0-10	3.7	1.5	1.6	73.4	18.5	7.6	16.5
	M2	B	10-20	3.6	0.0	5.8	80.5	10.7	8.0	9.3
		C	20-30							
	Al	D	30-40	3.7	2.5	1.0	85.7	8.7	5.2	2.8
		E	40-50							
Bt	F	50-60	3.9	5.4	1.7	89.3	6.2	4.3	1.3	
G	60-70									
RIES3	(M2) Ah	A	0-10	3.8	0.0	0.0	80.5	12.3	6.9	34.0
	M2 Bv	B	10-20	4.7	0.8	0.0	73.0	19.0	7.7	13.5
		C	20-30							
	Al	D	30-40	5.0	4.8	3.3	81.8	11.3	6.8	7.8
E		40-50								
Bt	F	50-60	5.1	5.8	2.3	69.6	21.9	8.4	0.5	
RIES4	(M2) Ah	A	0-10	3.7	0.0	0.0	69.3	24.1	6.3	36.5
	M2 Bv	B	10-20	4.1	2.8	3.1	74.0	20.7	4.5	14.7
		C	20-30							
	D	30-40								
Al	E	40-50	4.4	2.1	3.4	75.0	17.5	6.9	2.4	
RIESP1	M5	A	5-15	4.6	1.2	2.6	80.4	11.3	7.9	4.3
	M4	B	25-35	4.7	1.5	10.6	76.8	16.4	6.8	1.6
	M3	C	40-50	4.9	1.0	5.2	82.7	12.0	5.2	0.5
	M2	D	55-65	6.4	0.4	4.1	80.0	13.9	6.0	0.4
	M1	E	70-90	7.3	0.3	14.7	82.2	12.3	5.2	0.1
RIESP2	M2 fAp Bv	A	5-15	4.6	2.4	8.2	62.3	30.9	6.6	6.8
	M2 Bv	B	15-28	6.1	2.2	3.8	49.6	42.1	8.2	6.7
	M1	C	28-38	4.8	3.1	4.3	63.7	31.5	4.3	0.9
	Al	D	38-59	5.4	2.1	12.5	67.2	24.5	7.8	5.7

Table 4. Riesewohld forest investigation site of RIES: soil horizon features for the five soil profiles sampled.

485 kg of earth were sampled for the soil charcoal investigation, from both investigation sites, including 11 soil profiles in all. From that amount of earth, 6538 mg of charcoal were extracted, of which about 2632 mg were taxonomically analyzed (i.e. 1040 single charcoal pieces). About 22 % of the taxonomically analyzed charcoal mass was indeterminable (226 single charcoal pieces). Those charcoal pieces were too dirty or deformed (e.g. vitrified charcoal; McParland *et al.* 2010). Those indeterminate charcoal data are not usable for long-term forest history and therefore were excluded from the taxonomical results.

The total soil charcoal concentrations of both sites are comparable (i.e. 16 mg.kg⁻¹ for RIEN and 19 mg.kg⁻¹ for RIES). However, within each study plot, there is a wide heterogeneity of specific anthracomass per profile (SAP) and per layer of sampling (SAL). The SAP varies from ca. 4 to 70 mg.kg⁻¹, respectively for RIEN1 and RIEN2, and from ca. 3 to 55 mg.kg⁻¹ respectively for RIES4 and RIES2. On each plot, two profiles were particularly richer in charcoal than the others, the profiles RIES2 and RIEN2. Looking at the charcoal concentration along the deep (Figs. 7 and 8), it is noted that the larger values of SAL are for intermediate levels of depth (from 20 to 30 cm, depending on the soil profiles). The upper levels of sampling are not as rich in charcoal, but are richer than the deepest level of sampling (deeper than 30 to 40 cm, depending on the soil profiles from which the samples came), which present a very small soil charcoal concentration or none at all.

The results of the taxonomical analysis of the soil charcoal assemblages permitted the global species spectrum for the two plots to be identified. *Quercus* dominate the soil charcoal assemblages, along with less represented species, notably *Pinus* and *Fagus*. Moreover, *Acer* and *Alnus* charcoal pieces have been identified only on a few samples of RIES (Fig. 8). *Pomoideae* charcoal pieces have been identified, in very small quantity, only in the soil charcoal assemblage of RIENP1A (Fig. 7).

Of the 16 radiocarbon dates, three charcoal pieces dates are from modern times, seven from the Middle Ages, four from the Iron Age/Roman period, one from the Bronze Age, and one from the late Neolithic period (Figs. 7 and 8).

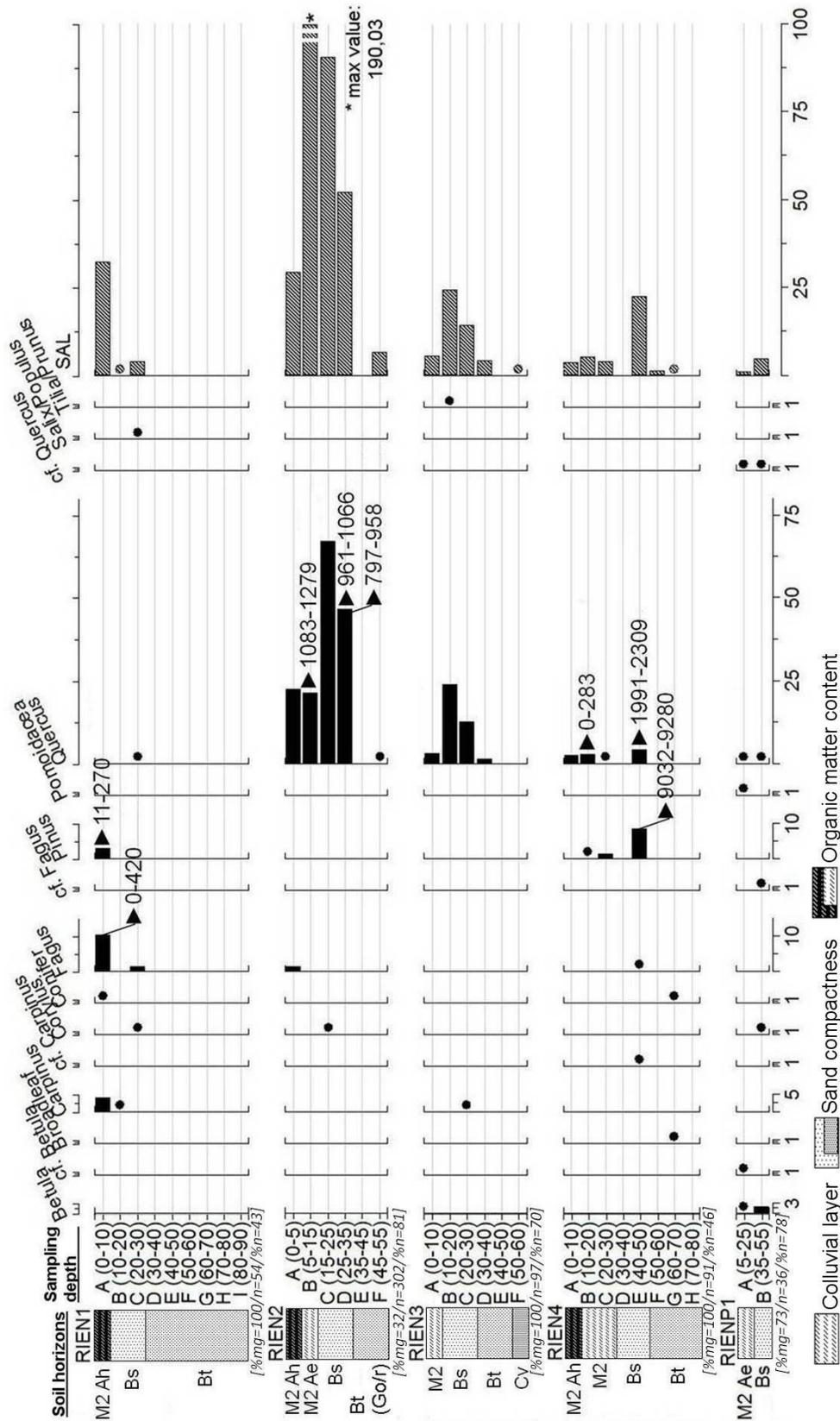


Figure 7. Rieseowhld forest, investigation site RIEN: Soil charcoal diagram; x-axis below: concentration in mg.kg⁻¹; x-axis above: identified taxa; y-axis: layers of sampling per soil horizon and corresponding depth in cm of the various soil profiles sampled. ● : charcoal concentration < 1 mg.kg⁻¹; ▲ : radiocarbon dates in calibrated BP (2σ interval); right column, grey stripes: specific anthracomass per layer (SAL); soil profile bottom: %mg-analyzed charcoal pieces/n=identified charcoal pieces/n=number of analyzed charcoal pieces/>1mm, extracted from earth sample/n=number of analyzed charcoal pieces/>1mm=identified charcoal pieces/>1mm=number of analyzed charcoal.

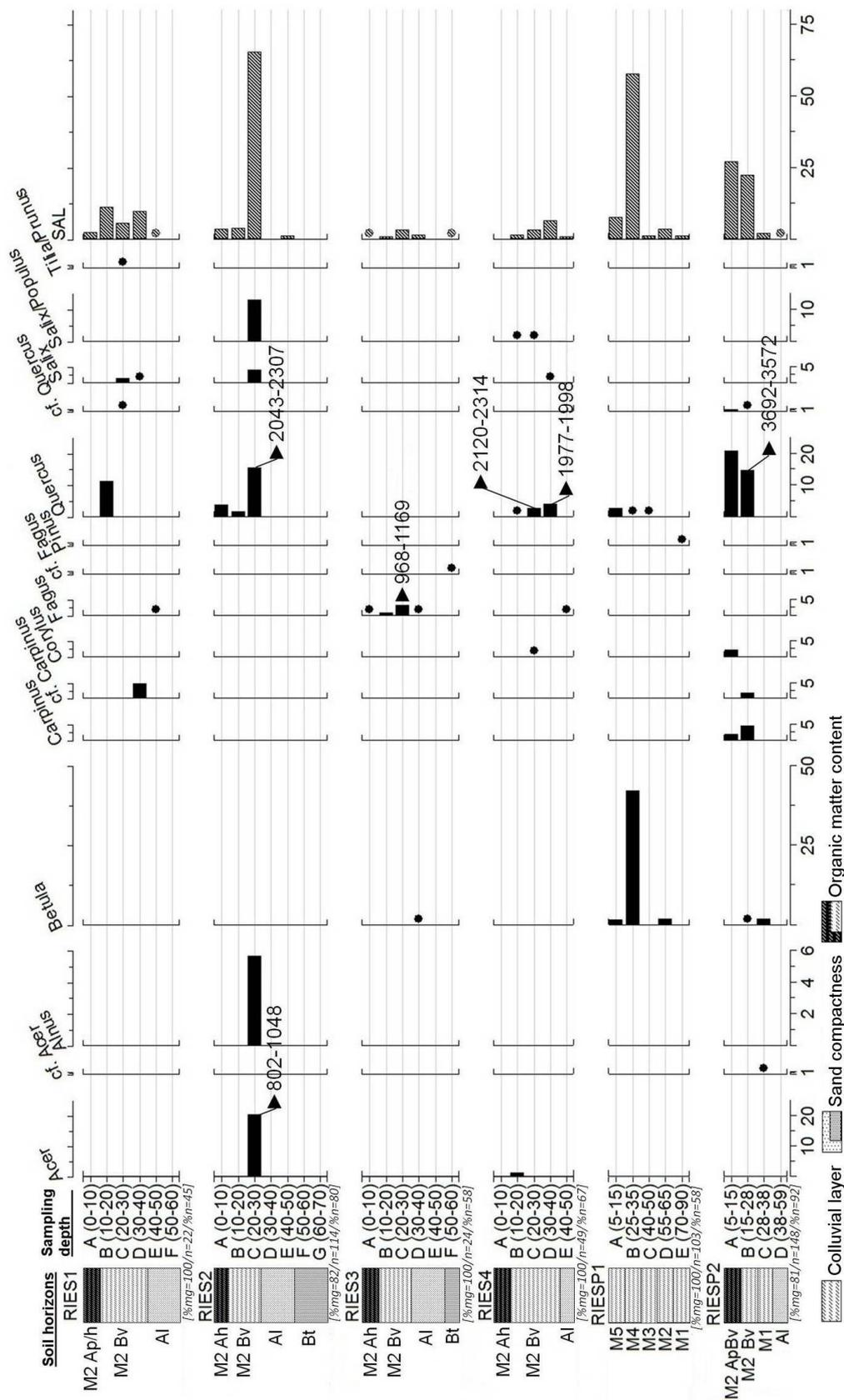


Figure 8.

Riesewald forest, investigation site RIES: Soil charcoal diagram; x-axis below: concentration in mg.kg⁻¹; x-axis above: identified taxa; y-axis: layers of sampling per soil horizon and corresponding depth in cm of the various soil profiles sampled. ●: charcoal concentration < 1 mg.kg⁻¹; ▲: radiocarbon dates in calibrated BP (2σ interval); right column, grey stripes: specific anthracomass per layer (SAL); soil profile bottom: %mg=analyzed proportion of the total charcoal weight, > 1mm, extracted from earth sample/n=number of analyzed charcoal pieces/%n=identified proportion of the number of analyzed charcoal.

Discussion

The stand structure analysis of the two investigated plots indicates heterogeneities in the tree dimensions and so, potentially, in age structure (Fig. 2). The RIES plot presents a bimodal dbh canopy tree distribution, with a large and continuous range, which may fit a natural forest (e.g. old-growth dbh distribution; Gilg 2004, Messier *et al.* 2009, Podlaski 2010). RIEN presents a Gaussian dbh canopy tree distribution, with a smaller and simpler dbh canopy tree distribution than RIES. This dbh distribution may result from a “homogenization effect” of the tree dimension structure due to human management of the forest stand (Gilg 2004, Rouvinen and Kuuluvainen 2005) or because of the occurrence of stand scale disturbances (Pickett and White 1985, Podlaski 2008).

In RIES “large dimension trees” are present (i.e., larger than 60 cm dbh; McElhinny *et al.* 2005), indicating a more stable and “mature” growth condition. Such large dimension trees are important for biological conservation purposes since, by increasing the possibilities of micro-habitat creation and dead wood accumulation, they contribute to biodiversity (McElhinny *et al.* 2005). Therefore, such large dimension trees must be maintained on the sites.

The species and dbh mixing occur at a fine spatial scale with tendencies to the stems clustering on both plots indicated by the Clark-Evans index (Fig. 3). This may be explained by the important presence of shade-tolerant species, which are established and grown under the cover of mature trees (Oheimb *et al.* 2005). The spatial scale of ‘patch dynamic’, and even smaller, fit the possibly important role of “intermediate disturbance” occurrences (Roxburgh *et al.* 2004, Barnes *et al.* 2006, Podlaski 2008). In this dynamic model, the spatial patterns of forest regeneration played an important role. On the two study plots we observed a regeneration cohort species composition fitting the understory and canopy levels (Table 1). The current forest regeneration of understory and canopy levels present species with various autoecology. On both plots, *Fagus sylvatica* and *Fraxinus excelsior* are the dominant species in basal area and tree density. This illustrates the importance of mixing light-demanding and shade-tolerant species with the presence of other species like *Acer*, *Carpinus*, etc., in the canopy, understory trees, and regeneration cohort, as well (Table 1). *Quercus* spp. was only present in the canopy level of the two investigated forest stand, like *Fraxinus excelsior* on RIES. This may indicate a previous opening of the canopy, allowing the establishment and growing of light-demanding species, which might be intended for harvesting for Human usage. Moreover, on RIEN, some species are not present on one part of the sampling plot. Based on field observation and soil description and analysis, we can explain this distribution

pattern by this zone's higher water table level. This is supported by the important density of water-demanding tree species like *Fraxinus* and *Alnus* on this part of the sampling plot (Fig. 3D). This is an indication of fine scale forest stand heterogeneity due to a micro-environmental variable condition.

We observed a relatively simple vertical structure of both forest stands. This might be an indication of human impact at the stand scale (Larsen 1995), in regards to the potential complex vertical structure of European temperate natural forests (Peterken 1996).

The dead wood inventory indicates relatively small volume, especially on RIEN. On both plots, the much smaller volume of dead wood in an advanced decay state (i.e. decay class 5; Fig. 4), indicates that dead wood volume has not been accumulating on both plots for too long. Those previous aspects constitute a major distinction to a natural old-growth forest where dead wood cycle is a crucial component (Christensen *et al.* 2005, Harmon 2009), and may present large volumes (Meyer and Schmidt 2010). Nevertheless, the volume of dead wood on RIES might correspond to a 'young-growth' forest stand model. The smaller volume of dead wood on RIEN fits "managed, semi-natural stands" (Green and Peterken 1997). The volume of dead wood on RIEN is mostly composed of stumps, apparently resulting from harvested stems. This also observation allows one to postulate a human role in dead wood accumulation. On RIES the important dead wood volume proportion from standing and lying pieces may indicate the importance of a competition process (Laarmann *et al.* 2009). This is supported by dead wood piece from both light-demanding and shade-tolerant species for both plots (Fig. 4).

The heterogeneity of the environmental condition induced heterogeneity in the growth patterns (Fig. 5). The analyzed tree ring series present considerable variability within trees of the same plot, with weak CDI and standard deviation values, and between plots, with low correlation between the mean sites chronologies (Table 2). The high frequency growth variations did not present any temporal synchronies between the two sampled forest stand (Fig. 5C and D). This is probably due to the important heterogeneity of the measured and correlated tree ring series within and between the sampled forests stands (Table 2). The low values of mean sensitivity and the relatively high autocorrelation values (Table 2C), indicate a small year-to-year variation of the width of rings, supporting the weakness of the large-scale climatic control on the growth. Those previous aspects allow one to postulate the importance of the micro-environmental conditions (e.g. water table level at stand scale), on the growth and the dynamic of the two characterized and sampled forest stand plots.

The low- and mid-frequency signals indicate change in growth patterns over longer temporal windows than the high frequency signal (Figs. 5A and B, and Fig. 6). These growing patterns present certain cyclicity, on ca. 20-year windows, with growing changes of relative homogenous amplitude. Such growing patterns may fit to a coppice management system by humans (Schweingruber 1996, Haneca *et al.* 2005). A large amplitude growth change phase appears only on RIES mid-frequency signals. These large amplitude growth change phases seem to correspond to a juvenile phase of the stand tree population that was recorded in the low-frequency signal from 1886 to ca. 1906 (Fig. 5B). During such stage of growth, tree response to growing conditions changes vigorously, and especially shade-tolerant species (Black and Abrams 2003). This juvenile phase is not recorded in the RIEN chronologies.

Looking further back in time might provide insights on long-term dynamic trends (Feurdean and Willis 2008, Willis *et al.* 2010). Soil charcoal, combined with soil description and analysis allow one to identify information about the long-term forest stand's dynamics. The spatial resolution of charcoal data has been discussed by many authors (e.g. Clark 1988, Scott *et al.* 2000, Touflan *et al.* 2010). These discussions globally conclude that macro-charcoal records are interpretable as local signal. Macro-charcoal records means charcoal assemblages made of charcoal pieces larger than a size range of 100 to 200 μm , depending on the authors. Because the soil charcoal assemblages include charcoal pieces that are larger than 1 mm (i.e. the minimum size necessary to obtain charcoal pieces that are taxonomically identifiable), we may postulate that the soil charcoal signal is significant at the local spatial scale. However, this depends on the topographical situation, because of possible secondary transport of charcoal assemblages in the soil matrix, a long slope, during erosive events (Bork and Lang 2003, Walther *et al.* 2009). Because of the relatively flat and homogenous relief feature of the two forest stands (Fig. 1), we assume that those erosion/deposit events occurred at the stand scale (i.e. few meters to a hundred meters distant).

The deepest part of the sampled soil profiles (i.e. deeper than 30/40 cm) is made of in-situ formed soil horizons. They were probably formed during the late Pleistocene/early Holocene period, as supported by the old pine radiocarbon date from RIEN4 (i.e. 9032-9280 cal yrs BP; Fig. 7). This charcoal record is probably due to natural ignition and burning of the pioneer post-glacial woodland, as postulated for most of the fire occurrences at that period. This woodland was then pristine post-glacial woodland, but this was a "pioneer stage" of forest dynamics. The forest probably changed a lot by natural processes, before the first strong human impact occurred (e.g. with the temperate tree species migration; Petit *et al.* 2002).

The presence on both plots of colluvial layers in the upper 0/5 cm to 30/40 cm indicates the occurrence of erosive events and sedimentary deposits. Those colluvial layers are rich in charcoal (Figs. 7 and 8). These rich charcoal records in the colluvial layers support the connection between the erosive event and the occurrences of fire. We may consider that when the period with higher fire frequency began, the amount of fuel was greater than later, after the fire occurrences and in the absence of a reforestation phase. Therefore, the charcoal amount formed by the first fire events is greater than later. Consequently, the charcoal assemblages embedded, transported and deposited into the downiest colluvial layers would correspond to the earliest erosive events that followed the first fire events. Such a process occurred since the Bronze Age. However, we cannot exclude that on-site erosion began earlier.

The taxonomical analysis of the charcoal assemblages of the colluvial layers fit well the Bronze Age/Iron Age forest composition in Northern Germany (Behre *et al.* 1996, Wiethold 1998, Nelle and Dörfler 2008), with a notable dominance of *Quercus*, with *Tilia*, and *Corylus*. Because European temperate broad-leaves forest presented locally, like the taxonomical analysis of soil charcoal assemblages indicates, are not as good fuel for natural fire ignition and development, we postulate that those identified fire events were man-made fire. Probably Human population deforested the woodland for agricultural purposes, as was identified in some other areas nearby the investigated plots (Hoffmann 2004, Reiss *et al.* 2006, Reiss *et al.* 2009). This is supported by the presence of plugging marks in the upper 10 to 15 cm of some profiles of RIES (Fig. 8). In the colluvial layer M2, the presence of *Fagus*, with *Carpinus* and *Acer*, and with moreover dates from the late Medieval, early modern times, support a relatively young age of this colluvial layer.

Based on the soil charcoal taxonomic variations along the slope (Fig. 7 and 8), we assume that, within the two main identified colluvial layers, a reforestation phase occurred, with a *Fagus* mixed woodland, including *Carpinus*, *Acer*, *Betula*, *Pinus*, etc. Maybe this reforestation stage correlates to the migration period (Dressler *et al.* 2006). This mixed soil charcoal assemblages of light-demanding and shade-tolerant species, since at least 968-1169 cal BP, fits well the forest composition indicated from short-term investigation (Table 1). However, some heterogeneity was observed, with e.g. *Acer* and *Alnus* recorded in the soil charcoal assemblages of RIES, which differs from the current forest stand composition (Table 1). Another significant different between the past and current forest composition is the absence of any wood charcoal pieces of *Fraxinus* in the soil, which presently is a dominating species. If we cannot exclude that it was present on-site when fire occurred, we assume that it

was not so dominant a species in the forest stand composition in the past as it is today. This heterogeneity in the soil charcoal records illustrates the importance of micro-environmental factors for the long-term dynamics of the two forest stands investigated.

Conclusion

The role of micro-environmental conditions on the current state of the forest and on the short-term scale has been illustrated, and the influences of human activities have been postulated, since at least the Bronze Age. The short-term investigation highlighted variations in stand structure and composition, allowing one to say that the plot RIES presents more natural features, than RIEN. However, both plots present common heterogeneous patterns on short and long temporal scales. These heterogeneity signals support the hypothesis of the weak influence on the forest stand dynamic of large scale disturbances control, which would make stand features more homogenous. Fine scale processes, like patch dynamic, seems to be the main process of forest systems' change over the last millennium, centuries, and decades, inducing fine spatial scale heterogeneity, on a short temporal scale. It remains difficult to determine more precisely if either natural or anthropogenic forcing was the main “dynamic driver”. Nevertheless, changes occur and consequences have been identified, on both plots, thanks to the multiproxy data set provided by the forest stands' characterization, tree ring series and soil charcoal analysis, relevant on a comparable spatial scale. The long-term investigation illustrated the fact that the reference state as a static state before human impact occurred is not so easy to identify. Therefore, it seems much more relevant to attempt to identify the event of changes (i.e. disturbances), of their determinism and consequences. This requires assessing the degree of naturalness of the investigated forest stands.

Conservation planning should take into consideration the fact that, if there is no more, strong, human impact on the forest stand, the stands would evolve toward a more “mature” stage, leading to a forest structure that is close to an old-growth forest. However, due to micro-environmental conditions, fine scale disturbance events would regularly occur, inducing “renewal” of forest stand structure and composition (e.g. establishment of light-demanding species), as was the case also on the long-temporal scale. Such disturbance events contribute to heterogeneity and therefore to biodiversity. So, they should be maintained by conservation planning and management, at the stand scale, within a global landscape planning. Maintaining such micro-environmental variations would also contribute to maintaining, and even to restoring, the adaptive capacities of the forest systems (i.e. resistance and resilience capacities).

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5.3 Assessing Holocene vegetation and fire history by a multiproxy approach: the case of Stodthagen Forest (Northern Germany).

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Abstract

The woodland history of the forest of Stodthagen (northern Germany) was investigated by using complementary palaeobotanical indicators. Six soil profiles from the study plot were sampled, the wood charcoal pieces extracted from the soil samples were quantified, taxonomically identified, and some were radiocarbon dated. Peat sequences from a small adjacent mire were also sampled and the pollen, micro-charcoal, and macro-charcoal were analysed. The pollen record shows a continuous forestation during the Holocene, with small indication of a disturbance phase during the late Holocene. This continuity of the woodland presence is confirmed by the weak quantity of macro-charcoal, indicating that fire did not have a serious impact during the Holocene in terms of canopy opening, despite the identification of three local fire events. However, large amounts of wood charcoal pieces were found in the soil samples allowing the identification of at least one more fire event, dated in the Iron Age, unrecorded in the charcoal signal from the peat sequences. The taxonomical charcoal assemblage is in agreement with the pollen data.

This innovating multiproxy approach allows the assessment of the ancient and continual presence of a woodland at the study site, which highlights the biological and patrimonial interest of the area and justifies the ongoing conservation management of the woodland.

Key words

Fire history, forest continuity, Holocene, Central Europe, multiproxy approach, charcoal analysis, pollen analysis.

Introduction

The Holocene vegetation history of Central Europe has been studied extensively, providing information about the major temporal and spatial patterns of vegetation dynamics linked to climate and/or human determinism (e.g. Berglund *et al.*, 1996; Birks, 1993; Kalis *et al.*, 2003; Lang, 1994). However, there are still many open questions, especially in the case of the assessment of the Holocene fire history in Central Europe. Long-term fire history investigations in Central Europe are rare. Moreover, most of the existing knowledge is based on the analysis of charcoal-signals combined with palynological studies (e.g. micro-charcoal counting on pollen slides, Clark *et al.*, 1989). Nevertheless, this approach provides reliable and relevant data, which allows to conclude that ecosystems of Central Europe burnt in the past (under oceanic and continental climate as well), even if they are less ‘fire sensitive’ than e.g. Mediterranean and Boreal biomes (Carcaillet *et al.*, 2002; Power *et al.*, 2008). In that context, human practices (i.e. fire ignition and /or fire usage) had an important role in the past fire regime (Berglund, 2011), at least since the Neolithic and following the Human development (Goldammer and Page, 2000), but also during older phases (e.g. Mason, 2000). However, despite this general assessment, there is still a lack in fire history investigation analyzing charcoal records in depth, especially from natural archives, using modern investigation methods (e.g. Higuera *et al.*, 2010). This is an important issue for understanding past ecosystem dynamics, since fires might be one of their important drivers, as disturbance events (Pickett and White, 1985).

Another important current issue of palaeoecological approaches is how they can contribute to the ecosystems sustainable management, conservation and/or restoration. In the context of the current ecosystem threats (e.g. global warming; IPCC, 2007; diminishing biodiversity; Giam *et al.*, 2010), the role of palaeoecological studies is to contribute to the understanding of the long-term dynamics of ecosystems and provide data able to contribute to a sustainable management and/or conservation of the ecosystem (Birks, 1996; Callicott *et al.*, 1999; Willis and Birks, 2006). However, one characteristic of palaeoecological data is to be segmented. A single proxy provides restricted information about ecosystems’ history. In this context, multiproxy approaches are essential, providing a more complete reconstruction of the past dynamics of ecological systems (e.g. Birks and Birks, 2006; Mazier *et al.*, 2009).

In this paper, we present a palaeoecological multiproxy investigation of the Holocene woodland dynamic and fire history of a woodland, under a biological conservation act, combining pollen analysis, sedimentary anthracology (i.e. micro- and macro-charcoal records), and pedoanthracology. Such combination of methods is for the first time applied on

the forest stand scale to (1) assess the occurrences of fires and their potential impact on woodland dynamics by (2) the reconstruction of the history of a forest in fine spatial resolution including the question of Holocene woodland continuity. Therefore it was aimed to test whether such multiproxy analysis can provide new insight into fire history. Based on this multi-methodological approach, we discuss the potential source of fire, i.e. whether they were ignited by natural or human forcing.

Study area

The Stodthagen Forest is situated in the eastern part of Schleswig-Holstein (northern Germany, N54.25/E10.03), in northern Central Europe (Figure 1). This is the bio-geographic domain of temperate deciduous forests with an oceanic climate (annual rainfall average: 880 mm, annual temperature average: 9.1°C; Deutscher Wetterdienst, 2008).

During the maximum of the Weichselian glacial this area was covered by ice. The ice withdrawal left a heterogeneous micro-topography on a young-moraine substratum (Nelle and Dörfler, 2008), producing numerous small mires embedded in a slightly hilly landscape with elevations between 20 m and 30 m a.s.l. These small mires have an area of less than 500 m², and are not totally covered by the forest canopy. The small mire which was cored twice is about 250 m², with a canopy opening over it of about 100 m².

The forest area under study is owned by the ‘Stiftung Naturschutz’ and managed for ecosystem conservation since 1994. Prior to this, the area was managed for timber production and some exotic tree species (e.g. *Picea abies*, *Picea sitchensis*) were planted and are still present today. However, nowadays the woodland is dominated by beech (*Fagus sylvatica*), with some oaks (*Quercus robur*), ash (*Fraxinus excelsior*), birch (*Betula* spp.), maple (*Acer pseudoplatanus*) and alder (*Alnus glutinosa*).

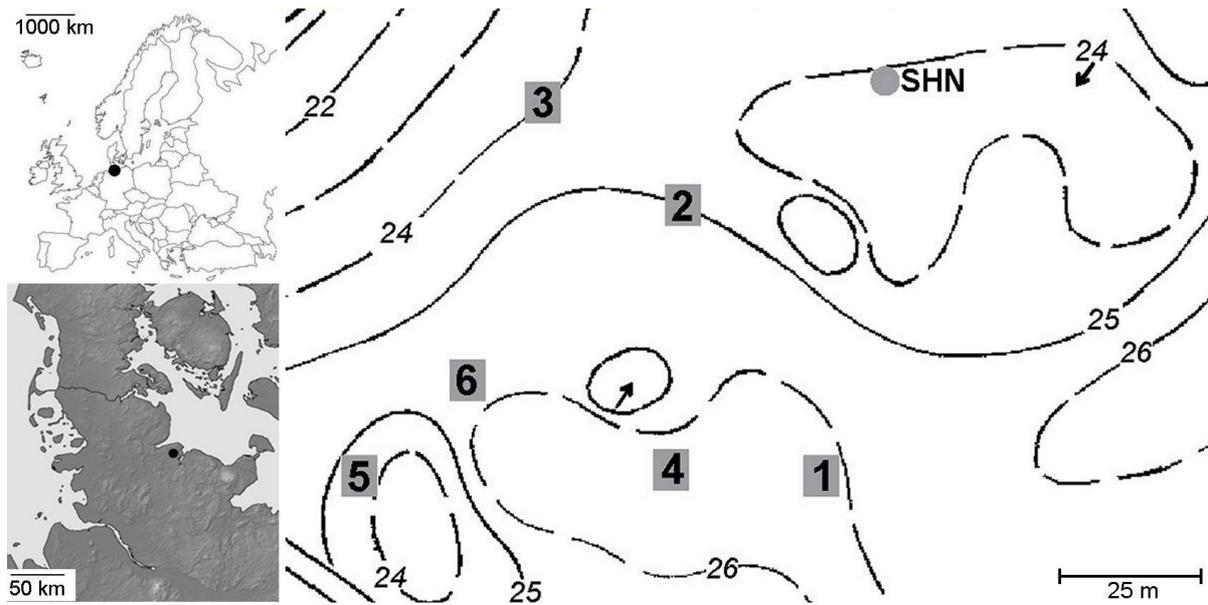


Figure 1. Study area Stodthagen Forest (Northern Germany). Left up and down: localization of the study site (black dot). Right: topographical map with elevation isolines (1m resolution). Number in grey squares: Soil samples location. Grey circle: Peat coring location.

Methods

Pedoanthracology

Six soil profiles, separated by about 50 m, have been dug, in the immediate vicinity (max. ca. 60 m) of a small mire (Figure 1). Soil samples were taken on each profile, for continuous 10 cm arbitrarily fixed layers (0-10 cm, 10-20 cm, etc., up to 60-70 cm), from the bottom to the top. The bottom of the soil profiles correspond to the presence of a compact soil horizon (i.e. compacted sand) or to the presence of the water table level. Between 5 and 10 liters of soil was collected per layer. Wood charcoal pieces bigger than 1 mm were extracted from the soil samples by wet and dry sieving, providing the ‘mega-charcoal’ signal. Charcoal assemblages made of pieces smaller than 1 mm were not taken into account in this investigation, since they are usually too small for the taxonomical identification. We expressed the total soil charcoal richness in charcoal concentration per unit of sediment: specific anthracomass (SA), in mg.kg^{-1} . This is the dry weight in mg of wood charcoal pieces bigger than 1 mm, divided by the dry weight of either soil profile (SAP), or layer (SAL), in kg (Carcaillet and Thinon, 1996; Talon, 2010). This provides comparable quantitative data. We also got comparative data for the pedoanthracological taxonomic assemblages. Part of the charcoal fragments extracted from soil samples were taxonomically identified with a stereo lens (Nikon SMZ1500, magnifications x7.5 to 112.5) and an episcopic microscope (Nikon ME600, x100, x200, x500), based on wood anatomy atlases (Schweingruber, 1990a; 1990b) and on the carbonized wood reference collection of the Institute for Ecosystem Research (Christian-

Albrechts-University of Kiel). For every sample 90 pieces of charcoal (or the total amount of charcoal pieces if less than a total of 90 pieces) have been randomly selected equitably shared in different size classes: > 5mm, 5 to 2 mm, and 2 to 1 mm (i.e. 30 charcoal pieces per class of size), for microscopic analysis. We express the results of the taxonomic analysis in concentration: specific anthracomass per taxon (i.e. SAT in mg.kg^{-1}). SAT is the dry weight of a taxon in one sample (all size classes added up) in mg, divided by the dry weight of earth of the corresponding sample in kg. We observed the SAT per layers of all the profiles of sampling cumulatively, by doing a principal component analysis of the data set in a correlation matrix, including 11 variables corresponding to the identified taxa. Before running the PCA, the overall SAT data set was centered and standardized to make the data comparable. This allowed to analyze together large charcoal amounts and small charcoal records. These data sets have been correlated to the depth of sampling on the six soil profiles, which are the 'explicative parameters' of the analysis. Because of the various depth of sampling we separated the data set in two different PCA: one with the SAT from the deepest profiles of sampling (STO1, 3 and 5; with seven 'parameters': A/0-10 cm, B/10-20, C/20-30, D/30-40, E/40-50, F/50-60, G/60-70) and another one with the data set from the less deep profiles (STO2, 4 and 6; with four 'parameters': A/0-10 cm, B/10-20, C/20-30, D/30-40).

Macro-charcoal analysis

A peat sequence was cored in 2004, from one of the small mires of the study site, for pollen and micro-charcoal analysis (Rickert, 2006). A second peat sequence "SHN", about one meter distant from the first coring location was cored in 2008 to obtain additional material. Both coring were done with a rod-operated Usinger piston corer which enables the retrieval of 1 m long and 80 mm diameter round undisturbed cores (Mingram *et al.*, 2007).

One longitudinal half of the most recent core was used for macro-charcoal analysis, following the "Oregon sieving method" (Millsbaugh and Whitlock, 1995) and using a digital picture treatment to obtain quantitative measurement (Mooney and Radford, 2001). Samples of 5 cm^3 were taken continuously every cm along the core, treated with 75 ml of sodium hypochlorite solution (NaOCl 13%) during 24 hours and sieved using a 200 μm mesh. Then, the samples were sorted with a stereo lens (magnification x10 to x110) to keep only charcoal pieces. The samples were digitally photographed with identical camera settings, and digitally analyzed with the Scion Image Program (Scion Corporation) to obtain the number and the surface area of macro-charcoals (density slice function; Mooney and Black, 2003). It is a matter of debate whether the quantification of the charcoal should be based on the number or on the area of

charcoal pieces per sample. Indeed, the quantification based on the counting of charcoal pieces might be a limiting factor, since secondary fragmentation might bias the signal (Ali *et al.*, 2009). However, the strong correlation (i.e. $R^2 = 0.98$), of the linear regression between the amount of charcoals (no.cm³) and the charcoal area (mm².cm³) per sample of the investigated peat sequence, indicate that the number and the area of charcoal pieces follow comparable trends. Therefore, we quantified the macro-charcoal record with the program CharAnalysis 0.9 (Higuera, 2009; Higuera *et al.*, 2009), which allows to model charcoal records along interpolated temporal series based on the counted number of macro-charcoal pieces (Higuera, 2009). Thus, the charcoal concentration per cm³ was estimated based on the macro-charcoal counting and was multiplied by the growth rate of the peat sequence (cm*year) to get the macro-charcoal accumulation rate. The low-frequency trends (i.e. 'background', C_{back} , reflecting rate changes of charcoal formation, secondary deposit, sediment mixing) was estimated in the interpolated macro-charcoal signal (i.e. C_{int}), with a weighted regression with a window of 500 yrs. Local fire events were identified based on macro-charcoal peak identification, while removing the low-frequency trend from the interpolated macro-charcoal signal (i.e. $C_{peak} = C_{int} - C_{back}$).

Pollen and micro-charcoal analysis

The other longitudinal half of the most recent peat sequence was used for pollen and micro-charcoal analysis. The new pollen data was correlated with the comprehensive description of the forest history based on the detailed pollen diagram and additional analysis of plant macro-fossils given in Rickert (2006).

Peat samples of 1 cm³ were treated according to standard methods (Faegri and Iversen, 1989), including the use of hot KOH and acetolysis. Pollen, spores and micro-charcoals (i.e. >10 µm) were counted on microscopic slides with a light microscope (magnification x400 and x1000). The nomenclature for pollen types follows Beug (2004). A minimum of 300 arboreal pollen (excl. *Corylus*) were counted per sample. The calculation of the pollen-percentage-values is based on the sum of arboreal pollen. Calculations and diagrams were done with TILIA and TGView (Grimm, 1993).

Radiocarbon dating

Eight taxonomically identified single wood charcoal pieces from soil samples were dated by AMS-¹⁴C (noted STO; Table 1). They were selected according to their position in the soil profiles, their size, their taxonomical significance and the general charcoal quantities and taxa

distribution in their respective charcoal assemblages. Four peat samples (noted SHN; Table 1), and a single wood charcoal piece (i.e. SHN63) from the 2008 sequence were also dated.

The radiocarbon ages were calibrated with a 2σ confidence interval, using Oxcal 4.1.56 program (Bronk-Ramsey, 2010) and the IntCal09 dataset (Reimer *et al.*, 2009).

The relation age / depth of the peat sequence was modeled based on the five SHN calibrated AMS- ^{14}C dates, using the tool ‘deposition model’ of Oxcal 4.1.56 program (P_sequence modeling with a ‘k’ value of 1 cm^{-1} ; Bronk-Ramsey, 2008).

Results

Pedoanthracology

In total, 38.8 g of wood charcoal was extracted from 236 kg of sampled soil. The profiles 1 and 2 are particularly rich in charcoal. Profiles 3 to 6 contained lower amounts. The Specific Anthracomass per Layer (SAL) of the different profiles shows a pronounced heterogeneity (Figure 2). However, the three profiles which were sampled in greater depth (P1, P3, P5) showed low SAL in the deeper layers.

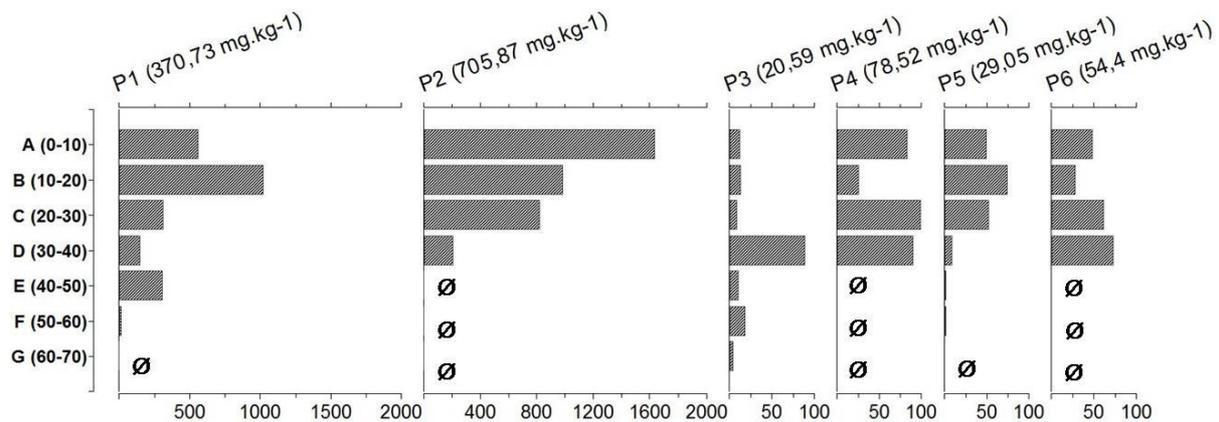


Figure 2. Wood charcoal total quantities per layer for the six soil profiles of Stodthagen Forest. x-axis: anthracomass in mg.kg^{-1} ; y-axis: layer name and depth in cm. Symbol Ø meaning no sample.

From the total amount of extracted charcoal, 1922 pieces, or 18.9 g, have been taxonomically analysed. From this amount, 358 pieces were indeterminable (about 5 % of the extracted charcoal weight), mainly due to their small size. The ratio ‘total weight of the wood charcoal pieces analyzed / total number of the wood charcoal pieces analyzed’ provides an average weight per fragment of c. 10 mg. Because of this small average weight/size some pieces have been identified to a limited taxonomical type (e.g. ‘cf. *Carpinus*’).

Nevertheless, 11 taxa were identified (Figure 3). In all the six profiles, the two clearly dominant taxa are *Quercus* and *Fagus*. Other taxa present a small amount and are irregularly

distributed in the different profiles and at different depths (*Acer*, *Alnus*, *Carpinus*, *Corylus*, *Tilia*). Low SAT of conifer type was identified in P6.

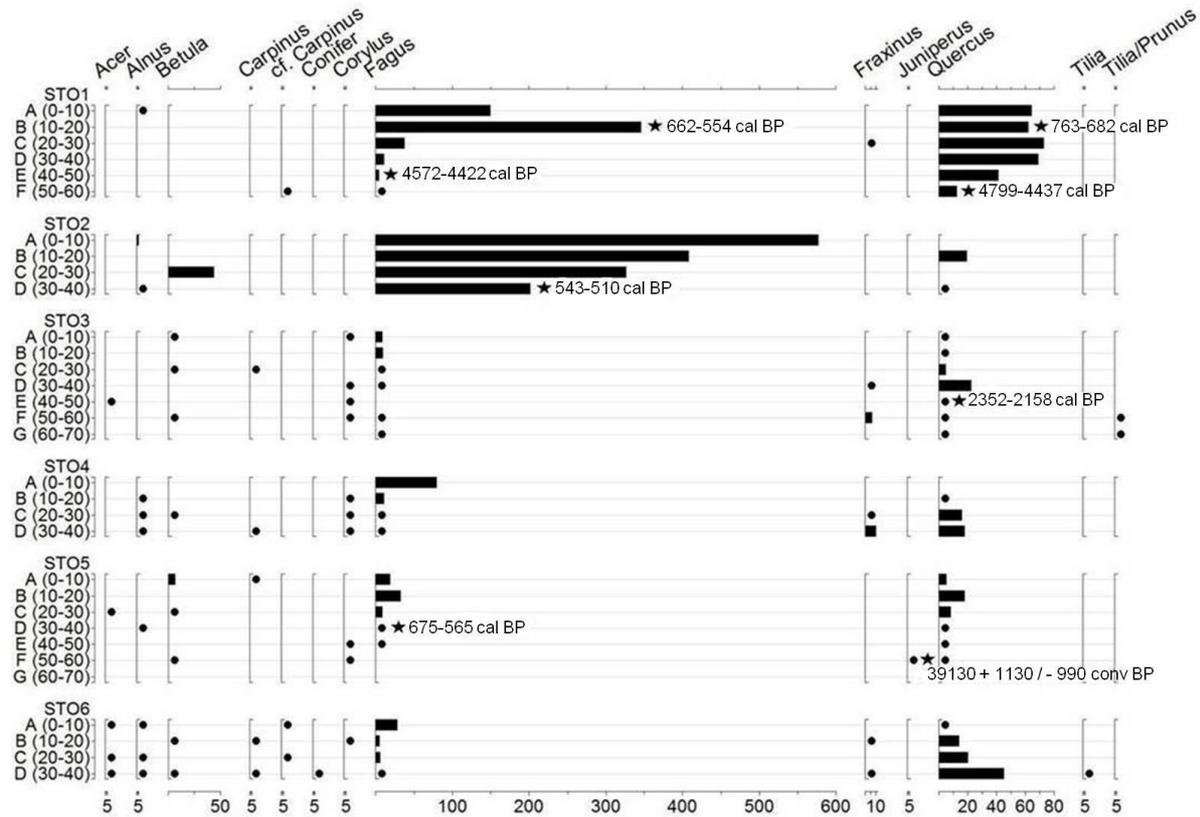


Figure 3. Wood charcoal total quantities identified per taxa (SAT), for the different layers of sampling of the six soil profiles of Stodthagen Forest. x-axis above: identified taxa; x-axis below: anthracomass in mg.kg^{-1} ; y-axis: profile name and layers of sampling in cm; dot: $\text{SAT} < 5 \text{ mg.kg}^{-1}$; star: radiocarbon dates in calibrated years BP.

Sampling Site	Lab. ref.	Depth (cm)	Taxa	Radiocarbon age (BP)	BP cal. age (2σ)*	BC/AD cal. age (2σ)*
STO1-B	KIA41179	15	<i>Fagus</i>	630 ± 25	662-554	AD 1288-1397
STO1-B	KIA37431	15	<i>Quercus</i>	810 ± 20	763-682	AD 1187-1269
STO1-E	KIA37433	45	<i>Fagus</i>	4030 ± 30	4572-4422	BC 2623-2473
STO1-F	KIA41180	55	<i>Quercus</i>	4065 ± 30	4799-4437	BC 2850-2488
STO5-D	KIA38759	35	<i>Fagus</i>	680 ± 20	675-565	AD 1276-1386
STO5-F	KIA38761	45	<i>Juniperus</i>	39130 + 1130 / - 990	\emptyset	\emptyset
STO2-D	KIA37434	35	<i>Fagus</i>	505 ± 20	543-510	AD 1407-1441
STO3-E	KIA38760	45	<i>Quercus</i>	2280 ± 35	2352-2158	BC 403-209
SHN	KIA42502	19	\emptyset	760 ± 25	728-669	AD 1223-1281
SHN	KIA42504	99	\emptyset	5215 ± 40	6176-5906	BC 4227-3957
SHN	KIA42505	173	\emptyset	8740 ± 45	9892-9558	BC 7943-7609
SHN	KIA38762	63	<i>Quercus</i>	3880 ± 35	4419-4161	BC 2470-2212
SHN	KIA41186	50	\emptyset	1570 ± 25	1526-1404	AD 425-546

Table 1. AMS-14C dates from single charcoal pieces from soil samples (STO) and from the peat sequence (SHN) (Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research, University of Kiel, Germany). * 2σ calibrated with Oxcal 4.1.56 (Bronk-Ramsey, 2010).

Only one piece of *Juniperus* was identified in P5. *Fraxinus* and *Betula* have more important SAT, but are also irregularly distributed among the profiles and the layers. Moreover, in the PCA (Figure 4) we principally observed that in both plotted data sets the *Fagus* record, with *Alnus*, is connected to the upper layers A, whereas *Quercus* and *Corylus* seems to be more connected to the layers B and C. The *Betula* layers richness distribution seems to be correlated to the upper layers (A, B and C), and the one for *Acer* seems to be connected to the layer D and, when considering the deeper layers of sampling, to layer G.

Four of the radiocarbon dates correspond to the middle Ages (three pieces of *Fagus* and one of *Quercus*), one piece of *Quercus* is from the Iron Age, and two pieces are from the Bronze Age (one *Fagus* and one *Quercus* piece). One piece of *Juniperus* dates from the Weichselian glacial time.

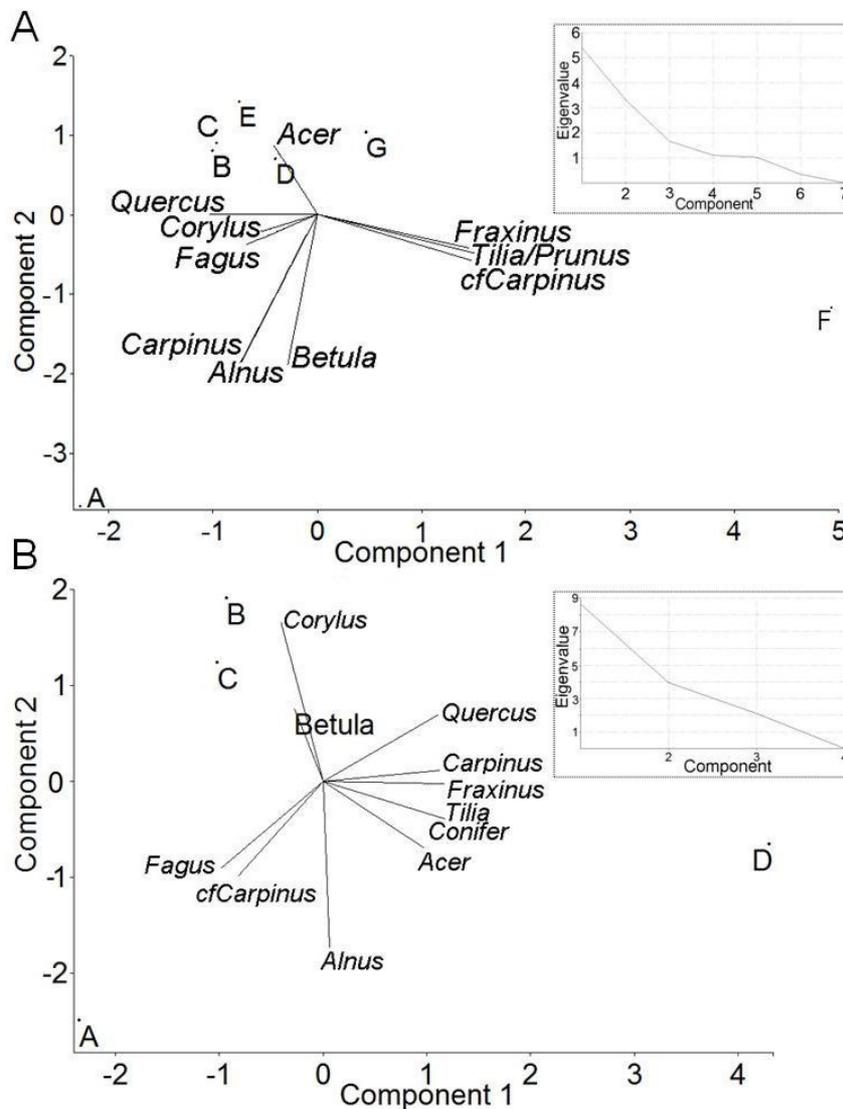


Figure 4. Principal Component Analysis of the identified taxa in soil charcoal assemblages of the Stodthagen Forest, compiled per layer of sampling. A: from deep soil profiles (n=7 layers of sampling, A=0-10 cm; B=10-20; C=20-30; D=30-40; E=40-50; F=50-60; G=60-70, and p=11 identified taxa all samples cumulatively); B: from short soil profiles (n=4 layers of sampling, A=0-10 cm; B=10-20; C=20-30; D=30-40, and p=11 identified taxa all samples cumulatively). The eigenvalues per components are presented in the upper-right corner. Plotted by PALaeontological Statistics software, version 1.90, (Hammer, 2009).

Macro-charcoal analysis

Macro-charcoal pieces were present in only 15 samples out of a total of 218 one-cm samples of the total length of the peat sequence. Macro-charcoal accumulation happened only rarely during the Holocene. The age / depth relation indicates different peat growth rate phases along the time span covered by the peat sequence (Figure 5).

According to this age model, the macro-charcoal signal indicates weak charcoal accumulation during the Preboreal, the Atlantic, and the Subatlantic phases. A richer macro-charcoal accumulation is recorded during the Subboreal at a depth of 63 cm (i.e. charcoal pieces dated at 4419-4161cal BP).

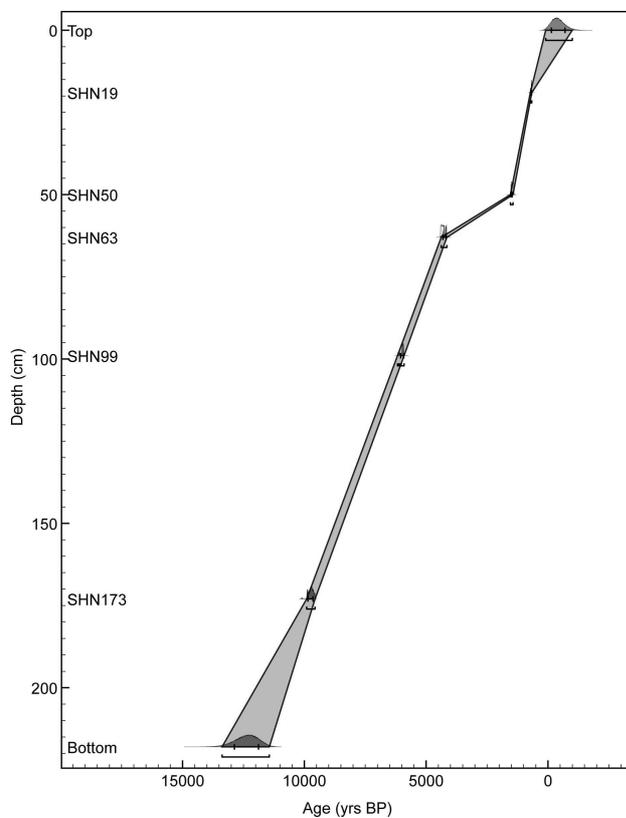


Figure 5. Age / depth modeling of the second peat core “Stodthagen 2” (SHN). x-axis: age in cal. yrs BP, with plotted for all of the five dates the 2 σ confidence interval. y-axis: depth in cm. Plotted by OxCal 4.1.56 program (Bronk-Ramsey, 2010).

Three macro-charcoal peaks have been identified (Figure 6): one during the Subboreal, with an important macro-charcoal accumulation, and two others during the Subatlantic (i.e. about 380 cal BP and 544 cal BP, based on the peat growth rate).

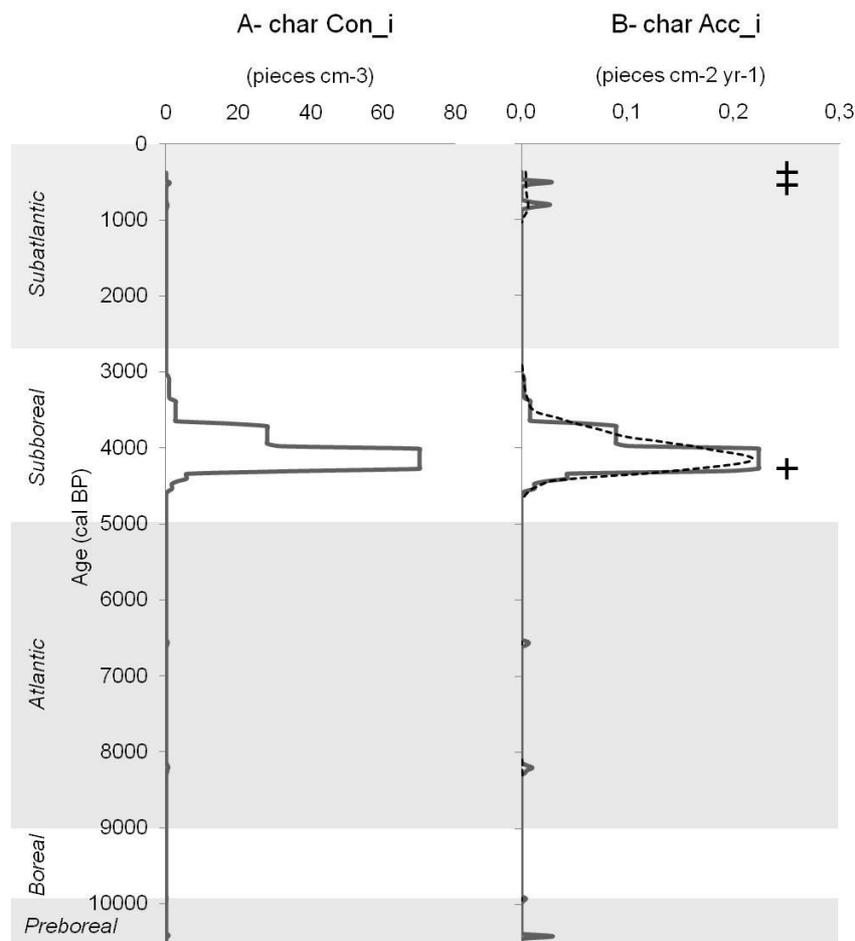


Figure 6. Macro-charcoal signal of the peat sequence SHN. A- char Con_i: macro-charcoal concentration (x-axis: number of pieces per cm³), along time in cal. yrs BP (y-axis). B- char Acc_i: full line: macro-charcoal accumulation rate (x-axis), along time in cal. BP (y-axis); dotted line: macro-charcoal signal background; plus: fire event.

Pollen analysis and micro-charcoal analysis

The main palynological information is summarized per local pollen assemblage zones (LPAZ) identified on the two peat sequences in table 2. Since the age / depth model of the most recent peat sequence (Figure 5) fits to the chronological indication based on the identified Local Pollen Assemblages Zone of the first peat sequence (LPAZ; Overbeck, 1975), we use the LPAZ identified on the two peat sequences to make them fitting chronologically (Figure 7).

LPAZ	core 1 [cm]	core 2 [cm]	Pollen spectrum description	yrs [cal BP]
G	0-38	-	Curves of <i>Plantago lanceolata</i> and <i>Rumex</i> type are continuous again; wild grass-type increases slightly; amount of micro-charcoals increases considerably in the second half of the zone	present - 1100
F	38-50	37-47	Indicators for an opening of the forest canopy (<i>Pinus</i> , <i>Betula</i> , <i>Corylus</i> , <i>Salix</i> , wild grass-type, <i>Calluna</i> , and <i>Pteridium</i>) reach values which are as low as before the beginning of E1; curves of <i>Plantago lanceolata</i> and <i>Rumex</i> -type reach only very low values	1100 - 1500
E2	50-55	47-52	Indicators for a forest opening in E1 and the amount of micro-charcoals decline; rise of <i>Fagus</i> -curve	1500 - 2000
E1	55-64	52-64	Wild grass-type, as well as <i>Corylus</i> , <i>Salix</i> , <i>Pinus</i> , and <i>Betula</i> increase considerably; <i>Plantago lanceolata</i> , <i>Rumex</i> type, <i>Calluna</i> , and <i>Pteridium</i> increase slightly; high amounts of micro-charcoals	2000 - 4300
D	64-74	64-79	<i>Ulmus</i> has declined ("elm fall"); <i>Tilia</i> is decreasing; continuous curves of <i>Plantago lanceolata</i> , <i>Rumex</i> type and later <i>Fagus</i> starts; higher amounts of microcharcoals esp. in core 2	4300 - 5000
C	74-151	79-145	<i>Pinus</i> and <i>Corylus</i> decline; <i>Tilia</i> and <i>Quercus</i> dominate; <i>Alnus</i> starts to rise; <i>Ulmus</i> declines at the end	5000 - 8300
B2	151-186	145-185	<i>Pinus</i> dominating, <i>Quercus</i> reaches first maximum. <i>Ulmus</i> and <i>Tilia</i> are present. <i>Corylus</i> rises steeply towards a first maximum. Microcharcoals slightly increase	8300 - 10500
B1	186-204	185-215	<i>Pinus</i> and <i>Betula</i> dominant, <i>Corylus</i> and <i>Salix</i> with low amounts. Microcharcoals have a high no. in the first core	10500 - 11500
A	214	-	Typical taxa for late glacial times as <i>Hippophae</i> , <i>Helianthemum</i> , <i>Thalictrum</i> and <i>Artemisia</i>	-

Table 2. Main palynological results per Local Pollen Assemblage Zone of the two peat sequences "Stodthagen 2 (SHN)". Core 1 from Rickert (2006); Core 2 from parallel coring 2008; Yrs in cal BP of the LPAZ base on age / depth modeling of the core 2.

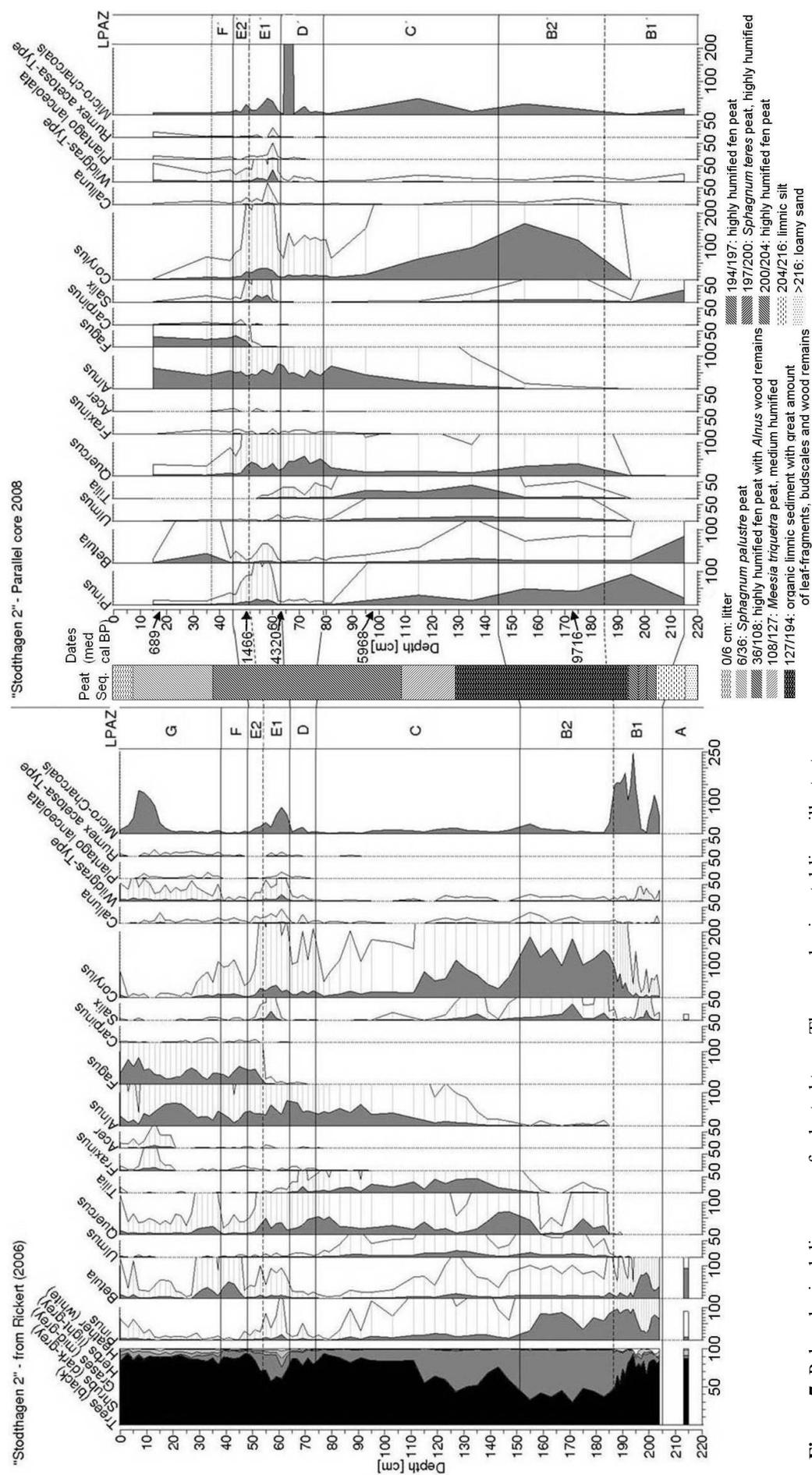


Figure 7. Pollenological diagrams of selected taxa. The grey horizontal lines illustrate the connection of the two cores from the small mire SHN along the LPAZ. For the detailed diagram of the first core see Rickert (2006). Date in medium age BP of the calibrated range with 2σ interval.

Discussion

Taphonomical considerations

It has been difficult to identify any correlation between soil stratigraphy and vertical distribution of charcoals, especially because the sampled soil profiles did not have clearly marked soil horizons, except for a richer content in organic matter in the upper part (i.e. from the current soil surface to 5/10 cm) and an increasing compactness with the depth, from 40 cm (i.e. general soil sequence: O/Ah – Bv; FAO, 2006). However, based on the comparison of the pedoanthracological and the pollen spectra, we assume that vertical charcoal distribution in the soil is globally correlated to the age (Figure 3). This is supported by principal component analysis (Figure 4), which principally has shown the correlation of the upper soil layer of sampling to *Fagus* charcoal richness, and the correlation of the underneath layers to *Quercus* charcoal richness. Nevertheless, the soil charcoal vertical distribution does not follow a strict age / depth deposition since the soil is a ‘dynamic archive’. Charcoal pieces might be mixed notably due to pedoturbation, bioturbation, and uprooting processes (Yeates and Meulen, 1995; Carcaillet, 2001). Nevertheless, we identified clear patterns (i.e. trends) of the Holocene forest dynamic in the charcoal spectra along the depth, especially the change from oak dominated to beech dominated forest. This is why the Pleistocene age of the single identified *Juniperus* charcoal is unexpected. It does not fit to the charcoal taxonomical assemblage of this soil layer. Its presence in the local charcoal record might be due to large scale transport during ice withdrawal or soil movement connected to Weichselian ice cover fluctuations (Lagerlund *et al.*, 1995; Siegert *et al.*, 2001). This is supported by the rarity of other conifer taxa identified in all pedoanthracological assemblages (Figure 3) and the presence of charcoal pieces dated to the mid- and early-Holocene from a comparable sampling depth (Table 1). The occurrence of this taxon can also be the indication of the presence of a few Junipers, as pioneers. *Juniperus* might have grown on-site during a warmer phase of the Weichselian Glaciation (i.e. isotope stages three; Harrison and Sanchez Goñi, 2010; Hubberten *et al.*, 2004).

The flat local relief, with small heterogeneity, and the minimum mesh size of sieving of 1 mm (providing 'mega-charcoals') allows us to interpret the pedoanthracological assemblage as being relevant locally (i.e. stand-scale resolution; Carcaillet and Thinon, 1996; Touflan *et al.*, 2010). It is very improbable that the charcoals were transported from further away. This is also the case for the macro-charcoals from the peat sequence (i.e. >200 µm; Clark *et al.*, 1998; Scott *et al.*, 2000; Whitlock and Millspaugh, 1996).

Pollen and micro-charcoal reflect predominantly stand-scale signals as well, because of the small size of the cored palaeoarchive (Bjune *et al.*, 2009; Calcote, 1998; Higuera *et al.*, 2005). However, we do not exclude the recording of regional signals in the peat sequence, especially during the early Holocene, when the surrounding of the mire was not yet densely forested allowing pollen transportation at greater distances.

As can be seen in Figure 5, peat grew more slowly during the Atlantic, with more than 220 yrs per cm of peat from 50 to 63 cm depth. Because we did not observe a change in the lithology at this depth (Figure 7), and since the age / depth model is well fitting to the LPAZ, we assume that the peat cores are complete sequences covering the Holocene without any hiatus. The change in peat growth rate might be due to changes in the hydrological regime of the mire system but no clear data can elucidate this. The modeled 'top' and 'bottom' ages in figure 5 have a large 2 sigma range due to the fact that the layers from which ¹⁴C ages were measured are distant from the top and bottom of the core. However, since the indications from the biostratigraphy fit with the modeled peat growth rate, we use that record to precise the chronology of these parts of the peat sequence. Thus, the beginning of the peat sequence is certainly close to the youngest part of the modeled temporal range (about 11000 yrs BP), and the end is certainly close to present days, as indicates the LAPZ.

Forest dynamic and fire history

Early- and mid Holocene

According to the pollen data, chronologically referenced by the age-depth model, the area under study was covered by a pine and birch woodland during the early-Holocene (LPAZ B). This fits to the global chronological and palaeobotanical regional knowledge (Litt *et al.*, 2001, Overbeck, 1975). Micro- and macro-charcoal amounts are high, indicating a relatively high fire activity. These early-Holocene fires should have occurred under climatic control (e.g. lightning and dry phase), as suggested by some studies (Goldammer and Page, 2000; Power *et al.*, 2008).

The steep increase of *Corylus* pollen accompanied by the beginning of the *Ulmus*- and the *Quercus*-curves marks the early Holocene vegetation change in north-western European lowlands (LPAZ B1 to B2; Overbeck, 1975) when a still open oak forest was established. The simultaneous occurrence of *Tilia* and *Alnus* around 9000-8500 cal BP (end of LPAZ B2) seems to be the first manifestation of the immigrating species in the local woodland. From c. 8500 cal BP onwards, *Quercus* and *Tilia*, together with *Ulmus* formed the arboreal vegetation, while *Alnus* grew on sites close to the ground-water table and at the margin of the mire

(LPAZ C). Low non-arboreal pollen percentages during the second half of LPAZ C (i.e. mid-Atlantic) indicate a dense forest with just a sparse herbal layer. *Tilia* and *Ulmus* are continually declining in the vicinity of the mire. The rarity of these taxa in the charcoal spectra fits well with the absence of any local fire event during the Atlantic according to the macro-charcoal record.

Late Holocene

Quercus and *Alnus* are the dominating trees since c. 5000 cal BP (LPAZ D). *Alnus* is part of the mire vegetation, and *Quercus*, together with *Corylus*, is located on the mineral soil. Pollen and soil charcoal spectra both support this fact. Considering that the pollen productivity of hazel is promoted by a more open forest structure (Andersen, 1980), the small increase of the *Corylus* pollen, together with the first occurrence of *Plantago lanceolata*, indicates a moderate first human impact, possibly as a small opening. This impact must have been very weak since the tree pollen percentages are still high (80 – 90%). During the LPAZ E1 (c. 2000-4300 cal BP), the forest was opened by human activity. Micro- and macro-charcoal records show high accumulation rates. At a depth of 60-66 cm, a layer of charcoal is clearly visible in the second core and is made entirely of *Quercus* charcoal. This local fire event was dated to 4419-4161 cal BP (Figure 6). Due to the restricted horizontal extension of this charcoal layer in the peat (i.e. this charcoal layer is not visible in the first coring sequence), we assume that a burning stem or branch fell onto the mire, and this fire event was probably not intensive since there is no indication at all in the first core (Rickert, 2006). This highlights the heterogeneity of the peat palaeo-data archiving, correlated to local situations, even when analysing closely localized peat sequences from the same mire (Dietz, 2001; Rohrer, 2006; De Klerk and Hölzer, 2009). Two other soil charcoal pieces were dated within this time period (Table 1). Considering the possibility of an ‘old wood effect’ on the radiocarbon dating (Gavin 2001), these dates might be the legacy of the same fire event. Local fires might have opened the canopy. Those fire events are probably connected to human activities since, as different to other biomes, fires in Central Europe are very likely ignited by humans, at least since the Neolithic (Carcaillet *et al.*, 2002; Higuera *et al.*, 2008; Huerta *et al.*, 2009). Moreover, with an oceanic climate prevailing, Subboreal broad-leaf forest is very unlikely to burn without the action of humans (Wanner *et al.*, 2008). Tree pollen values drop to a total of 60 %. *Corylus* and wild *Poaceae* pollen records increase due the more open conditions, which is also supported by the increase of long-distance transported *Pinus* pollen. However, the opening must have remained local since the amounts of indicators for human impact stay low. There is no evidence for arable fields or clearance of the forest on a larger scale, so the

forest continuity seems to remain uninterrupted in this part of the woodland. During the LPAZ E2, decreasing percentages of anthropogenic indicators, as well as those of indicators for forest grazing, and peat macro-charcoals reflect the decrease of human impact and its associated fire disturbances. As a possible consequence, *Fagus* spread rapidly (Björkman, 1999). This spread of *Fagus* indicated in the pollen record happened later than the *Fagus* soil charcoal date of 4572-4422 cal BP, which is the oldest radiocarbon dated *Fagus* macroremain so far in Northern Germany. That demonstrates the ancient local presence of *Fagus*, earlier than expected from the local pollen record, but also from the general knowledge about *Fagus* immigration in the northern part of Central Europe (Bradshaw *et al.*, 2010; Hannon, 2002; Tinner and Lotter, 2006). Since the pollen records show only a few grains of *Fagus* during this period, we assume that only a few beech trees were present in the oak-dominated forest, which were hardly recorded in the pollen archive. Moreover, based on pollen indication, the opening of the woodland seems to have, in the long-term, favored the *Fagus* development. We observe that, after the fire event of the Bronze Age, detected at a local scale (Figure 6), the woodland stayed at a low forest density, maybe maintained by human activities, for a possibly long period until the forest canopy closed again especially due to the development of *Fagus* (Figure 7). At a larger scale, the development of *Fagus* corresponds well to the early Subatlantic transition from an oak forest to a beech forest generally found in Northern Germany (Nelle and Dörfler, 2008), in Denmark (Hannon *et al.*, 2000), and in southern Sweden (Berglund *et al.*, 2008), as well as in Central Europe (Berglund *et al.*, 1996, Kalis *et al.*, 2003), which is also clearly identified in the pollen record of this study. This transition is also clearly visible in the pedoanthracological assemblages (Figure 3). During LPAZ F, a dense forest prevailed, probably little or not affected by human activities. The recovery of forests and the onset of beech-dominated forests is common for Northern Germany during the Migration Period. This reflects the decline of the human population during this time of deteriorating climate (Dressler *et al.*, 2006; Wiethold, 1998). In opposite, the middle Ages show an important increase in micro-charcoal accumulation rates, two macro-charcoal peaks in the peat cores are identified as local fire events (LPAZ G). Four soil wood charcoal pieces were also dated to Medieval Times. There are no signs of an opening of the forest canopy in the pollen record; it must be assumed that the woodland in the vicinity of the small mire was not affected by the occurrence of these two recorded fire events. This is also the case for a local fire event which was identified by the dating of a wood charcoal piece from soil during the Iron Age, which was not observed in the peat sequence as neither micro- nor macro-charcoal. Though we have only one chronological evidence for this fire event, the dating

illustrate that a fire of whatever source produced this charcoal piece. Moreover, the general soil charcoal distribution over the study site and the similarities in terms of the charcoal taxonomic assemblages of the samples of the different profiles, allow to rule out the possibility of a single ‘campsite fire’ as an explanation for the signal. The small charcoal signal, and the heterogeneity in the amount of charcoal and in the chronological indication, might also be due to the fact that the charcoal recording depends on the type of fire. Indeed, variability in fire regime potentially changes the charcoal formation (especially fire magnitude, surface extension, and frequency), and thus might change the charcoal accumulation and conservation (Scott and Damblon, 2010). One possibility is that the fire events which formed the charcoals conserved in the soil were limited in intensity and extension, and might have been driven by humans to manage the landscape as it was done over most of the continent during the late Holocene (e.g. Carcaillet *et al.*, 2002; Tinner *et al.*, 2003; Valsecchi *et al.*, 2010). Higuera *et al.* (2005) postulated that this type of fire does not have enough severity to be always clearly recorded, even in a small-hollow (Gardner and Whitlock, 2001; Niklasson *et al.*, 2002). However, the reasons for the formation of the charcoal remain a matter of debate. This highlights the relevance and the importance of the use of a multiproxy approach at a stand scale.

Conclusion

The combined approach of this investigation provides complementary data at various spatial scales, showing a high potential for reconstructions of Holocene woodland history. It is especially interesting for the investigation of forest dynamics at the stand scale.

The pollen record indicates the continuity of forestation at the site studied. The soil charcoal spectra is not only in agreement with this indication but complements it by showing the on-site presence of beech earlier than expected from the pollen diagram “Stodthagen 2”, as well as from other regional diagrams. Moreover, this multiproxy approach is also valuable for the assessment of the fire history. This shows the identification of fire events based on the pedoanthracological data, which are not recorded in the sedimentary charcoal signal, and vice versa. This investigation provides many data that can be interpreted at a local spatial resolution (i.e. stand scale). These palaeoecological data could be linked to forest conservation action. Indeed, stand scale is the basic spatial unit for forest planning and management. Consequently, assessing the history of a site, it is important to provide data at the corresponding scale, which some proxies, e.g. pollen analysis can do only with some restrictions. In the case of the Stodthagen Forest, the major insights for forest conservation,

mostly based on late-Holocene data, are the following. The current forest stand composition and structure (i.e. with undergrowing trees and scrub vegetation records in pollen and pedoanthracological records as well) are made of indigenous species with ancient presence on-site. The long-term forest dynamic is characterized by the ‘classical’ Holocene forest tree succession in northern Central Europe, with apparently a weak human disturbance. This information increases the biological and patrimonial value of the site, as an ancient and moderately disturbed woodland area and justifies the conservation management of the area by the ‘Stiftung Naturschutz’. The on-site identified ancient presence of *Fagus*, support the interest and importance for the nature conservation of the Stodthagen Forest, as an ancient *Fagus* dominated forest.

Concerning fire history, macro- and mega-charcoal records proved that fire occurred on-site. During the early Holocene, the past fire regime seems to be natural, under climatic control. During the late Holocene, we postulate that the fire regime was human controlled, occurring at a fine spatial scale, maybe for specific human purpose like forest canopy opening. This is supported by the on-site charcoal records, combined to the fact that late Holocene temperate broadleaf forests are not easily inflammable forests without human ignition.

This multiproxy approach might be applied to other, potentially ancient forests to better understand their history, notably at local scale. The combination of several stand-scale investigations from on a region might allow for regional and even supra-regional conclusions in the future.

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6. Central Germany

6.1 Holocene fire history and forest composition in the Upper Harz Mountains (Central Germany), based on the analysis of charcoal records from peat and soil archives

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Abstract

Having identified a lack of fire history investigations in Central Europe, including areas with ‘fire sensitive’ forests, charcoal records from soil and peat archives were analysed in two areas in the upper part of the Harz Mountains in Central Germany. At each area, a mire was used for peat sequence coring (macro-charcoal analysis), as well as a forest site for soil charcoal sampling. The local fire signals were obtained, as well as an indication of the fuel material from taxonomical identification of soil charcoals.

These various records have been compared to the known forest history of the investigated area from pollen records. The identification and the radiocarbon dating of local fire events shows a fire signal synchrony on a larger spatial scale during the medieval period fitting to the general knowledge about the local forest history. However, local fire events unexpectedly older than medieval time were identified. The fires occurred during different periods at the diverse sites. This asynchrony allows the identification of fire occurrences on restricted areas. The ancient local presence of *Picea* forest and wood charcoal of *Fagus*, which was recorded in very small quantities, have been identified as main taxonomical indications.

Key words

Fire history, soil mega-charcoal, peat macro-charcoal, taxonomical analysis, Central Europe

Introduction

In Central Europe ecosystem dynamics have been strongly impacted by human activities (Behre, 1988; Berglund, 2011; Magri, 1995), parallel to human societies development (Kalis *et al.*, 2003). One of the most important factors of the ecosystem dynamics change under anthropogenic control has been the human usage of fire (Patterson III and Backman, 1988), either for domestic usage or as a tool to ‘manage landscapes’, e.g. by canopy opening for grazing or cultural fields (Bork and Lang, 2003). As a consequence, the natural fire regime has also been considerably influenced by the anthropogenic usage of fire (Clark *et al.*, 1989; Whitlock *et al.*, 2010). However, Central European fire history has been less investigated than in biomes in Mediterranean (Vanni re *et al.*, 2008), alpine (Carcaillet and Thimon, 1996), and Boreal regions (Olsson *et al.*, 2009). This lack in fire history investigation is probably due to the fact that most of the Central European woodlands are composed of broad-leaf temperate species (Bohn *et al.*, 2000), which are not easily ignited woodlands. However, some high altitude parts of low mountain ranges of Central Europe are covered by coniferous forest, which is potentially more sensible to fire ignition. Here, fire might have a more crucial role in forest dynamics than previously presumed. However, so far only few data exist to assess this, especially on a long temporal scale.

This is the case concerning the most northern low mountain range of Central Europe, the Harz Mountains. The vegetation history of the upper part of this mountain range is well investigated on a regional scale (Beug *et al.*, 1999). The important role of *Picea abies* forest and its history, as well as the broad temporal and spatial development patterns of *Fagus sylvatica* are assessed. Considerable human impact on the forest especially for mining purposes is clearly identified in the ‘‘Upper Harz’’ since the Middle Age, leading to a more or less complete deforestation, because of the immense wood and charcoal resources needed (Matschullat *et al.*, 1997; Monna *et al.*, 2000). So far no work has been done on the fire history, based on charcoal records from natural archives, which store relevant data to investigate the past fire regime (Whitlock and Larsen, 2001).

Here, we present new data on fire events in the Harz Mountains. A combined analysis of charcoal records extracted from soil profiles as well as from peat sequences from mires, at two selected areas in the upper Harz Mountains, in the Brocken area, has been used. Local fire history and forest tree composition were assessed with a multiproxy approach which was hitherto rarely done.

Study area

The Harz, the most northern low mountain range of Central Europe, has a north-west/south-east orientation. Its highest mountain top is the Brocken with 1142 m a.s.l. Soil charcoal sampling has been done on two sites in the Harz National Park. The site Heinrichshöhe (HEI; N51°47'5''/E10°38'1'') is a south-eastern facing slope at c. 920 m a.s.l., the site Renneckenberg (REB; N51°47'7''/E10°39'7'') is located on an east facing slope at c. 700 m a.s.l. (Fig. 1).

The HEI local climatic data, from the closest meteorological station, at comparable elevation, are 1814 mm of annual mean rain fall and 2.9°C of annual mean temperature (Brocken station, mean 1961-1990; Deutscher Wetterdienst, 2011), and 1275 mm of annual mean rain fall and 5.3°C of annual mean temperature for REB (Schierke station, mean 1961-1990; Deutscher Wetterdienst, 2011). Both sites have regular slope inclinations of about 25/30°, on granitic bedrock (Gabriel *et al.*, 1997), and are currently covered by closed *Picea abies* forest. Correlated to each of the soil charcoal sampling sites mires have been cored to get peat sequences for macro-charcoal analysis. In direct vicinity to the site HEI, the peat bog Brockenbettmoor (sequence BBM) at about 900 m a.s.l. is located at the base of the Heinrichshöhe hill slope. The mire Blumentopfmoor (sequence BTM), directly neighbouring the site REB, is located at the base of the Renneckenberg hill slope, at about 670 m a.s.l. (Fig. 1).

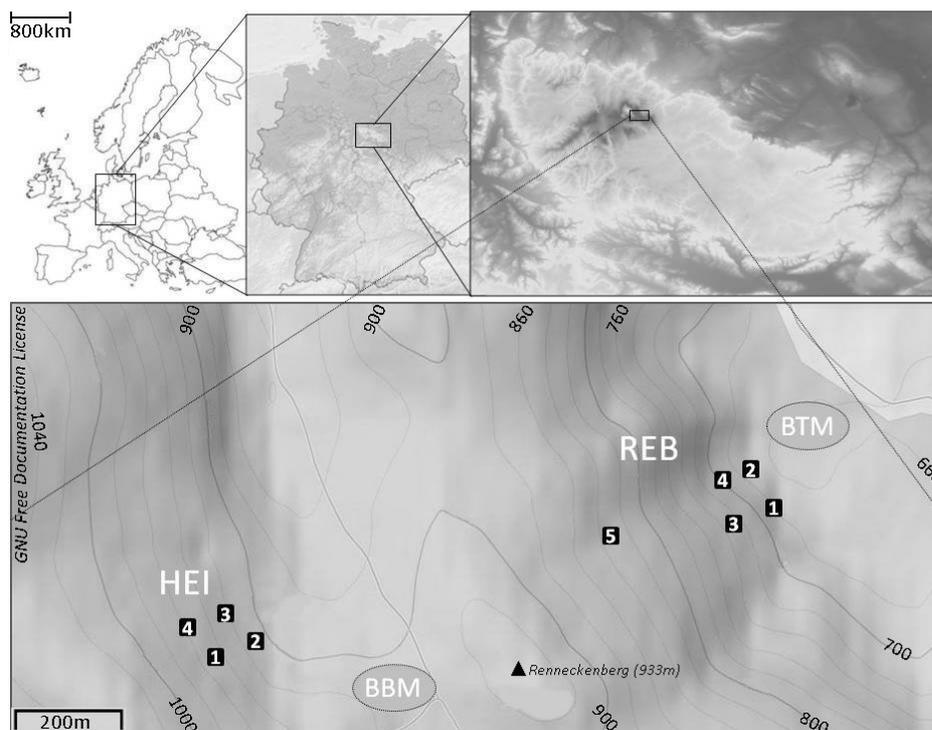


Figure 1. Maps of localization of the sampling sites in the Upper Harz Mountains, Germany. Heinrichshöhe: HEI, soil profile 1 to 4; Renneckenberg: REB, soil profile 1 to 5; peat sequences of Brockenbettmoor (BBM) and of Blumentopfmoor (BTM).

Sampling strategy

To get reliable and comparable soil charcoal assemblages we applied a repeatable protocol of sampling (Carcaillet and Thinon, 1996; Touflan *et al.*, 2010). On each site we manually dug several soil profiles of ca. one meter length, with varying depth depending on the bedrock deepness. These soil profiles were about 100 m distant from each other. Four soil profiles have been dug at HEI, between 910 to 950 m a.s.l., four others have been dug at REB, between 680 and 720 m a.s.l., with one additive soil profile, slightly more distant from the others, at about 830 m a.s.l. (Fig. 1).

Soil profiles were described concerning the identification of soil horizons, colour, depth, etc. (Schoeneberger *et al.*, 2002). On every soil profile, layers of soil sampling of a maximum of 10 cm height were defined, to keep a small sampling resolution along the depth, and which were correlated to the previously identified soil horizons. For each of those layers of sampling, named with a big letter by alphabetic order from the surface to the profile bottom, we took 5 to 10 litter of soil, starting from the profile base towards the soil surface.

To get the peat macro-charcoal signal, several peat sequences were cored using the rod-operated Usinger piston corer, which provides undisturbed cores 1 m long and with 80 mm diameter (Mingram *et al.*, 2007). Based on previous mire description for the Brockenbettmoor (Beug *et al.*, 1999), we tried to core at the deepest point, to get the longest possible cores with thus the best time resolution. Here, two parallel peat sequences were cored to get overlapping material, (i.e. BBM sequence; N51°47'832"/E10°39'724"). At the Blumentopfmoor a single peat core sequence was gained after assessing the maximal peat deepness (i.e. BTM; N51°47'843"/E10°39'811").

Data collection

Soil charcoal analysis

Charcoal assemblages have been extracted from soil samples, including all charcoal pieces bigger than one mm, which is the minimal size for routine taxonomical charcoal identification (Thinon, 1992). For every sample, mineral and organic material has been separated by wet sieving. The organic matter, which contains the charcoal pieces, was dried and divided, by dry sieving, in three classes of size (i.e. 1-2; 2-5; >5 mm). After this, single charcoal pieces have been extracted by manual sorting under a stereo lens (Nikon SMZ 1500, magnification x7.5 to x112.5). The amounts of charcoal material were quantified as weight concentration. This is the ratio between the charcoal amount (in mg) and the amount of earth smaller than 5 mm (in kg), providing Specific Anthracomass (i.e. SA, in mg.kg⁻¹), calculated

per profile (SAP) and per layer of sampling (SAL; Carcaillet and Thinon, 1996; Talon, 2010). For each sample, a part of the extracted charcoal was taxonomically analyzed with an episcopic microscope (Nikon ME600, magnifications x100 to x500), using wood anatomy atlases (Jacquot *et al.*, 1973; Schweingruber, 1990a; Schweingruber, 1990b) and the carbonized wood reference collection of the palaeoecology working group (Insitute for Ecosystem Research, University of Kiel). A maximum of 90 charcoals was identified per soil sample (indeterminable pieces excluded), randomly selected from the complete charcoal assemblage and equitably shared in the different size classes (i.e. 30 charcoal pieces per class). Charcoal amounts were quantified as Specific Anthracomass per identified taxa (SAT, in mg per kg).

Soil analysis was done to characterize the soil proprieties, in addition to the field description, using soil samples of ca. 500 g from at least one layer of sampling per identified soil horizon. Ph values were measured with an electronic diode on sub-sampled material put in solution with distilled water. Organic matter content has been quantified by loss-on-ignition (ignition at 650°C during 6 hours; Reeuwijk, 2002). The proportion of soil particles larger than 2 mm was measured in parallel to the wet sieve for the soil charcoal assemblage extraction. Two particle sizes have been measured: 2 to 5 mm and < 5 mm (Carcaillet and Thinon, 1996). The proportion of soil particles smaller than 2 mm have been measured for sand, silt and clay classes of size (Schoeneberger *et al.*, 2002), by particle laser scanning (mastersizer2000, Malvern Instruments Limited, 2005).

Peat macro-charcoal analysis

On the longitudinal half of every peat sequence 5 cm³ of samples were taken every cm and sieved according to Millspaugh and Whitlock (1995). The extracted macro-charcoal records were digitally photographed and quantitatively measured (Mooney and Radford, 2001). Every sample was treated with 75 ml of sodium hypochlorite solution (15 ml of NaOCl 13% per cm³ of peat) during 24 hours and then sieved using a 200 µm mesh. The samples were manually sorted under a stereo lens (magnification x7.5 to x112.5) to keep only the charcoal pieces, centred in Petri dishes. Every single dish was then digitally photographed, with the same camera settings, on a light table, and digitally analyzed with the Scion Image Program (Scion Corporation), which calculates the number and the area of the macro-charcoals, based on the black and white contrast (density slice function; Mooney and Black, 2003).

Since the macro-charcoal records of the two peat sequences show weak linear correlation between their quantification in number (n.cm³) and area (mm².cm³) per sample, with R²=0.8

for BTM and 0.5 for BBM, the quantification of macro-charcoal per sample to calculate the macro-charcoal accumulation rates per year was done based on the area measurement. The use of area quantification instead of number of pieces avoids a possible bias due to change in the fragmentation rate through time (e.g. because of secondary transport or/and lab treatment; Ali *et al.*, 2009). With the CharAnalysis program version 0.9 (Higuera, 2009; Higuera *et al.*, 2009), the macro-charcoal records have been modelled providing the interpolated macro-charcoal accumulation rates per year (i.e. C_{int} ; $\text{mm}^2.\text{cm}^2.\text{yr}^{-1}$), and allowing to detect charcoal peaks. The low-frequency trends of the macro-charcoal accumulation rates (i.e. ‘background’, C_{back} ; $\text{mm}^2.\text{cm}^2.\text{yr}^{-1}$), reflecting rate changes of charcoal accumulation due to secondary deposition, sediment mixing, etc. (Higuera *et al.*, 2007), were estimated by moving a “smoothing regression” on successive 500 years windows. By removing the low-frequency trends of the interpolated macro-charcoal accumulation rates, local charcoal signals were identified (i.e. $C_{peak} = C_{int} - C_{back}$). Charcoal peaks were detected by comparing those local charcoal signals (i.e. C_{peak}), to threshold values corresponding to percentiles of the noise distribution calculated from a Gaussian mixture model to estimate the mean and variance of the C_{noise} distribution (Higuera, 2009). Based on the peak of macro-charcoal accumulation rates distribution over a 250 yrs window, the fire frequency has been estimated for the two peat sequences (i.e. in peaks 250 yrs^{-1}).

Dating strategy

To get chronological data several samples per record were dated by AMS radiocarbon measurement at the Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research (University of Kiel, Germany). From soil charcoal assemblages, 11 charcoal pieces have been dated, six from soil charcoal assemblages of HEI, and 5 from REB. The charcoals have been selected for dating due to their vertical localization in the soil profile, their size (i.e. enough carbon material for dating), their conservation state (i.e. dirtiness), and their taxonomical interest.

Three peat blocks per sequence were dated from various depths. Additionally, at the bottom of the BBM sequence a charcoal piece from a visible black layer was dated. Data were calibrated using the Oxcal program (Bronk-Ramsey, 2001) in BP and BC/AD with a 2σ confidence interval, and using the IntCal09 dataset (Reimer *et al.*, 2009).

Results

Soil charcoal analysis

In the following, the main general features and most significant profile particularities are pointed out to assess the soil stratigraphy. Detailed soil characteristics are presented in Table 1.

site	profile	soil horizon	layer & depth of sampling (cm)	ph H ₂ O	grain size %					OM %
					> 5 mm	5-2 mm	Sand	Slit	Clay	
Renneckenberg	REB1	MAh	A (0-10) B (10-20)	2.8	0	25.8	43.1	29.5	1.6	6.1
		M Sw	C (20-30) D (30-40)	3.2	0.1	27.8	37	31.3	3.8	2.3
		Sw	E (40-55)	3	0.9	15.9	45.7	35.2	2.4	1.7
	REB2	MAh	A (0-10) B (10-20)	3.1	1.9	5.3	36.1	52	4.8	7.2
		M Sw	C (20-30) D (30-40)	3.2	12.4	15.2	31.6	36.5	4.3	1.9
			E (40-45)	3.7	13.1	16.9	31.6	34.3	4.2	0.9
	REB3	M ah	A (0-10) B (10-20)	3.9	2.6	20.3	50.1	25.5	1.4	5.1
		M Sw	C (20-30) D (30-45)	4.1	0.4	1.3	17.7	73.9	6.7	1.5
	REB4	Ah	A (0-10)	3.1	5.6	12.7	46.4	31	4.2	8.1
		Bv	B (10-20) C (20-35)	3.8	8.1	11.6	36	39.6	4.8	2.1
				3.6	5.3	12.5	34.6	43.7	3.9	1.5
	REB5	MAh	A (0-10) B (10-20)	3.1	7	0	35.1	53.7	4.3	7
		M Bv	C (20-30) D (30-40) E (40-50)	2.8	7.5	14.7	32.6	41	4.1	1.4
			F (50-60) G (60-70)							
			H (70-85)	3.5	9.8	10	28.6	49	2.6	0.8
Cv										
HEI1	MAh	A (0-10)	3.4	0	19.9	29.6	46.4	4.1	2.9	
	M Bv	B (10-20) C (20-30) D (30-40)	3.3	3.5	8.5	34.7	49.4	4	1.8	
		E (40-50)	3.8	1.5	25	34.6	34.6	4.3	1.1	
	Cv									
Heinrichshöhe	HEI2	Anmoor	A (0-10) B (10-20) C (20-30)	2.7	35.6	3.3	12.8	41.5	6.8	14.5
			D (30-40) E (40-50) F (50-60) G (60-70)	3	0	5.4	41.7	48.4	4.5	14.5
	HEI3	Ah	A (0-10) B (10-20)	3.5	6.4	9.6	33.5	43.5	7.1	2.8
		Cv	C (20-30)	3.7	9.8	6.4	21.6	53.9	8.4	0.7
	HEI4	Ah	A (0-10)	2.9	5.8	11.1	41.5	39.7	2	1.1
		M Bv	B (10-20) C (20-30)	3.6	7	14.3	32.9	42.7	3.1	1.5
			D (30-40)							
Cv		E (40-50)	3.4	12.1	15.2	33.1	37.4	2.2	0.2	

Table 1. Soil profiles features for the sampling sites: Renneckenberg (profile REB1 to 5) and Heinrichshöhe (profile HEI1 to 4).

Soil field description and lab analysis allowed to identify in-situ soil formation and accumulated soil sediment. On REB, the data of the five profiles, reaching 80 cm at max for REB5, show that the deeper horizon Cv is made of weathered granitic parental material (i.e. below 70 cm, only identified on REB5), superimposed by a mineral/organic Bv horizon (i.e. from 70/60 cm to 20/10 cm, on REB4 and 5), or a temporary wet mineral Sw horizon (i.e. on REB3, 2 and 1). At the upper parts of the profiles an Ah horizon has been identified, reaching from 20 cm, at max, to the current soil surface. The analysis of the soil profile HEI1 and HEI4 shows the presence of the same bottom horizon than on REB (i.e. Cv, from about 50 to 40 cm), superimposed by a comparable mineral/organic Bv horizon (i.e. from 40 to 10cm), finally superimposed by a Ah horizon (i.e. on the upper 10 cm). The profile HEI3 presents a direct transition from Cv to Ah horizons. Finally, the profile HEI2 presents a totally different feature since this is a completely organic and moist soil profile (i.e. oligotrophic anmoor), reaching a Cv horizon below 70 cm of depth. The material in which most of the previously described soil horizons were formed have been identified as sediment earth material, mainly based on field observation like horizons colour, aggregate shape, compactness, etc., and on lab measurement like grain size and organic matter content (Table1). This sediment material formed colluvial layers (i.e. M) of various length and depth, embedding biotic records (Bork and Lang, 2003). However, it is important to consider that on both sampling sites, the profiles have been limited in their longitudinal size (1 to 1.5 m) because of the National Park conservation purposes, making it difficult to distinguish layers more precisely than one M layer, as the opening of trenches with several meters to tenth of meters length might allow (Bork and Lang, 2003). The soil profiles REB4 and HEI3 do not show any colluvial accumulation, thus their soil horizons were formed in-situ.

From the 103 kg of earth sampled on REB and the 60 kg on HEI, respectively 228.4 g and 17.3 g of charcoal have been extracted. 2181 charcoal pieces from REB and 1071 pieces from HEI were analyzed taxonomically, including respectively 1% and 6% of indeterminate pieces, which were too small, too dirty and/or too vitrified (i.e. with a “melted”, smoothed, wood structure, making it unidentifiable; McParland *et al.*, 2010) to be identified since diagnostic anatomical criteria are invisible. These have been excluded from the taxonomical results. However, the amounts of indeterminate charcoals have been included in the total charcoal concentration per profile (SAP) and per layer (SAL).

Considering the total soil charcoal concentration per profile (SAP) of the two sites we observe that (1) the two sites are rich in charcoal, and (2) there is a significant SAP heterogeneity (Fig. 2). Moreover, the REB soil profiles are much richer in charcoal than those

of HEI. The soil charcoal concentration per layer (SAL) combined to corresponding soil horizons shows a large heterogeneity without clear patterns (Figs 3 and 4). Nevertheless, some general trends are observable. The profiles on which no colluvial layer was identified (REB4 and HEI3) exhibit smaller amounts of charcoal, in regard to SAP and SAL. This is also the case when looking at soil profiles which present a Cv horizon at their bottom. The corresponding layers have smaller charcoal concentrations. Moreover, on HEI2 below a depth of 40 cm no charcoal pieces were recorded. On REB there are charcoal rich layers at the profile surface, but also at deeper levels (e.g. REB2E).

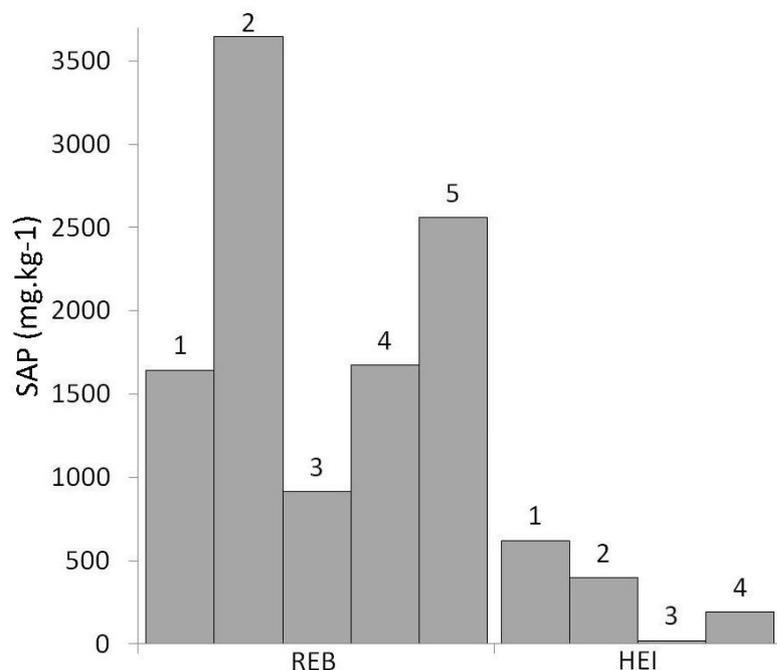


Figure 2. Total soil charcoal concentration per soil profile (SAP > than 1mm), of the two sampling sites Heinrichshöhe (HEI1 to 4) and Renneckenberg (REB1 to 5).

The taxonomical analysis of the soil charcoal assemblages revealed five taxa on REB, and six on HEI (Figs 3 and 4). All the assemblages are largely dominated by *Picea* charcoal, and the taxonomic type *Picea/Larix*. This type results from the difficulty to discriminate charcoal pieces from *Picea* and *Larix* wood which have very similar anatomy, making their taxonomical distinction much time consuming and strongly depending on the size of the charcoal pieces (Anagnost *et al.*, 1994; Talon, 1997). Therefore a large number of charcoal pieces were only identified as *Picea/Larix*. However, when charcoal pieces were big enough, allowing the observation of the diagnostic criteria, the identification provided always a *Picea* charcoal. Based on the regional palaeobotanical insight (Beug *et al.*, 1999), it is assumed that *Larix* did not naturally establish on the Harz Mountains. Therefore, the taxonomic type *Picea/Larix* is assumed to represent *Picea* charcoal records.

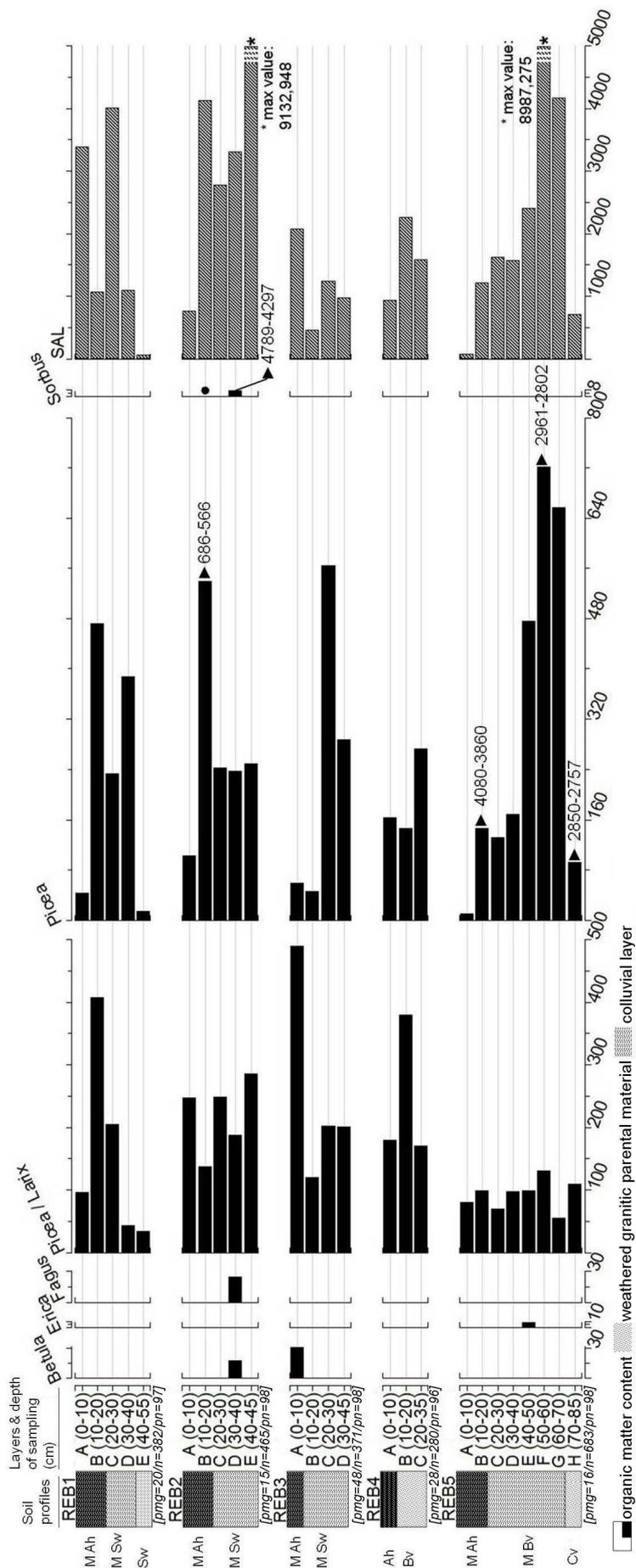


Figure 3. Renneckenberg (REB) soil charcoal concentration (in mg.kg^{-1} ; x-axis below) per identified taxon (x-axis above) in soil charcoal assemblages of the soil profiles REB1 to REB5. Soil horizons, layers of sampling and analyzed charcoal assemblages described on y-axis. pmg = weight (mg) proportion of taxonomically analyzed charcoal from the total charcoal concentration per profile; n = total number of taxonomically analyzed charcoal pieces ($> 1 \text{ mm}$); pn = number proportion of identified charcoal pieces. ● : charcoal concentration $< 1 \text{ mg.kg}^{-1}$; ▲ : radiocarbon dates in calibrated BP (2σ interval); right column, grey stripes: total soil charcoal concentration per layer of sampling (SAL).

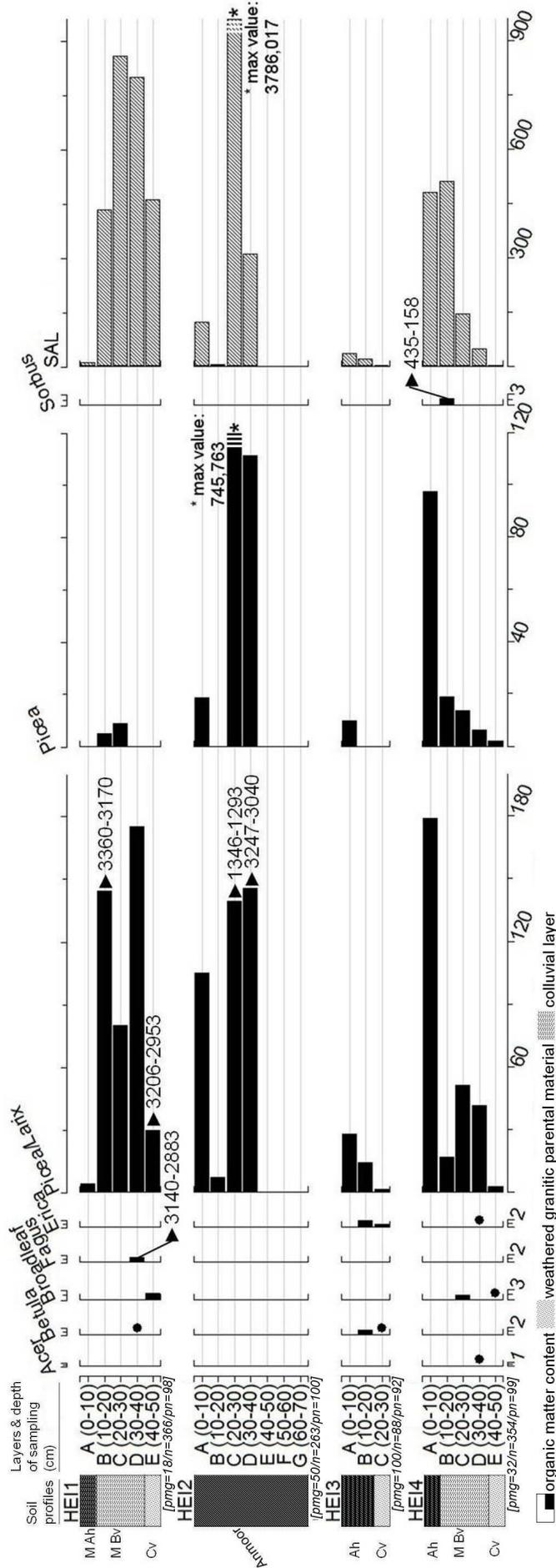


Figure 4. Heinrichshöhe (HEI) soil charcoal concentration (in mg.kg⁻¹; x-axis below) per identified taxon (in mg.kg⁻¹; x-axis above) in soil charcoal assemblages of the soil profiles HEI1 to HEI4. Soil horizons, layers of sampling and analyzed charcoal assemblages described on y-axis. *pmg*= weight (mg) proportion of taxonomically analyzed charcoal from the total charcoal concentration per profile; *n*= total number of taxonomically analyzed charcoal pieces (> 1mm); *pn*= number proportion of identified charcoal pieces. ●: charcoal concentration < 1 mg.kg⁻¹; ▲: radiocarbon dates in calibrated BP (2σ interval); right column, grey stripes: total soil charcoal concentration per layer of sampling (SAL).

Despite their very small representation, it is interesting to highlight the presence of broad-leaved taxa, including scrub vegetation with *Ericaceae* and species of the *Piceion abietis* phytosociological assemblage, with *Betula*, *Sorbus*, and, on HEI4, *Acer*, whose species *A. pseudoplatanus* also associates to the *Picea*). A few pieces of *Fagus* were identified, with one dated at 3247-3040 year cal BP. Two other dates were obtained from broad-leaf charcoal pieces, of *Sorbus* charcoals from HEI4B and REB2D, at 435-158 and 4789-4297 yrs. cal BP respectively. Eight *Picea* charcoal pieces were dated: At HEI, three were dated to the Bronze Age and one to the Medieval Period. From REB profiles three *Picea* charcoals were dated to the Bronze Age, and one to the Medieval Period (Fig. 5 and Table 2).

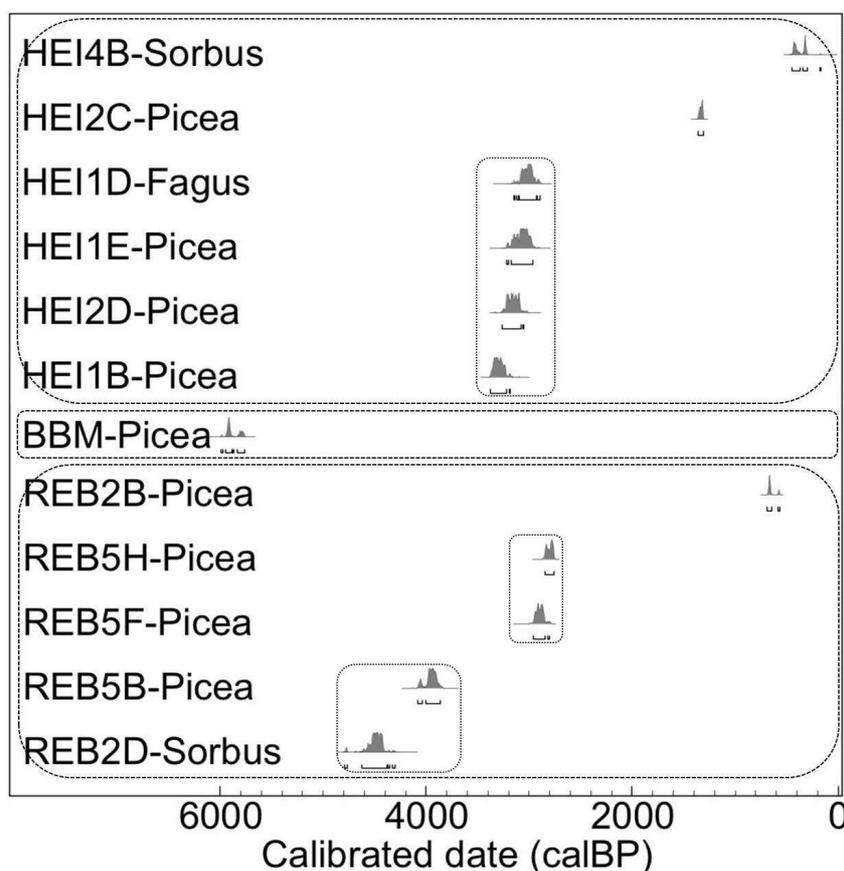


Figure 5. Multigraphical representation of the radiocarbon range of the AMS-C14 measurements on single species-identified charcoals from Heinrichshöhe (soil profiles HEI), Brockenbettmoor (peat sequence BBM), and Renneckenberg (soil profiles REB). Age range in yrs cal BP (2σ interval); plotted on OxCal 4.1 program (Ramsey, 2001). Dashed square: overlapping radiocarbon range.

lab ref	site	depth (cm)	taxa	age conv BP	cal BP	cal BC/AD
KIA41182	BBM	245	<i>Picea</i>	5135 ± 30	5985-5753	AD4036-3804
KIA37286	HEI1B	15	<i>Picea</i>	3055 ± 30	3360-3170	AD1411-1221
KIA37432	HEI1D	35	<i>Fagus</i>	2875 ± 30	3140-2883	AD1191-934
KIA37287	HEI1E	45	<i>Picea</i>	2910 ± 35	3206-2953	AD1257-1004
KIA 43757	HEI2C	25	<i>Picea</i>	1415 ± 20	1346-1293	604-657BC
KIA38767	HEI2D	35	<i>Picea</i>	2965 ± 25	3247-3040	AD1298-1091
KIA42900	HEI4B	15	<i>Sorbus</i>	280 ± 25	435-158	1516-1793BC
KIA 43765	REB2B	15	<i>Picea</i>	700 ± 25	686-566	1264-1385BC
KIA 43766	REB2D	35	<i>Sorbus</i>	4010 ± 50	4789-4297	AD2840-2348
KIA 43767	REB5B	15	<i>Picea</i>	3635 ± 30	4080-3860	AD2131-1911
KIA 43768	REB5F	55	<i>Picea</i>	2795 ± 25	2961-2802	AD1012-853
KIA 43769	REB5H	75	<i>Picea</i>	2700 ± 25	2850-2757	AD901-808

Table 2. AMS-14C dates from single charcoal pieces from the peat sequence BBM, and soil charcoal assemblages of HEI and REB. Dated by the Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research - University of Kiel, Germany. Calibration in BP and BC/AC done at 2 σ confidence interval, base on the IntCal09 dataset.

Peat macro-charcoal analysis

The coring of the Blumentopfmoor (BTM) mire provided a sequence of 153 cm of peat with different grades of humification. The age/depth relation shows that this peat sequence reaches ca. 11680 yrs, with a relatively slow growing rate from the base of the sequence to 80 cm (ca. 42 yrs.cm⁻¹), and with a very slow growing rate of the peat of the upper 80 cm (ca. 108 yrs.cm⁻¹; Fig. 6). Preliminary pollen analysis from this peat sequence seems to indicate that a part of the peat sequence may miss on the upper part of the sequence due to peat cutting or decomposition as a consequence of past drainage, which might explain the very slow growth rate. Due to the coring process, a gap in the peat sequence occurred between the two single cores from 94 to 99 cm. Based on the age/depth relation the gap in this peat sequence is from ca. 8950 to ca. 9240 yrs cal BP.

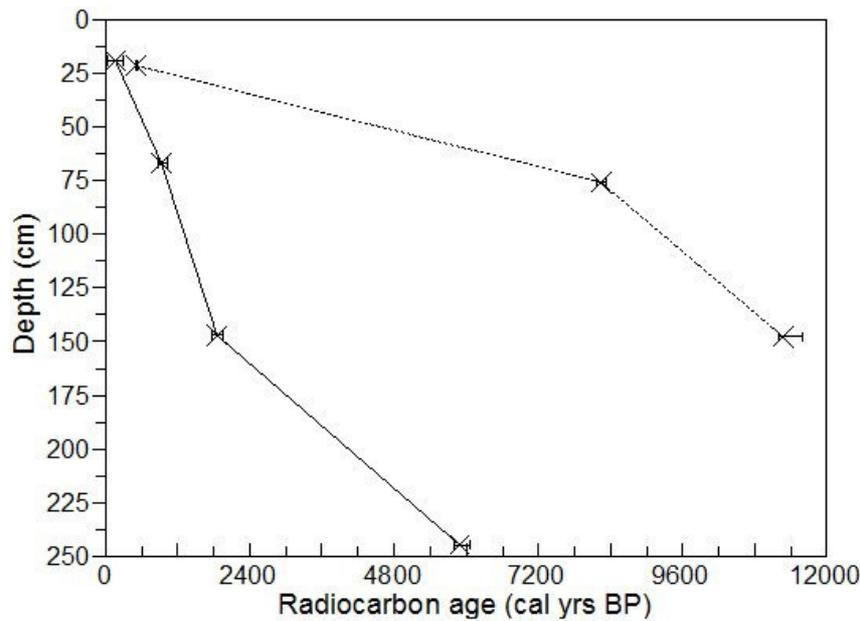


Figure 6. Interpolated age/depth relation of the peat sequences BBM (full line) and BTM (dash line). Cross: C14-AMS dates (in calibrate BP at 2σ confidence interval, base on the IntCal09 dataset) and error bar.

At the Brockenbettmoor (BBM) mire a complete peat sequence of 252 cm was obtained, with moderately humified peat below 154 cm and with well preserved sphagnum peat for the upper part. Based on the age/depth relation, this peat sequence spans over ca. 6270 yrs cal BP, with a slow peat growing rate from the bottom of the sequence to about 150 cm (ca. 42 yrs.cm⁻¹), and with a bit faster, but still relatively slow peat growing rate from about 150 cm to the mire surface (ca. 12 yrs.cm⁻¹ Fig. 6).

The peat sequence BBM has a much higher macro-charcoal content than BTM, while covering a shorter temporal span. The BTM sequence content in macro-charcoal is very small, with macro-charcoal pieces in only 10 samples of 157, while on the BBM sequence 92 samples of 252 contained macro-charcoals. Macro-charcoal accumulation rates are variable within and between the two sequences. Looking at the global patterns of the macro-charcoal accumulation rates of the BTM sequence, macro-charcoal accumulation happened only during two phases: an old one during the Boreal and a much more recent one during the Subatlantic. Both cover relatively short time spans and present one macro-charcoal accumulation peak (Fig. 7A). On the BBM sequence the oldest phase of macro-charcoal accumulation happened during the Atlantic/Subboreal transition, with two peaks, and a second main phase of macro-charcoal accumulation during the Subatlantic phase, with four peaks. Finally, one macro-charcoal peak was identified during modern time (Fig. 7B).

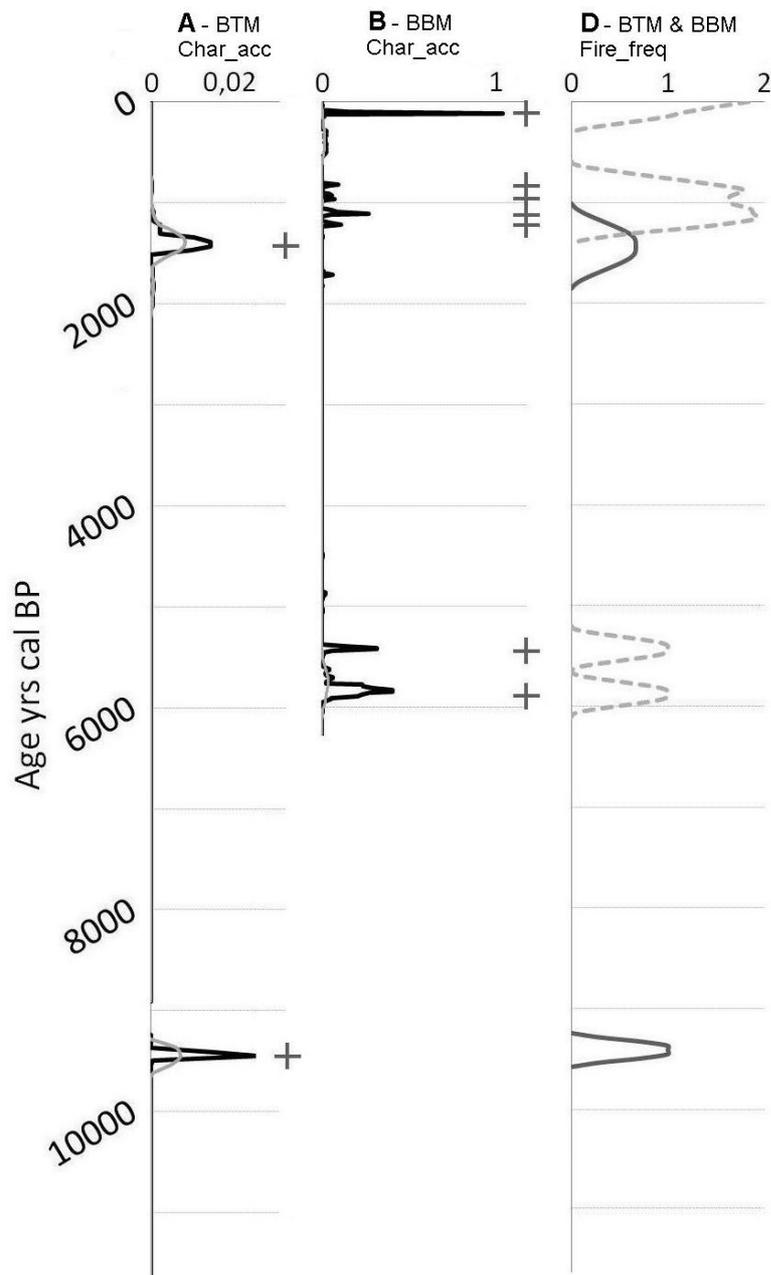


Figure 7. Macro-charcoal (>200 μm) signal of the peat sequences BTM (A) and BBM (B), y-axis: age yrs cal BP. Black line: macro-charcoal accumulation rates in $\text{mm}^2.\text{cm}^2.\text{yr}^{-1}$ (C_{int}); grey line: macro-charcoal accumulation rates background in $\text{mm}^2.\text{cm}^2.\text{yr}^{-1}$ (C_{back}); plus: fire peak (C_{peak}). Fire frequency (C) in (peaks 250yrs-1) for BTM (full line) and BBM (dash line).

Based on accumulation rates and the identification of macro-charcoal peaks, as well as their distribution over temporal windows, various phases of higher fire frequency were identified (Fig. 7C). When comparing the macro-charcoal signal of the two peat sequences along comparable temporal scales (i.e. over a minimum common span of ca. 6600 yrs), it may be observed that there is no clear signal synchrony, neither in accumulation rate nor in peak identification. Only a short overlapping of a temporal phase with higher fire frequency during the Subatlantic is detected on both peat sequences (Fig. 7C).

Discussion

Signal resolution and taphonomical aspects

Charcoal is produced by a fire event, whatever was the ignition factor, may it be natural or human, and is afterwards archived in various types of ‘traps’ (e.g. lake, peat bog, etc.). It passes through multiple taphonomical processes, eventually constituting the charcoal record, which is exploitable as past fire signal (Conedera *et al.*, 2009; Whitlock and Larsen, 2001). Consequently, taphonomical processes, especially transport, fragmentation and burying, have a great importance in the interpretation of the charcoal record for the assessment of fire history (Scott and Damblon, 2010; Thinon, 1992).

To investigate past fire regimes it is of uppermost interest to assess the spatial resolution of the analyzed charcoal records (Whitlock *et al.*, 2010). Even if possible macro-charcoal transportation must be considered (Tinner *et al.*, 2006), many authors consider ca. 150 / 200 μm as a relevant minimal size so that larger charcoal pieces have a local relevance, and thus provide the macro-charcoal record (Clark, 1988; Gardner and Whitlock, 2001; Lynch *et al.*, 2004). Therefore, by analyzing such macro-charcoal records from peat sequences, and especially by detecting macro-charcoal accumulation peaks indicating local fire events, fire signals at the local scale (i.e. 1–3 km^2) have been obtained (e.g. Greisman and Gaillard, 2009). The charcoal pieces observed during sorting with a stereo lens showed different aspects than charred peat material (e.g. shapes; Enache and Cumming, 2006). Moreover, if charcoal pieces were big enough to be observed taxonomically with a microscope, tree wood structure was visible. Thus, we assume that a part of the macro-charcoal records extracted from the sequences BBM and BTM are from forest fires at the adjacent hills, and/or from the burning of trees growing on the mire. This is further supported by the one identified *Picea* charcoal piece from the BBM sequence, at 245 cm depth, which has been dated (Table 2 and Fig. 5). Thanks to the age/depth relation (Fig. 6), the identified local fire events of both peat sequences have been chronologically referenced, and statistically modelled to get fire history correlated to a temporal frame, in relatively high temporal resolution, with 25 years.cm^{-1} for BBM and 74 yrs.cm^{-1} for BTM (Fig. 7).

The “mega-charcoal” record (i.e. charcoal pieces larger than 1 mm), extracted from the soil samples, can be interpreted in high spatial resolution (Dutoit *et al.*, 2009; Touflan *et al.*, 2010). Such soil charcoal assemblages, once on-site deposited, are incorporated into the soil, in parallel to soil formation, by burying and fragmentation processes (Thinon, 1992). In this, physical factors such as uprooting, especially relevant with trees like *Picea abies*, having flat roots (Šamonil *et al.*, 2010) and biological factors, such as bioturbation (mainly connected to

earth worm activity; Darwin, 1881; Jégou *et al.*, 1998) have both a crucial role. Because these processes are not linear, the charcoal incorporation into the soil is not occurring linearly through time, with moreover a non linear mixing of the soil matrix embedding charcoal pieces. However, no clear features of soil mixing (e.g. bioturbation evidences) have been observed on the in-situ soil horizons of the soil profiles of sampling (REB4 and HEI3; Fig. 3 and 4). This makes it very delicate to interpret any chronostratigraphy in soil charcoal assemblages, even based on the relatively high number of radiocarbon dates which are available for certain soil profiles (Carcaillet, 2001).

Moreover, the taphonomic processes of charcoal transport along the slope surface or embedded in soil aggregates must be considered as an important factor for an enlargement of the spatial resolution of the charcoal record (Bork and Lang, 2003; Walther *et al.*, 2009). Colluvial layers were identified in most of the sampled soil profiles, and due to the location of both soil sampling sites at slopes, it must be assumed that 'mega-charcoals' in colluvial layers possibly originated from uphill slopes. Colluvial sediments might have been transported along the slope, by one or many diachronic event(s) of erosion and deposition, or redeposition, at the bottom slope when the slope degree decreases (Leopold and Völkel, 2007). Thus, considering the distance from the top hills to the sampling site, the charcoal catchment area of both HEI and REB sites might be estimated at ca. 500m² to 1 km² for intensive events. Correlated to a soil surface transport by water, which has been observed on the REB site during field campaign, both soil sampling sites are situated in between the hill slope and the cored mire, being the last, lowest trap of charcoal. This spatial connection of the various types of archives allows us to get a robust charcoal signal, which is assumed to be representative of the local fire history.

Other sources of charcoal formation must be considered, especially concerning the soil charcoal records. First, human made campsite fires might have contributed to a charcoal recording in the soil (and then possibly in the peat by transportation, depending on the distance of the fire place to the peat). However, by applying a multisampling strategy at the site scale, it is improbable that the local recording is biased by charcoals from fire places. Secondly, a possible charcoal input into the soil might be a result of charcoal production sites (i.e. kilns; Nelle, 2003). While no kiln sites were observed at the Heinrichshöhe site, many such production sites were observed at the Renneckenberg hill (estimated density of one kiln site per ca. 500/700m²). Thus, soil charcoal enrichment from kilns cannot be excluded. However, based on the chronological information, with four out of five radiocarbon dates from REB soil charcoal pieces being much older than Medieval times (Fig. 5), we assume

that only a smaller proportion of the charcoal comes from these kiln sites, which date according to their size and shape to Modern Times.

Fire history

Despite the absence of any clear soil charcoal SAL stratigraphy in sampled soil profiles of both sites, the quantification of soil charcoal amounts provides insight into past fire activity. The SAP and SAL values are high, especially from REB. These soil charcoal concentrations are comparable to other investigations done in Alpine mountain areas (Carcaillet and Thinon, 1996; Touflan *et al.*, 2010), Boreal forests (Ohlson and Tryterud, 2000) and in Mediterranean areas (Bergaglio *et al.*, 2006; Vernet, 2006). The high level of soil charcoal seems to indicate a considerable past fire activity, at a local scale (i.e. hill slope). This is supported by the presence of important volumes of sediment material (i.e. most of the sampled soil horizons are colluvial layers), resulting from erosive events, which are often correlated to fire occurrences, since fire destroyed or harmed the vegetation covering the soil surface, exposing it to erosive action (Cerdan *et al.*, 2010; Dreibrodt *et al.*, 2010).

Moreover, the radiocarbon dates got from soil charcoal assemblages indicate a number of local fire events (Table 2 and Fig. 5). Taking into account a possible old-tree effect (Gavin, 2001), looking at the radiocarbon indications from REB it can be distinguished a minimum of three local fire events. The most recent is from medieval times. Radiocarbon dates from charcoals at HEI also indicates at least two fire occurrences during this period. Fire events of this period are also indicated by a phase of high fire frequency and by identified charcoal peaks either on BBM and BTM peat sequences (Fig. 7). These fire indications fit to the general knowledge about the human impact on the local forests with increasing need for timber and charcoal to provide the mining activities, inducing strong impact on the surrounding environment (Beug *et al.*, 1999; Matschullat *et al.*, 1997; Monna *et al.*, 2000; Hillebrecht, 1982; von Kortzfleisch, 2008). However, older fire events have also been recorded. On the BBM sequence local fire events during the Neolithic have been identified, with one dated *Picea* charcoal piece (Table 2), prior or with the start of the peat growth during the Subboreal (Beug *et al.*, 1999). The REB soil charcoals show at least one local fire event during the Bronze Age, and another from HEI, with moreover one last fire event dated from REB soil charcoal records to the Iron Age (Fig. 5). Though archaeological evidences older than Medieval Period were hardly found in the Upper Harz (Beug *et al.*, 1999), the identified ancient fire occurrences are possibly connected to human activities. This is notably supported by the absence of indication of that fire phase, on the BTM peat sequence, while it

is recorded in the nearby REB soil charcoal assemblages. This signal asynchrony might indicate the occurrences of fire events with restricted spatial resolution. This does not fit with a wildfire occurring at landscape scale (Whitlock *et al.*, 2010), especially in an easily flammable *Picea* forest, as indicated by the soil charcoal taxonomical identification (Figs 3 and 4). To explain such spatially restricted fire events it may be postulated human control. However, the analyzed data set does not allow the identification of the fire controls, since the occurrence of natural fires in a restricted area is also possible.

While the Neolithic/Bronze Age fire indications are not present on the BTM peat sequence, older fire events are recorded. One early Holocene local fire event has been detected (Fig. 7). Because of the very ancient age of this macro-charcoal peak a natural ignition is postulated. No soil charcoals correlated to this fire event have been found, either from dating or from taxonomical identification. The taxonomical analysis does not provide any indication of early Holocene trees like pine and birch, indicated by several pollen profiles (Beug *et al.*, 1999). To explain the absence of those early Holocene charcoal assemblages in the soil samples from REB it can be postulated that the detected local fire event on the BTM peat sequence occurred only on the mire, on a so much restricted surface that the surrounding forest did not burn and therefore charcoal of that period were not formed.

Forest history

Looking at the forest history based on the taxonomical identification and chronological indications the ancient presence of *Picea* at the site is affirmed, with the oldest *Picea* charcoal dating from 5985-5753 yrs cal BP, which is in accordance to pollen evidence. This chronological indication fits with the postulated age of establishment in the area of *Picea* at ca. 7000-5000 yrs BP (Beug *et al.*, 1999; Latalowaa and van der Knaap, 2006). This taxon, *Picea*, and the taxonomic type *Picea/Larix*, is so largely dominating the assemblages that even some general trends of a change of the forest dynamics are not detectable. Nevertheless, the identified evidences of broad-leaved trees indicate their on-site presence at both sites. The *Betula*, *Sorbus* and *Acer* identification (and radiocarbon dates of *Sorbus* pieces) might fit to phases of forest canopy opening due to fire, followed by the establishment of pioneer mountain forest trees, like those previously cited with *Picea abies*. The identification and dating of *Fagus* charcoal pieces shows the old (3000 yrs cal BP) presence in heights of 900 m a.s.l. at Heinrichshöhe, at an elevation which is today completely covered by *Picea* stands, but might become colonized by *Fagus* trees again in the future, when natural processes in the National Park regain their power.

Conclusion

Picea trees constitute the only forest tree dominating the investigated areas, since, at least the transition early- mid-Holocene. The local presence of *Fagus* charcoal suggests interesting discussion points about the *Picea/Fagus* altitude transition in the past, which is of particular importance for the Harz National park management planning.

Fires have played a role in the ecosystem dynamics of the Upper Harz. This partly fits with the well known strong human impact on forest systems since medieval times. But there is now strong evidence for older fire occurrences, either ignited by humans or lightning, at a local scale, only occurring at the higher altitude site. Overall, the analyzed charcoal records indicate that past fires were more frequent during the Subatlantic, and less during earlier times.

The methodological combination of mega-charcoal from soil and macro-charcoal from peat provides quantitative and qualitative information about past fire occurrences and the burnt vegetation over long temporal scales and at a fine spatial scale, being thus a promising multiproxy approach.

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6.2 Holocene Fire and Forest History of the Eastern Part of the Harz Mountains (Germany, Central Europe), Based on Soil Charcoal Analysis and the Recording of Non-linear Ecosystems Changes

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Abstract

Soil charcoal analyses and soil historical investigations have been used to assess fire and forest history on the eastern part of the Harz Mountains (Germany). Soil profiles from three investigation sites along climatic-altitudinal transect, have been described and sampled for soil analysis and charcoal assemblage extraction. On each site several past fire events, forest composition and trends in changes of forest domination have been identified. This was notably based on soil formation and erosion/deposition patterns and on 23 radiocarbon dates. These dates are mostly distributed in two temporal phases, fitting with soil formation and erosion/deposition patterns and to the general representation of the taxonomic charcoal assemblages. The older phases happened during the late Pleistocene/early Holocene, corresponding to a post glacial woodland development with pioneer vegetation. The second fire phases occurred during the late Holocene, with the identification of broadleaf forest fire, dominated by *Fagus* or *Quercus*. These comparable trends in total charcoal richness, main taxonomic and chronological information at local stand scale allowed to point out regional patterns of fire history. The identified chronological patterns of fire phases and corresponding forest types allow the assumption of climatic and human control on the older and younger past fire events.

Key words

Charcoal analysis, colluvial layers, soil horizons, fire events, forest composition, Unterharz

Introduction

The long-term vegetation history of Central Europe has been investigated in detail over several decades (e.g. Berglund et al., 1996; Kalis et al., 2003). Nevertheless, the fire history and the ecosystem dynamics of the south-eastern part of the Harz Mountains in Central Europe are still unknown. However, increased knowledge of the vegetation dynamics and fire history of this area might be of great importance and interest to a global understanding of Central European vegetation history. The Harz Mountain Range is the northernmost low mountain range in Central Europe (i.e. up to 50°N), isolated between the Central European Highlands to the south and the North European Plain. Such a geographical position, combined with the Northwest-Southeast orientation of this mountain range, and the local topographical and soil heterogeneity, allows to postulate that the Harz Mountains was an important area in post glacial and Holocene vegetation development and for forest tree migration through Central Europe. However, the climatic, soil, and topographical context of the south-eastern part of this low mountain range make the presence of chronologically stratified archives, suitable for palaeoecological investigations in a long temporal scale such as peat bogs or mires, rare. Therefore, to investigate vegetation and fire history since the last glacial phase in this area, soil charcoal analysis (Carcaillet and Thimon, 1996) has been used in this study. By the quantification and the taxonomical analysis of the charcoal pieces assemblages extracted from natural soil formation or/and earth sediment deposits, identified by soil history and geomorphological investigations, and supported by radiocarbon dating, past fire occurrences (contributing to the fire history assessment; e.g. Hart et al., 2008) and past forest species composition (e.g. Robin *et al.*, 2011) could be investigated.

In this paper, one of the first palaeoecological investigations of Central Europe based on the previously described methods is presented. A reconstruction of the Holocene fire and corresponding forest history of selected sites in the eastern part of the Harz Mountains has been done. With that, the reliability and relevance of the reconstruction of past changes in ecosystem dynamics over a long temporal scale and at a local spatial scale, based on the combination of biotic (i.e. charcoal records) and abiotic indicators (soil features; Bork and Lang, 2003), was tested.

Investigation area

The Harz Mountains is the northernmost low mountain range in Central Europe. This mountain range, oriented north-west/south-east, exhibits a rapid altitude elevation in the north-western part from ca. 300 m a.s.l., reaching the maximum elevation at the Brocken top

(1142 m a.s.l.), and progressively decreasing in elevation, over about 80 km, to the southeast, to reach the Elbe alluvial lowland at ca. 200 m a.s.l. Along this elevation decrease, the climate changes from sub-oceanic in the northwest part at higher elevation, to continental climatic conditions at the south-eastern part at lower elevation. Following the same gradient, the dominant forest tree species at present switches from *Picea abies* at the highest elevation, *Fagus sylvatica* at an intermediate level of altitude, and *Quercus* spp. at the lowest altitude (Bohn et al., 2000).

Along this altitudinal, climatic, and vegetation northwest-southeast gradient, three investigation sites have been selected (Fig. 1).

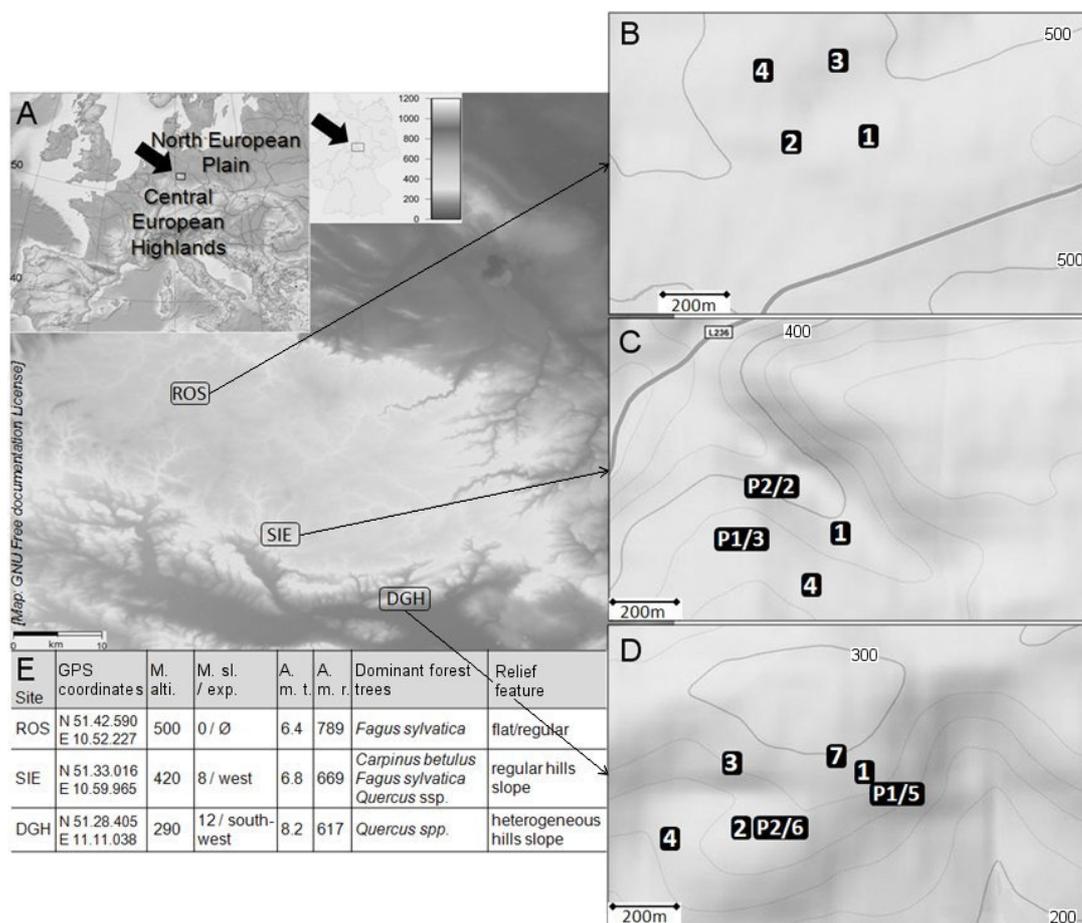


Figure 1. Maps of localization: A- The Southeastern part of the Harz Mountains and sites of investigation ROS (Rosentalskopf), SIE (Siebengemeindewald), DGH (Das Große Holz); Topographical maps (with isolines of 20 m resolution) of the investigated sites and localization of the soil trenches (P) and profiles (1 to X): B – ROS and soil profiles 1,2,3,4; C – SIE, soil profiles 1,4, and soil trenches P1/3, P2/2; D – DGH, Soil profiles 1,2,3,4,7, and soil trenches P1/5, P2/6; E – main characteristics of the investigated sites [M. alti.: mean site altitude (m a.s.l.); M. sl. / exp.: Mean slope (°) / exposure; A. m. t.: Annual mean temperature (°); A. m. r.: Annual mean rainfall (mm)] (climate data from meteorological station of Hasselfelde, Stiege, Questenberg-Agnesdorf, Vatterode-Graefenstuhl, Hayn/Harz, and Harzgerode; Deutscher Wetterdienst, 2011).

The most northwestern site, “Rosentalskopf” (ROS) is located in the central Harz hinterland, near the city of Hasselfelde. The site “Siebengemeindewald” (SIE) is situated about 30 km to the southeast. At the most southeastern location, on the last hillsides of the Harz, reaching the Helme alluvial plain, the site “Das Große Holz” (DGH) is to be found. The main site characteristics are presented in figure 1E.

Methods

Field work

Field investigation and sampling was done based on the methods described by Bork (2006) and Carcaillet and Thinon (1996). On every site a variable number of soil profiles, with a length of 1 m and down to the bedrock were dug by hand with a spade. Moreover, at two sites soil trenches of about 10 m long, reaching the bedrock at the bottom, were dug with an excavator, and then carefully cleaned (i.e. roots cutting and face racking; Fig. 2).



Figure 2. Pictures of the soil trenches of the Das Große Holz bei Wallhausen (DGH). A: soil trenches P2/5 during digging with the excavator (picture V. Robin); B: soil trenches P1/6 after “face cleaning” (picture O. Nelle).

The profiles and trenches were localized at relevant places taking into account the local topography, aiming to have a representative overview by comparing on-site data. Metric references were put along over the complete trenches for the measurement and drawing of the soil horizons. Observable horizon structures, aggregates as well as horizon border shapes, colours, and skeleton patterns have been used to identify and describe soil horizons and

stratigraphy (Munsell, 2000; Schoeneberger et al., 2002). Obviously disturbed soil structures (e.g. bioturbation evidences) have been documented. On ROS, because of the relatively simple topographical and soil context only four soil profiles were done (ROS1 to 4). On SIE, aiming to take into account the relatively important soil heterogeneity, two soil trenches have been opened on which soil profiles have been sampled (SIEP1/3 and SIEP2/2), with two additional soil profiles (SIE1 and 4). DGH presents the biggest soil and topographical heterogeneity, therefore in addition to the two trenches, on which two soil profiles have been sampled (DGHP1/6 and DGHP2/5), five additive soil profiles have been dug and sampled (DGH1 to 4, and DGH7).

Sampling of ca. 10 l has been done, per vertical layers, from the profiles bottoms (i.e. bedrock) to the soil surface, when possible on a same vertical column, following soil horizons, with a maximum height per layer of sampling of 10 cm, to keep a fine vertical resolution. Layers are labelled from “A” at the surface downwards in alphabetical order.

Soil analysis

Soil laboratory analyses have been done to complement the soil field description, to be able to identify and differentiate soil formation and erosion/deposition processes (i.e. colluviation; Leopold and Völkel, 2007). This provides data to investigate soils in an historical perspective (Emadodin et al., 2010).

Using soil samples of ca. 500 g, ph, texture and the content in organic matter of some layers of sampling corresponding to the soil horizon (Reeuwijk, 2002; Sponagel et al., 2005) was measured.

During the wet sieving of the soil charcoal assemblage extraction, the proportions of soil particles > 5 mm and $5/2$ mm were quantified (Carcaillet and Thinon, 1996). The fine-particles amount (i.e. < 2 mm) have been quantified by particle laser scanning (mastersizer2000; Malvern Instruments Limited, 2005). The measured quantities per size of particles have been compiled for sand, silt and clay particle class proportions (Schoeneberger et al., 2002). The content in organic matter has been quantified, in proportion of the sub-sample weight, by loss-on-ignition, at 650°C during 6 hours. Finally, the ph in water has been measured with an electronic diode, on a sample mix in solution with distilled water. The soil horizons were described following the “German soil nomenclature” (Sponagel et al., 2005).

Charcoal analysis

Soil charcoal analysis, combined with AMS radiocarbon dating, allows the investigation of fire history (Fesenmyer and Christensen, 2010) and past forest composition (Carnelli et al., 2004), based on the quantification (i.e. charcoal concentration per weight of earth sampled) and the taxonomical identification (i.e. based on wood anatomical structures “fossilized” by the carbonization) of charcoal assemblages bigger than 1 mm extracted from soil samples, providing data with a high spatial resolution on the stand scale (Carcaillet and Thion, 1996; Dutoit et al., 2009; Touflan et al., 2010).

All samples were dried and then wet sieved to separate the organic matter and the mineral material smaller than 5 mm. Then the extracted organic matter was dried and sieved through three various mesh sizes resulting in three size fractions (i.e. 1/2, 2/5; >5 mm), containing charcoal pieces. Charcoals were manually picked under a stereo lens (Nikon SMZ1500, x7.5 to x112.5) for each size fraction. The weights of the charcoal assemblages were reported to the weight of soil of the corresponding sample to obtain charcoal concentrations, named Specific Anthracomass (SA), in mg.kg⁻¹ (Talon, 2010). This SA has been calculated per profile (SAP) and per layer of sampling (SAL).

A part of the extracted charcoals were taxonomically analyzed with an episcopic microscope (Nikon Eclipse ME600, x100, x200, x500). 30 charcoal pieces per size fraction were randomly selected, providing per soil sample a maximum of 90 charcoal pieces identified, excluding non-identified charcoal pieces. Samples presenting less than 90 charcoal pieces bigger than 1 mm have been completely analyzed, and if one of the three size fractions per sample presented less than 30 charcoal pieces, more pieces have been selected equitably from the other fractions. The taxonomical identification was done based on wood anatomical criteria, using charcoal pieces from the collection of reference of the Institute for Ecosystem Research of the Christian-Albrechts-University of Kiel and wood anatomy atlases (Jacquot et al., 1973; Schweingruber, 1990a; Schweingruber, 1990b). Finally, the amount of charcoal identified per sample has been quantified in Specific Anthracomass per Taxon (SAT; mg.kg⁻¹; Talon, 2010).

Dating strategy

AMS radiocarbon dating of 23 soil charcoal pieces was done to get chronological references about soil horizons and taxonomically identified charcoals. Those charcoals were selected based on the apparent best compromise between their taxonomical interests (i.e. identified taxa), their size (i.e. enough carbon for AMS dating), their conservation state (i.e. dirtiness),

the localization of their profile of sampling on the site, and their origin on the soil profile (i.e. deepness).

On the site DGH, four charcoal pieces from the profile P2/5, three from the profile 3, and two from the profile 2, have been dated. On ROS four pieces from the profile 1 and two from the profile 4 have been dated. On SIE, three charcoal pieces have been dated from the profile 1, four from the profile 4, and one from the profile 2. Radiocarbon AMS measurements were done at the Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research (Christian-Albrechts-University of Kiel, Germany) and calibrated with a 2σ confidence interval, on the Oxcal program (Bronk-Ramsey, 2001) by using the IntCal09 dataset (Reimer et al., 2009).

Results

Soil description

Field descriptions and soil analysis allowed for the identification and description of various soil features. Detailed results about soil profile nomenclature, pH values, grain size and organic matter proportions of the whole sampled soil horizons are presented in Table 1 for ROS, on Table 2 for SIE, and on Table 3 for DGH.

profile	soil layer	sampling layers & depth (cm)	pH	grain size %					OM %
				> 5 mm	5-2 mm	sand	slit	clay	
ROS1	Ah rAp	A (0-5)	3.9	17.8	5	18.8	49.7	8.7	3.5
		B (5-15)	4.2	12.3	10.4	19.6	49.6	8.2	1.4
		C (15-25)							
	Bv	D (25-35)	4.5	8.2	11.7	16.4	57.4	6.4	0.7
		E (35-45)							
ROS2	Ah rAp	A (0-5)	3.9	11.7	11.5	15.5	51.3	10.1	3.4
		B (5-15)	4.2	17.9	13.5	17.7	43	8	1.9
		C (15-25)							
	Bv	D (25-35)	4.7	21.5	10.2	22.1	41.3	4.9	0.5
		E (35-45)							
ROS3	Ah rAp	A (0-5)	3.8	19.7	7.2	16.2	50.8	6.2	4.4
		B (5-15)	4.3	18.3	9.8	18.4	45.4	8.2	1.3
		C (15-25)							
	Bv	D (25-35)	4.2	24.9	11.2	16.5	43.2	4.2	0.7
		E (35-45)							
ROS4	Ah rAp	A (0-10)	3.5	26.9	6.5	42.1	23.9	0.7	4.6
		B (10-20)	4.1	31.9	12.2	17.5	31.6	6.8	1.3
		C (20-30)							
	Bv	D (30-40)							
		E (40-50)	4.3	32.4	7.2	14.9	40.7	4.8	0.7
		F (50-60)							

Table 1
Soil profiles characteristics for the sampling sites ROS (Rosentalskopf).

profile	soil horizon	sampling layers & depth (cm)	ph	grain size %					OM %
				> 5 mm	5-2 mm	sand	slit	clay	
SIE1	M Ah	A (0-10)	3.9	34.6	17	18.8	27.9	1.7	3.8
		B (10-20)	4.2	81.4	18.6	33.7	60.9	5.4	0.9
	C (20-30)	5		33.9	15	20.4	28.8	1.9	1.2
	D (30-40)			5.1	30.7	10.4	22.2	34.1	2.6
	E (40-50)								
	Bt	F (50-60)	5.1	30.7	10.4	22.2	34.1	2.6	1.1
		G (60-70)							
	SIE2 (P2)	M2 Ah	A (0-5)	4.8	11.4	18.9	16.8	47.6	5.4
B (5-15)			4.7	8.9	25.5	17	44.1	4.6	1.1
C (15-25)									
D (25-35)		4.8							
Bt		E (35-45)	4.9	10.2	21.7	20.2	43.7	4.3	1
SIE3 (P1)	M2 Ah	A (0-10)	3.9	15.8	13	21.2	39.7	10.3	3.4
		B (10-20)	4.1	10.1	25	18	40.4	6.5	1
	C (20-30)								
	D (30-40)								
SIE4	M	A (0-5)	4.2	10.4	11.5	16.4	53.4	8.3	1.3
		B (5-15)	4.1	10	10.4	22.7	49.1	7.9	1.1
		C (15-25)							
		D (25-35)							

Table 2
Soil profiles characteristics for the sampling sites SIE (Siebengemeindewald).

Moreover, soil profile description is found in Figure 3 for ROS, Figure 4 for SIE, and Figure 5 for DGH. A maximum depth of ca. 50 to 60 cm has been reached, at a stone rich layer, on the ROS soil profiles. A weathered organo-mineral horizon (Bv) has been identified with a thickness of ca. 20 to 30 cm, corresponding to two or three distinct layers of sampling (D, E and F), at the bottom of the soil profiles. Above this horizon, a humified organic horizon (Ah), from ca. 25/30 cm to the current soil surface, with visible ploughing marks over the upper ca. 20/15 cm (Ap), has been identified. This corresponds to the three upper layers of sampling (A, B, and C). In regards to soil feature and the location on an uphill plateau, the complete soil sequence of the four profiles results from in-situ soil formation. Therefore, the Ah horizons have been defined as relictual (Ahr). Sediment deposits were not identified. In contrast, an erosion/deposition process has been identified on the site SIE. The soil profiles reached a stony layer at variable depth levels, depending on their topographical location (Fig. 1). Up the slope, the profiles SIEP1/3 and SIE4 reached ca. 40/35 cm depth, while profiles SIEP2/2 and SIE1, down the hill side, have a maximum depth of ca. 80 to 50 cm depth. The corresponding deepest soil horizon is an organo-mineral horizon of accumulation (Bt), in-situ formed below ca. 45/50 cm (layers of sampling H, G, F in SIE1 and E in SIEP2/2). Up to that horizon, colluvial layers are present on all the soil profiles (layers of sampling E/D to B/A). Two colluvial layers (M1 and M2) have been distinguished on long soil trenches providing soil profiles SIEP1/3 and SIEP2/2, while those various colluvial layers were not distinguishable on SIE1 and SIE4, providing one general colluvial layer (M).

profile	soil layer	sampling layers & depth (cm)	grain size %					OM %		
			ph	> 5 mm	5-2 mm	sand	slit clay			
DGH1	M	A (0-10)	3.9	9.5	5.8	24.3	48.4	11.9	1	
		B (10-20)								
		C (20-30)								
		D (30-40)	4.2	11.6	12.1	31.6	36.8	7.9	0.6	
		E (40-50)								
		F (50-60)								
	Bt	G (60-70)								
		H (70-80)	4	2.9	9.6	37.9	41.6	8	0.8	
		I (80-90)								
		J (90-100)								
DGH2	M Ah	A (0-5)	3.1	0	0	23.6	64.3	12.1	3.2	
	M3	B (5-15)	3.3	0	0	18.2	65.9	15.8	1.8	
	M	C (15-25)	3.8	0	0	29.2	59.7	11.1	1.5	
		D (25-35)								
		E (35-45)	4.1	0	0	16.9	71.3	11.8	0.6	
		F (45-55)								
DGH3	M Ah	A (0-10)	3.3	2.8	2.5	28.6	54.3	11.8	2.7	
	M	B (10-20)								
		C (20-30)	4.6	2.5	7.2	28.9	50.3	11.2	0.8	
		D (30-40)								
		E (40-50)								
		F (50-60)	4.2	3.2	5.9	34	49.4	7.9	0.7	
		G (60-70)								
DGH4	M Ah	A (0-10)	4	0	5.7	14.1	67.4	12.9	2.2	
	M	B (10-20)	4	0	7.6	18.9	61.1	12.5	1.3	
		C (20-30)								
		D (30-40)	4.3	0	9.2	42.6	45.2	3	0.8	
		E (40-50)								
DGH5 (P2)	M3	A (0-23)	4	2	7.2	18.4	60.6	11.8	1.3	
	M2	B (23-33)	4	0	34	15.2	43.1	7.7	0.7	
	M1	C (33-51)	3.8	0	5.4	23.7	58.1	12.8	0.6	
	Bt	D (51-77)	3.5	0	17.6	21.9	52	8.5	0.7	
	Bv(t)	E (77-86)	3.6	13.9	15.6	25.8	38	6.7	0.6	
	DGH6 (P1)	M3	A (0-36)	4.2	0	9.1	12.5	61.3	17.1	1.4
M2		B (36-58)	4.1	0	12.5	14	58	15.5	0.9	
M1		C (58-76)	4.9	0	27.5	16.3	45.9	10.3	0.7	
Gully2		E (60-84)	4.7	0	10.2	21.8	51.5	16.5	0.6	
Gully1		F (76-112)	4.2	0	11.5	26.4	49.4	12.7	0.8	
Bt		J (85-105)	5.4	14.3	4.3	13.1	56	12.3	0.6	
Bv(t)		K (130-160)	6.6	9	6.6	20.9	53.6	10	0.7	
DGH7		A	A (0-20)	4	5.4	7.2	18.5	60.9	8	1
		B	B (20-40)	4.6	1.8	7.9	12.3	66.3	11.8	0.8
	C (40-60)									
C	D (60-80)	4.2	0	4.9	15.3	66.5	13.3	0.7		

Table 3
Soil profiles characteristics for the sampling sites DGH (Das Große Holz).

In the upper ca. 5/10 cm of the colluvial layer of the profiles SIE1, 2 and 3, an organic horizon rich in humified matter (Ah; layer of sampling A) is formed. Finally, soil analysis on DGH identified considerable soil heterogeneity. DGH soil profiles present variable depths, with profiles bottom at a maximum of ca. 170 cm (DGHP1/6) to a minimum of ca. 45 (DGH4) cm depth. For the deepest profiles, below ca. 50/70 cm an organo-mineral horizon weathered and/or with accumulation (Bt; Bv(t)) has been identified, except in DGH7. Above these horizons, colluvial layers are present (M). Within this colluvial accumulation, some layering distinctions were possible, especially thanks to the stratigraphical description of long trenches. Therefore, the most detailed layer distinction was done on DGHP2/5 and DGHP1/6,

with the identification of three various colluvial layers (layers of sampling A, B, C, corresponding respectively to colluvial layers M3, M2, and M1), while on DGH2 only the upper colluvial layer (M3, corresponding to the layers of sampling B and A) was distinguished from the colluvial sequence M (layers of sampling F to C). On the upper ca. 5/10 upper cm of the colluvial accumulation of the profiles DGH2 and DGH4, a humified organic horizon is formed (Ah; layer of sampling A). It is important to highlight that, depending on the location of the profiles, the soil presents diverse features, e.g. no Ah horizon is present on soil profiles along the stream, DGH1, 3 and P2/5, and those soil sequences present quite thicker colluvial accumulations than other profiles of the site. The analysis of this last soil trench P2/5 has shown the presence of two gully layers not identified on any other soil profiles.

Charcoal data

From the three sites of investigation about 480 kg of dry soil has been sampled (98 kg from ROS, 124 kg from SIE and 258 kg from DGH). From that, about 20 g of charcoal has been extracted (7.4 g from ROS, 2.4 g from SIE and 10 g from DGH), and about 12.5 g (5.3 g from ROS, 2.1 g from SIE and 5 g from DGH) has been taxonomically analyzed (3764 charcoal pieces, including 1174 from ROS, 982 from SIE and 1608 from DGH). Of the amount of charcoals taxonomically analyzed from ROS samples, 31 % were indeterminable, 66 % from SIE and 24 % from DGH, leaving 810 successfully identified charcoals from ROS, 334 from SIE and 1222 from DGH. The proportion of indeterminable charcoal was not included in the taxonomical results, while it is included in the SAP and SAL (Specific Anthracomass per Profile and per Layer), since this is carbonized material providing information about fire events.

The investigated ROS soil profiles are considerably rich in charcoal, especially ROS3 (Fig. 3). Observing the vertical charcoal distribution of the four soil profiles (SAL; Fig. 4) no common patterns are identifiable. However, deepest layers of sampling (D, E and F), corresponding to soil horizon Bt, show smaller charcoal concentrations. The taxonomical assemblages of ROS are diverse, with 12 identified taxa and two anatomical types (Fig. 4). There is no taxon clearly dominant, though *Fagus* and *Pinus* charcoal are found in amounts. These two taxa show a vertical succession, with a *Pinus* rich layer at a deeper level than a *Fagus* rich layer at about 20 cm depth. However, other taxa, regularly recorded at profiles and layer levels, present important SAT (Specific Anthracomass per Taxon), like *Acer* and *Betula*. It is interesting to observe that the SAT of *Quercus* are very small and it is only

recorded in ROS3A and ROS4F. Despite these small SAT, one *Quercus* piece was dated from modern times. Older dates were measured from three *Fagus* charcoals, and much older dates were obtained on two *Pinus* charcoals dated from the early Holocene (Table 4).

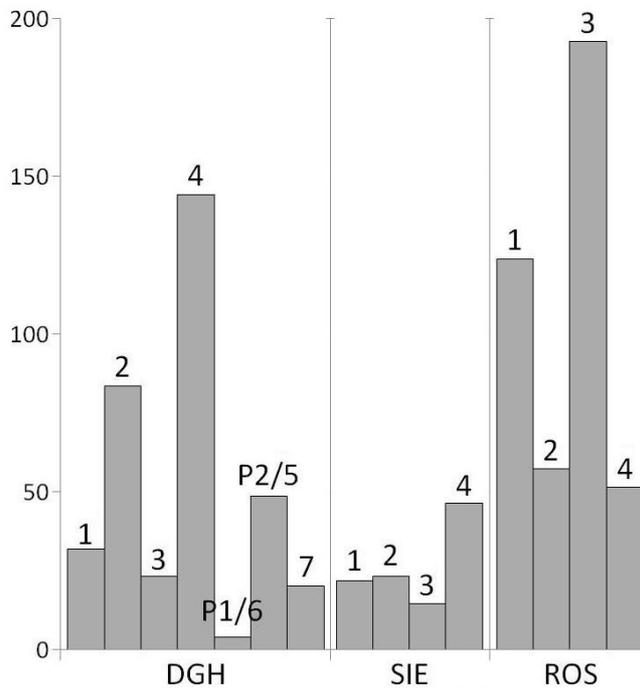


Figure 3. Total soil charcoal concentration per soil profile (SAP > than 1mm) of the sampling sites Rosentalskopf (ROS1,2,3,4), Siebengemeindewald (SIE1,2,3,4) and Das Große Holz bei Wallhausen (DGH1,2,3,4,7, P2/5, P1/6).

lab ref	site	depth (cm)	taxa	conv BP	cal BP	med cal BP	cal BC/AD
KIA42896	ROS1B	15	<i>Fagus</i>	860 ± 25	899-697	763	1052-1253 AD
KIA42897	ROS1C	25	<i>Pinus</i>	9610 ± 45	11165-10771	10941	BC 9216-8822
KIA 43763	ROS1D	35	<i>Fagus</i>	1075 ± 35	1057-931	982	894-1020 AD
KIA38768	ROS1E	45	<i>Pinus</i>	9140 ± 40	10415-10225	10288	BC 8466-8276
KIA 43764	ROS4B	35	<i>Fagus</i>	1180 ± 25	1175-1009	1108	775-942 AD
KIA38769	ROS4E	45	<i>Quercus</i>	50 ± 25	255-31	61	1695-1919 AD
KIA42902	SIE1B	15	<i>Pinus</i>	9600 ± 50	11161-10756	10940	BC 9212-8807
KIA 43758	SIE1C	25	<i>Pinus</i>	10300 ± 35	12378-11848	12083	BC 10429-9899
KIA38765	SIE1E	45	<i>Pinus</i>	9070 ± 40	10280-10180	10228	BC 8331-8231
KIA44624	SIE2A	5	<i>Fagus</i>	1120 ± 35	1168-938	1020	782-1013 AD
KIA 43759	SIE4A	5	<i>Fagus</i>	1260 ± 20	1275-1146	1220	675-804 AD
KIA42904	SIE4B	15	<i>Fagus</i>	1850 ± 25	1865-1715	1783	85-235 AD
KIA42903	SIE4B	15	<i>Pinus</i>	9810 ± 55	11331-11137	11226	BC 9382-9188
KIA38766	SIE4C	25	<i>Fagus</i>	1765 ± 25	1806-1573	1667	144-378 AD
KIA44619	DGH2B	15	<i>Quercus</i>	1995 ± 25	1995-1887	1944	BC 46-64 AD
KIA44620	DGH2F	55	<i>Quercus</i>	4030 ± 30	4572-4422	4485	BC 2623-2473
KIA44621	DGH3A	5	<i>Quercus</i>	2230 ± 25	2334-2154	2227	BC 385-205
KIA 43770	DGH3B	15	<i>Pinus</i>	11235 ± 40	13285-12956	13147	BC 11336-11007
KIA 43772	DGH3D	35	<i>Pinus</i>	11215 ± 60	13277-12910	13122	BC 11328-10961
KIA 43773	DGH5A	11	<i>Quercus</i>	2140 ± 25	2300-2009	2128	BC 351-60
KIA 43774	DGH5B	41	<i>Quercus</i>	2130 ± 30	2299-2001	2111	BC 350-52
KIA44623	DGH5E	80	<i>Quercus</i>	3610 ± 35	4070-3834	3919	BC 2121-1885
KIA 43775	DGH5E	80	<i>Quercus</i>	6610 ± 35	7566-7438	7502	BC 5617-5489

Table 4. AMS-14C dates of the single charcoal pieces from the investigated sites ROS (Rosentalskopf), SIE (Siebengemeindewald), DGH (Das Große Holz). Calibration in BP and BC/AC done at 2σ confidence interval, based on the IntCal09 dataset (Remier et al., 2009).

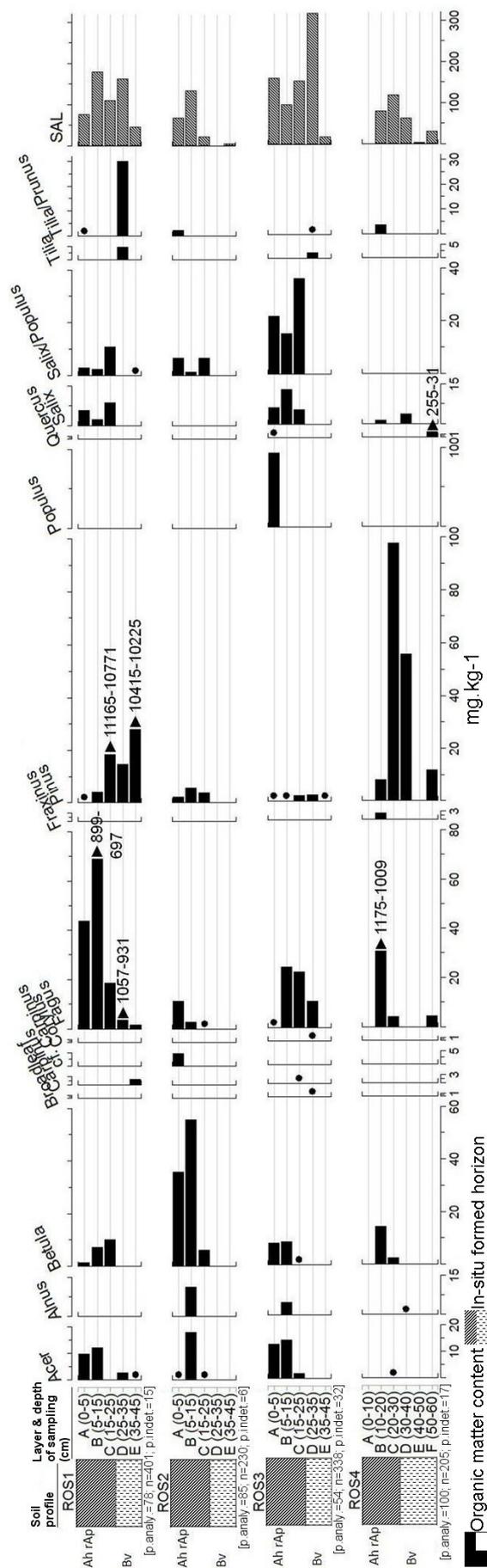


Figure 4. ROS (Rosentalskopf) soil charcoal concentration (in mg.kg^{-1} , x-axis below) per identified taxa (x-axis above) in soil charcoal assemblages of the soil profiles ROS1, 2, 3, 4. Soil nomenclature and profiles, layers and depth (cm) of sampling on y-axis. [p.analy= weight (mg) proportion of taxonomically analyzed charcoal from the total charcoal concentration per profile; n= total number of taxonomically analyzed charcoal pieces (identified + indeterminate charcoal pieces > 1mm); p.indet= number proportion in % of indeterminate charcoal pieces]. ● : charcoal concentration < 1 mg.kg^{-1} ; ▲ : radiocarbon dates in calibrated BP (2 σ interval); right column, grey stripes: total soil charcoal concentration per layer of sampling (SAL).

From SIE soil samples, relatively small SAP has been extracted compared to ROS and even to DGH (Fig. 3). No global patterns of vertical charcoal richness distribution are observable, either regarding layers of sampling or the corresponding soil horizons (Fig. 5), and even considering the distinguished colluvial layers. Six different taxa and one anatomical type were identified, constituting less diversified charcoal assemblages. A very large proportion of indeterminable charcoal fragments appeared. Based on a microscope view, it seems that most of those indeterminable charcoal pieces were not wood charcoal, but probably bark charcoal. A large dominance of *Fagus* was observed, especially in the soil profiles SIEP1/3 and SIE4, which are both localized on the top slope. In all the profiles, the *Fagus* records decrease with depth, showing much less rich SAT below ca. 20 cm depth. This is different to the *Pinus* vertical distribution, being identified in nearly all the layers of sampling, presenting variable SAT, sometimes relatively high (e.g. SIE1C and SIE4D).

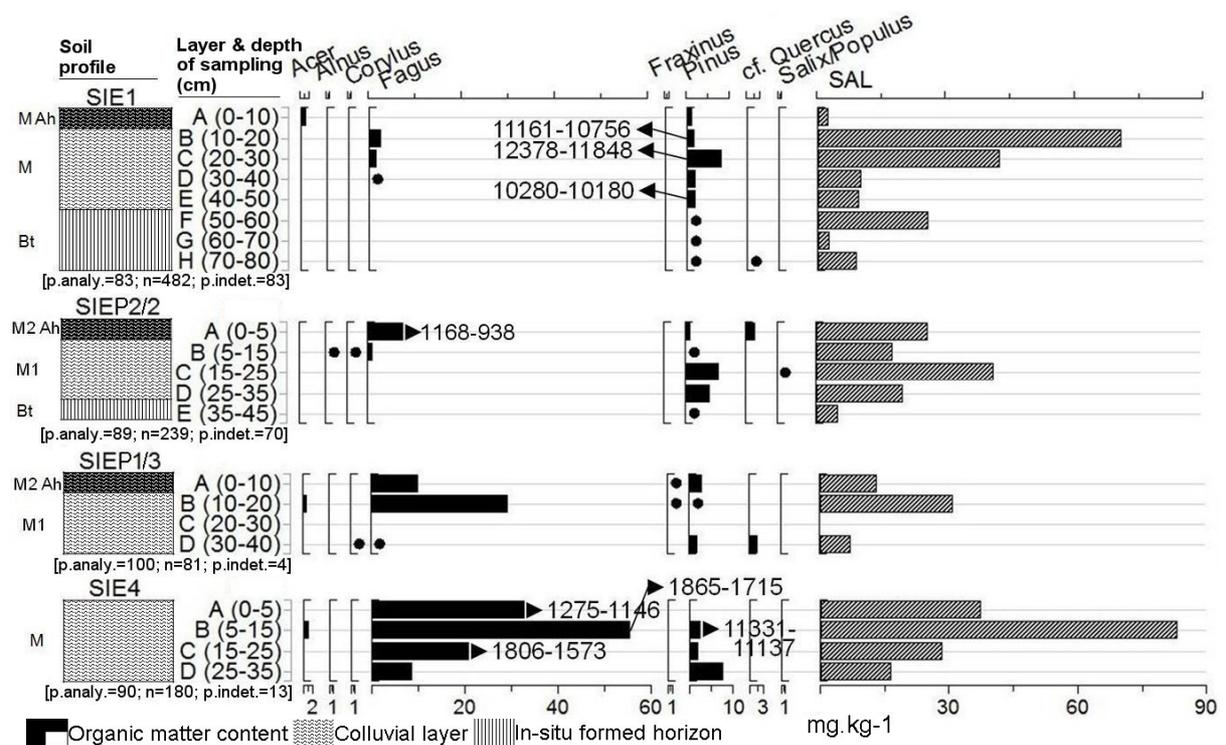


Figure 5. SIE (Siebengemeindewald) soil charcoal concentration (in mg.kg⁻¹; x-axis below) per identified taxa (x-axis above) in soil charcoal assemblages of the soil profiles SIE1, 4 and soil profile on trenches SIEP1/3 and SIEP2/2. Soil nomenclature and profiles, layers and depth (cm) of sampling on y-axis. [p.analy= weight (mg) proportion of taxonomically analyzed charcoal from the total charcoal concentration per profile; n= total number of taxonomically analyzed charcoal pieces (identified + indeterminable charcoal pieces > 1mm); p.indet= number proportion in % of indeterminate charcoal pieces]. ●: charcoal concentration < 1 mg.kg⁻¹; ►: radiocarbon dates in calibrated BP (2σ interval); right column, grey stripes: total soil charcoal concentration per layer of sampling (SAL).

Compared to ROS, *Fagus* and *Pinus* SAT present a vertical succession, with *Pinus* richer layers at a deeper level than *Fagus*, changing at about 20 cm. Four radiocarbon dates of *Pinus* charcoals from various depths are from the late Pleistocene/early Holocene, while four radiocarbon dates from the Subatlantic were obtained from *Fagus* pieces (Table 4). Other less represented taxa have been identified, in various concentrations, at various depths. As for ROS charcoal assemblages, only a few fragments were identified as *Quercus* or “probably” *Quercus* (i.e. cf. *Quercus*).

The SAP of the site DGH shows variable values, but overall those values are comparable to those of ROS and SIE (Fig. 3). Looking at the SAL, the upper ca. 40/30 cm of each soil profile contained larger amounts of charcoal, and the most important charcoal concentrations are at an intermediate level of depth (Fig. 6). However, the bottom Bt or Bv soil horizons provided small SAL. Only the Bv(t) horizon of DGH5 has an high charcoal concentration. At DGH seven different taxa and two anatomical groups were identified (Fig. 6). In contrast to SIE and ROS, *Quercus* charcoal largely dominate, especially in DGH2, 4 and P2/5. *Fagus* and *Pinus* pieces are very rare and small, except on DGH3 while they appear in weak concentrations compared to the SAT of the two other sites. Moreover, on the DGH3 profile, *Fagus* and *Pinus* present a vertical alternation of SAP domination, since *Pinus* charcoal is more present on the layers B, C, D and *Fagus* in the layers E and F. On that soil profile several radiocarbon dates have been obtained (Figs. 6 and 7). Two *Pinus* charcoal piece were dated from the late Pleistocene, and one *Quercus* piece from the Subatlantic. On DGHP2/5, two *Quercus* charcoal dates have been obtained for the deep Bv(t) soil horizon from the Atlantic and the Subboreal, and two more *Quercus* dates from the colluvial layers, dating both from the Subatlantic. Two *Quercus* dates have been obtained for the profile DGH2, from the Subatlantic for the layer B and from the Subboreal for the layer F (Table 4).

Discussion

Taphonomical considerations

From all the sampled profiles and from nearly all the layers of sampling (i.e. 74 over 86), charcoal fragments have been extracted. These records of “mega-charcoal” (as opposed to “macro-charcoal”, a term commonly used for charcoals with a size of 100-250 μm) indicate at least that in the past, charcoal was formed on-site. When a fire event occurs it burns wooden material, including dead wood and live vegetation, producing wood charcoals which are partly deposited, buried and conserved in the on-site soil, providing local charcoal records (Blackford, 2000; Scott et al., 2000). It has been demonstrated by several studies that charcoal pieces bigger than a range size from 100 to 250 μm (i.e. macro-charcoals), have a local spatial resolution (Clark, 1988; Clark and Royall, 1995; Whitlock and Millspaugh, 1996). Because of the taxonomical identification purpose, the soil charcoal analysis deals with pieces bigger than ca. 1 mm which is the minimal size for an anatomical identification. Therefore, the soil charcoal records can be interpreted in high spatial resolution (i.e. few tens of meters; Dutoit et al., 2009). However, it must be considered that following the fire event, often soil erosion occurs, since the vegetation cover has been partially or totally removed by the fire event (Cerdan et al., 2010). So, charcoal assemblages, once embedded in the soil matrix, might be transported by erosive events, but staying still within the catchment area of the erosive process, providing data at identifiable spatial scales (Touflan and Talon, 2009). Therefore, a multi-profile sampling strategy was applied at the catchment scale of each site. This investigation and sampling strategy allows the soil heterogeneity and the various possible sources of charcoal production (i.e. forest fire, human fire places, charcoal production sites, etc.) to be taken into consideration. Comparing this multi-sampled data set provides representative palaeo-data. The variability of the charcoal records in terms of SAP, SAL, and SAT, indicates the heterogeneity in charcoal formation and/or archiving processes. However, such large variability in the soil charcoal record and especially in regards to the various depths of sampling, combined with the chronological data obtained from the radiocarbon data, allows one to consider that most of the soil charcoal is from forest fires, whatever the ignition factor. Nevertheless, it cannot be excluded that parts of the charcoal assemblages are from other sources of production, like charcoal production sites, which are present in the surrounding of the ROS and SIE profiles.

The identification of erosion events and the resulting earth sediment deposits, like on SIE and DGH sites where colluvial layers have been identified, supports the detection of forest fire occurring at least at the stand scale, which probably removed the vegetation cover, favouring

the identified colluviation. The detection of colluvial layers might provide relative chronological information. Even if this temporal information must be correlated to absolute dating (Bork and Lang, 2003), it nevertheless provides a chronological framework useful for the interpretation of the soil charcoal assemblages. However, it must be taken into consideration that soils are not chronologically stratified archives, as is observable for the four radiocarbon dates of the soil profile SIE4 (Fig. 5). Soils are “dynamic” archives which do not allow a strict interpretation of the age/depth correlation (Table 4; Carcaillet, 2001). Because of physical (e.g. uprooting; Gavin, 2003; Šamonil et al., 2010) and biological processes (e.g. bioturbation due to earth worm activity; Darwin, 1881; Jégou et al., 1998), single charcoal pieces and/or charcoal assemblages embedded in soil aggregates might move in the soil in all directions. Therefore, absolute dating is of first importance for the interpretation of soil charcoal assemblages.

Fire history

Considering the soil charcoal concentration, the global patterns of stratigraphical distribution of SAT, and the radiocarbon dating, there are evidences of on-site past fire occurrences. Several past fire events have been detected at the local scale of each investigation site, even when considering radiocarbon dating range overlapping and old wood effect (Gavin, 2001). During the late Pleistocene, at least three fire events have been dated on SIE, and two on DGH. For the early Holocene, one fire event has been identified on ROS, and two on SIE. During the late Holocene, two fire occurrences have been dated on ROS and on SIE, with one more fire event dated on DGH. For the mid Holocene, three fire occurrences have been dated, only on DGH (i.e. the Subboreal fire occurrences are considered as late Holocene dates). The large scale synchronies of the locally identified past fire events allow to highlight two main temporal phases of fire occurrences: (1) during the late Pleistocene/early Holocene and (2) during the late Holocene. This chronological pattern of fire history fits to global trends of fire history in Central Europe, pointed out by a few other investigations (Clark et al., 1989; Robin *et al.*, 2011) and broad scale synthesis (Carcaillet et al., 2002; Power et al., 2008). Concerning the fire ignition factor and fire regime control, the two main identified phases of fire occurrence reflect quite well the two various dominant forcing factors of fire history since the last glacial phase. The late Pleistocene/early Holocene fire signal might be connected to climate forcing (Bos, 2010). An abrupt climate deterioration of the North Atlantic may explain the identified fire phase (Bond et al., 1997), especially the Bond event 7 (i.e. 10.3 ± 5 kyrs BP; Bond et al., 2001), as supported by radiocarbon dating from the SIE

and ROS and moreover with chronological synchrony between the Bond event 1 (i.e. 1.4 ± 5 kyr BP) and some DGH dated fire events during the Subatlantic. This remains to be tested by further research. Concerning the late Holocene, fire occurrences seem to be strongly connected to human usage of fire as a tool to manage the landscape - to open it up or keep it open –, from Neolithic times onwards (Innes & Blackford 2003, Greisman & Gaillard 2009). The human impact on forest systems, since at least the 10th century AD, has been discussed for the western and upper Harz regions (Beug et al., 1999). Human usage and its impact on natural resources for mining purposes have been especially strong on the Harz Mountains since, at least, Medieval times (Matschullat et al., 1997; von Kortzfleisch, 2008). This fits with the radiocarbon chronological evidences and the related taxonomical indications, with moreover indications of Iron Age fire event on SIE (Table 4).

Some dates from DGH point out the occurrences of fire events during the mid Holocene phase. Since the taxonomical analysis of the soil charcoal assemblages indicates that the corresponding charcoal records are from broadleaf tree species (i.e. *Quercus*; Fig. 6), the human forcing can be again postulated concerning these fire occurrences. This is especially true concerning the two Bronze Age fire events. Considering regional scale archaeological evidences (Lubos et al., 2011), the human forcing might also be relevant concerning the late Mesolithic fire event. Man-made fire earlier than the Neolithic has been highlighted several times in Central Europe (Mason, 2000; Power et al., 2008).

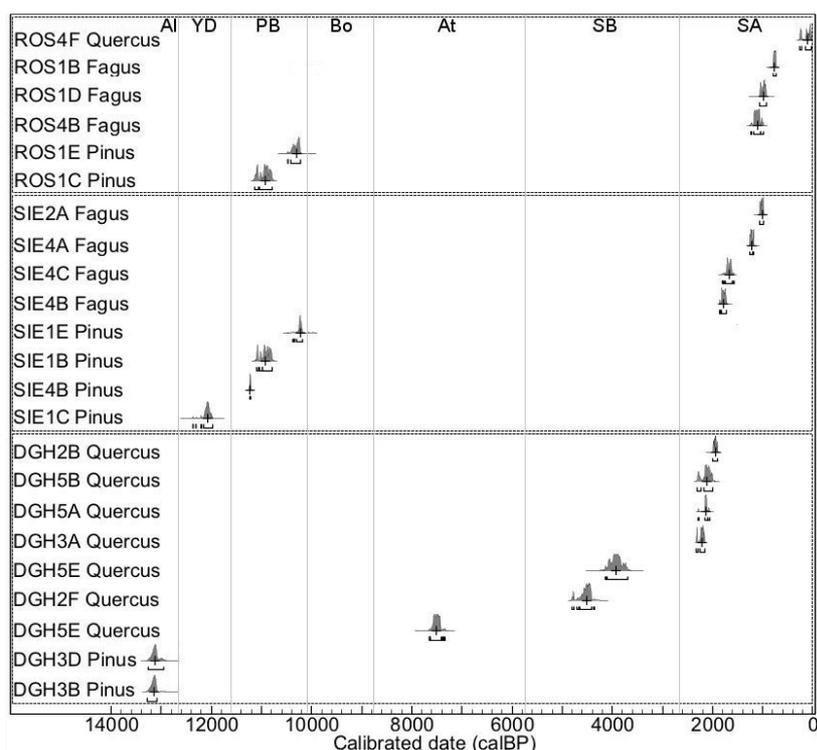


Figure 7. Multigraphical radiocarbon range of the AMS-C14 charcoal pieces measurement from ROS (upper box), SIE (middle box) and DGH (lower box). Age range in yrs cal BP (2σ interval; IntCal09 dataset); plotted on OxCal 4.1 program (Bronk-Ramsey, 2001). Al: Allerød; YD: Younger Dryas; PB: Preboreal; Bo: Boreal; At: Atlantic; SB: Subboreal; SA: Subatlantic (Lang, 1994; Litt et al., 2001).

Forest history

Forest history insight inferred from the taxonomical analysis of the soil charcoal assemblage of the three investigation sites support the previously described fire history.

Several dated charcoal pieces from late Pleistocene/early Holocene fire phase are *Pinus* charcoal pieces (Table 4). The *Pinus* charcoal record is regularly present, sometimes in high concentration, in the various charcoal assemblages extracted from the soil samples of the three sites (especially on ROS and SIE). When this taxon has been dated it was always from the late Pleistocene/early Holocene period. This *Pinus* charcoal record fits well to the woodland composition of the Allerød, Younger Dryas and Preboreal in Central Europe (e.g. Litt et al., 2001) and on a regional scale (Litt, 1992; Voigt et al., 2008), considering also that *Betula* and *Salix* are also identified in the charcoal assemblages. This taxonomical information also fits with a natural/climatic control of the fire events locally identified during the late Pleistocene and the early Holocene, since these pine dominated forests were easily flammable during dry phases (Bos, 2010). In contrary, late Holocene temperate broadleaf forests of Central Europe do not constitute an easy flammable structure and fuel (Pyne et al., 1996; Krivtsov et al., 2009). Nevertheless, the taxonomical analysis of the late Holocene dated charcoal pieces provides an indication of fires in woodland dominated by deciduous trees, especially by *Fagus* and *Quercus*. They are present in significant amounts in the charcoal assemblages at all sites. These on-site observations, regionally synchronous, support the postulated human control of fire occurrences during the late Holocene (i.e. Subatlantic). Temperate broadleaf forests would probably not burn without human ignition and fire management. Within the large representation of temperate broadleaf taxa in the analyzed soil charcoal assemblages, important variations in past forest composition occurred. Taxonomical charcoal assemblages extracted from the soil samples of ROS and SIE are largely dominated by *Fagus*, with taxa often associated to the late Holocene *Fagus* forest, like *Carpinus*, *Acer*, and depending on the water availability, *Alnus* and *Fraxinus* (Figs. 4 and 5). In comparison, the taxonomic soil charcoal assemblages of DGH are largely dominated by *Quercus*, with the recording of associated forest species like *Tilia*, *Acer* and *Corylus* (Fig. 6). Here, at the south facing slope of the Harz foothills, *Fagus* charcoal was only found in the assemblages of the profile DGH3. This variation of the taxonomical representation along the northwest/southeast transect of investigated sites, indicates an important variation in the past forest composition of the late Holocene between the inner part, *Fagus* dominated, and the *Quercus* dominated side hills area, of the Harz Mountains. This could be explained by the fact that at lower altitude, with less rainfall and a southern exposure, dryer conditions might have favoured oak

compared to beech, which might have never really established on this site. Only weak evidences of the mid-Holocene forest have been identified in the soil charcoal assemblages. To explain this it must be considered that soil charcoal assemblages only record the burnt vegetation. If one taxon, or one forest type, is not represented in soil charcoal records that does not mean it was not present on site, but just that it maybe did not burn. This is illustrated by the general taxonomical stratigraphy in most of the soil profiles of ROS and SIE. *Pinus* charcoal pieces assemblages, dated from late Pleistocene/early Holocene, mostly dominate the deepest layers of sampling, often correlated to soil horizons at the bottom of soil profiles (e.g. Bv horizon on ROS profiles; Fig. 4). To the contrary, *Fagus* charcoals, dated from the late Holocene, dominate the upper part of the profiles. The much weaker *Quercus* charcoal recording seems to indicate that the mid-Holocene *Quercus* dominated forests did not burn, or at least not intensively enough to provide its clear recording in the locally sampled soil charcoal assemblages. When considering the fact that late Holocene broadleaf fires are probably man-made fires, it could be postulated that no strong human impact on the forest structure happened before the establishment of *Fagus* in the Harz Mountains, estimated at about ca. 5700-4500 yrs cal BP (Bradshaw et al., 2010; Magri, 2008). This fits with the general knowledge regarding human development in the Harz mountains, especially connected to mining purposes and the necessity of huge wood and charcoal resources since at least the Middle Ages (Beug et al., 1999; von Kortzfleisch, 2008), but nevertheless human impact might have happened earlier than hitherto thought, as our few radiocarbon dates may suggest. Comparable information is given from the taxonomical charcoal assemblages extracted from colluvial layers of DGH, but highlights the *Quercus* dominated forest instead of *Fagus*, as discussed previously. Mid- and late Holocene fire events have identified as burning of temperate forests. Therefore, it has been postulated that such fire is from human forcing, as it was indicated by other investigations in Central Europe (Mason, 2000; Power et al., 2008). Such a hypothesis emphasizes the possible ancient human influence on natural systems on the southeast side hills of the Harz Mountains. This seems coherent to settlement sites identified nearby the DGH area, in the Helme alluvial plain (Lubos et al., 2011).

Conclusion

Throughout the investigation done on the three study sites it has been illustrated that the soil charcoal analysis, correlated to soil feature description and identification, allows for the detection of fire event(s) and the identification of the type of forest burnt. Such vegetation change might be correlated to the presence of colluvial layers, from which soil charcoal

assemblages have been extracted, but this is highly dependent on the topographical context. The identification of past fire occurrences and the corresponding past forest composition at the local scale of the catchment area of the three investigation sites allows for the identification of regional trends by identifying signal synchronies. It has been demonstrated that in the southeastern part of the Harz Low Mountains range, *Pinus* dominated landscapes burnt because of fire events occurring during the late Pleistocene/early Holocene, and during the late Holocene deciduous woodland burnt. The corresponding colluvial layers and/or in-situ ancient soil horizons have been identified. Due to the forest structure and its fuel characteristics at main fire phases, climatic control for the older fire phase and human control for the younger one is likely. Despite the relatively small radiocarbon data set, the chronological indications obtained for the mid- and late Holocene fit to the general insight about the human settling development on mountain ranges usually from margin to inner and higher parts, through time. Late Mesolithic and Bronzes Age dates have been obtained on the site on the Harz margin, DGH. Then, Iron Age dates have been obtained on the site in intermediate location, SIE. Finally, only medieval times dates have been obtained on the most inner site ROS.

Although soil charcoal analysis does not allow the detection of forest succession and continuity, it is a relevant tool to investigate past occurrences of ecosystems changes, at local and regional scale, depending on the sampling resolution.

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6.3 Forest characterization and tree ring analysis of the Heinrichöhe investigation site (Harz Mountains, Central Germany).

Introduction

Natural forest areas are rare in Central Europe (Parviainen 2005, Reif and Walentowski 2008). The ancient and strong human impact on forest dynamics have been well documented (e.g. Behre 1988, Berglund *et al.* 1996, Kalis *et al.* 2003, Berglund 2011). Those anthropogenic influences increased with cultural development, and human activities shaped the landscapes more and more, leading strongly to forest structure influenced by human usage and management (Larsen 1995). Therefore, areas with remaining pristine or restored natural, or semi-natural (Rouvinen and Kouki 2008), forests are of great interest for biological and patrimonial conservation (Gilg 2004, Branquart *et al.* 2008, Reif and Walentowski 2008). More precisely, from a biological point of view, such forests areas are of great biological value since there have high levels of naturalness and biodiversity (e.g. old-growth forest; Gilg 2004, ECONorthwest 2006, Wirth *et al.* 2009). From a biogeographical point of view, such natural forest areas are often isolated in fragmented landscapes, including lands that are intensively used at present, as well as being used in ancient times (e.g. agricultural lands; Greisman and Gaillard 2009), forming like “natural islands in a sea of man-shaped ecosystems”. Therefore, they may present particularly interesting and important features and components as “nature refuge” for conservation issues.

Moreover, for conservation/restoration purposes, those natural forests areas may be used in some cases as reference states of forest systems for restoration/conservation projects (Winter *et al.* 2010). More globally, such natural forests, and their dynamics of change, may provide insights to better understood the past and the present forests states, helping to anticipate future dynamics (Foster *et al.* 1990, Schnitzler and Borlea 1998, Siipi 2004), notably by improving the assessment of the human impact on forest systems, correlate to on-going global changes and the treatment of ecological systems (e.g. Tasser *et al.* 2007, Federici and Galluzzi 2010, Barnosky *et al.* 2011). To obtain such insights, and first to identify “natural forest areas,” it is necessary to assess and characterize the structure, the organization and its functioning. Taking into consideration the spatial and temporal continuity of the ecosystems dynamics (see Part 1, Chapter 2.1), it is crucial to use historical perspectives (Farrell *et al.* 2000, Egan and Howell 2001, Foster 2002). Such an approach is even more relevant when dealing with protected forest areas like national parks, where the natural model can usually be investigated. Therefore, a multiproxy data set has been used to characterize the current state

and the short-term past dynamics, correlated to long-term palaeo-investigations of a forest stand in the Harz National park in Central Germany (Nationalpark Harz 2011). By characterizing the forest stand structure and composition, and the centennial trees' growth patterns, it is aimed to assess the degree of naturalness of this protected forest, which is known as a natural conifer mountain forest.

Investigation area

The investigated forest stand is localized in the national park of the Harz Mountain, in Central Germany on the side slope of the Heinrichshöhe hill (i.e. HEI, Figure 1).

General features of the Harz Mountains and of the HEI site of investigation are described in Part 2, Chapter 3.2, and Chapter 6.1. of this Part. Nevertheless, when dealing with biological conservation, it is important to highlight that the geographical location and the relief of the Harz Mountains isolates it between the North European plain in the north and the Central European highlands in the south, like a “mountain range island” (Figure 1). Moreover, the national park includes areas at the highest elevation of the mountain range, presenting typical and rare (even at the Central European scale) mountain forest vegetation: the “Mountain to alti-mountain” forest types (Bohn *et al.* 2004, Kison and Wernecke 2004). This typical mountain forest area is supposed to be ‘untouched’, or at least to not have been strongly impacted by human activities for several centuries (Kison, personal communication). Therefore, even at the national park scale, such a typical mountain forest represents a small surface island within forested areas that have been strongly impacted by humans in the past (Beug *et al.* 1999, Hauhs and Lange 2000, see this Part, Chapter 6.1). The areas at lower elevation, where *Picea abies* was planted as a “routine” way of forest regeneration, are currently extensively managed to promote natural forest dynamics (e.g. re-establishment of *Fagus sylvatica*). However, a crucial question remains unanswered: “What is natural?”

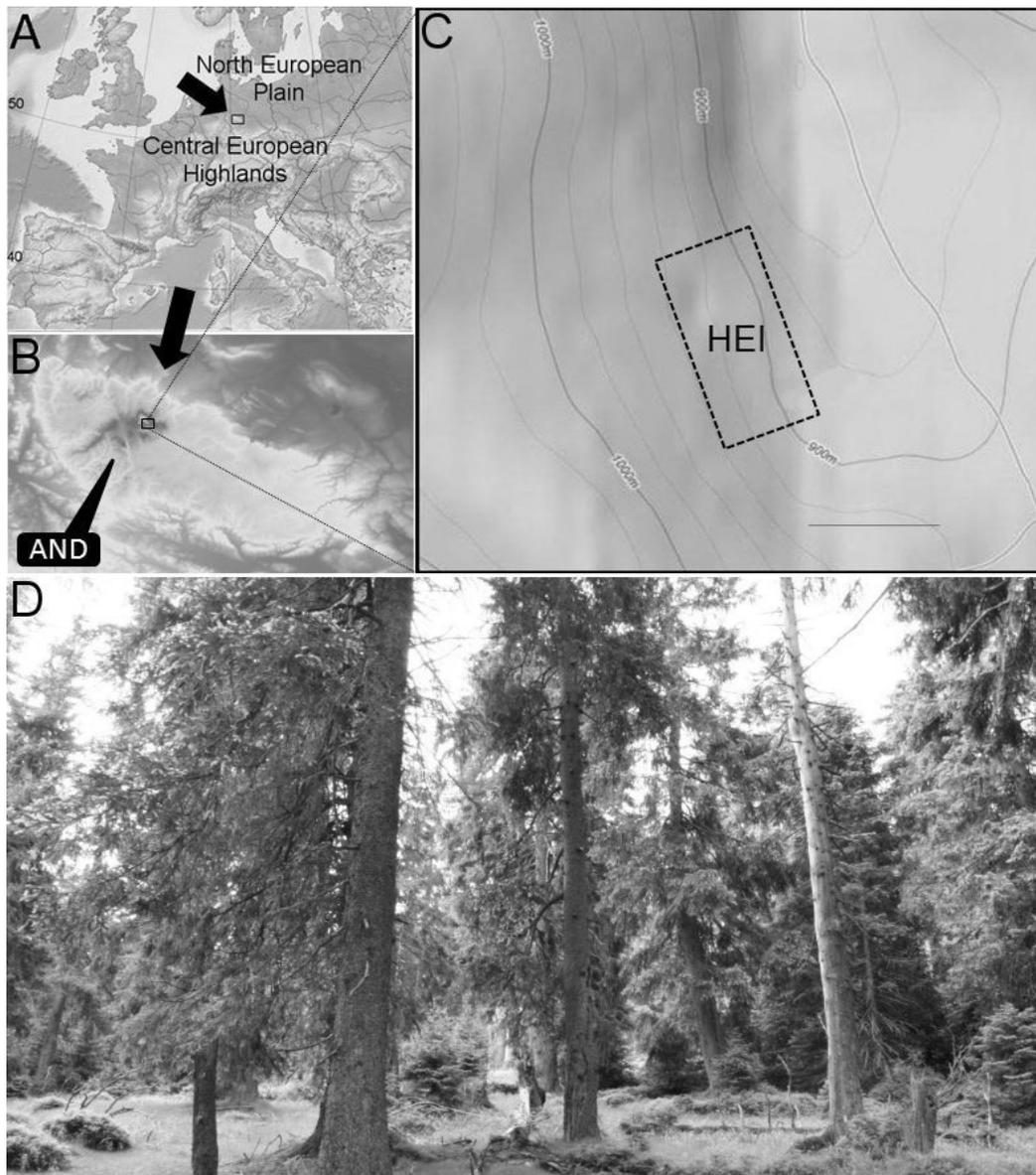


Figure 1. Heinrichshöhe (HEI) investigation plot. A: Map of localization of the Harz Mountains, in Europe; B: Map of localization of the HEI investigation plot, in the Harz Mountains, and of the Andreasberg area (AND); C: topographical map and localization of the HEI investigation plot at the Heinrichshöhe hill scale. D: HEI onsite picture (Juin 2008).

Methods

The characterization of the Heinrichshöhe forest stands and the identification of its growth patterns were based on inventory, measurement and tree rings radii sampling, on a defined investigation plot, roughly situated within the location of the sampled soil profiles for the long-term investigation (see this Part, Chapter 6.1). This forest plot, of rectangular shape because of the on-site relief constraint (i.e., small cliffs), measured ca. 3200 m² (i.e. 40*80 m; Figure 1). The on-site applied protocols are described in detail in Part 2, Chapter 4.2.1, about forest stand characterization and in Chapter 4.2.2 about tree ring series analysis (see also the Part 3, Chapters 5.1 and 5.2).

The tree species composition and the stems distribution per diameter at breast height (dbh) classes has been inventoried, per identified vertical forest level. To assess the spatial structure of the trees at the stand scale for each inventoried stem, the x/y coordinates were measured from bordering lines for mapping. Moreover, nearest-neighbour distances were measured allowing the calculation of the Clark-Evans index, providing indication about the level of aggregation of the spatial trees distribution (Clark and Evans 1954, Pretzsch 1997). The species composition of the regeneration level (seedling and sapling abundance) has been counted. The dead wood volume per identifiable species, and decay classes was also quantified (see Part 2, Chapter 2.2.1).

In order to identify patterns of growing condition changes, ring-series from on-site dominant trees were analyzed. Therefore, 16 *Picea abies* stems have been cored, providing a data set of 32 radii. Once the laboratory processes were done and the cross-dating of the measured tree ring series made (see Part 2, Chapter 4.2.2 and Part 3, Chapters 5.1 and 5.2), the mean site chronology was obtained by tree ring series averaging.

To obtain the high frequency signal that provides information of the yearly growing patterns, the measured tree ring series were standardized by “normalization in a moving window” (Bijak 2008). Such methods of standardization allows one to detect “pointer years”, which are years presenting growth “anomalies” based on the standard deviation values (Neuwirth *et al.* 2007). Moreover, the mean sensitivity (ms) and expressed population signal (EPS) were calculated, contributing to the assessment of the data set correlation and of the year-to-year changes in the width of rings (Wigley *et al.* 1984, Biffra 1995, Haneca *et al.* 2005).

To assess the mid-frequency growing patterns of the investigated forests stand, the growing change proportion of the measured tree ring series was calculated, on temporal windows of five years. This was done by using “running median” methods (see Part 2, Chapter 4.2.2; Nowacki and Abrams 1997, Rubino and McCarthy 2004). Such signal frequency provides information about the growth change correlated to environmental condition changes, notably due to disturbances events (Schweingruber 1996, Rubino and McCarthy 2004).

Moreover, the tree ring signals obtained on-site were compared to an “external reference” chronology. This chronology, gathered from the WSL Dendro Database (Schmatz 2011), is from the area of Andreasberg, to the West of the investigation plot HEI (Figure 1). The data set forming the “reference chronology” named AND presents features that are comparable to the HEI data set in terms of altitude level of the sampled stems (i.e. 900 m a.s.l.), about the analyzed species (i.e. *Picea abies*), and the close number of measured tree ring series (i.e. 14; Schweingruber 1978). These aspects make the two site chronologies

comparable. By comparing the high- and mid-frequency signals from both HEI and AND (i.e. calculated in the same way), and detecting synchronies and asynchronies, insights about the changes in growth condition at a regional scale were obtained.

Results and discussion

The investigated forest stand presented only *Picea abies* stems that did not present any homogenous vertical forest levels. The on-site stems present an important height range. Therefore, we considered only two global vertical levels. They were the understory stems, growing under the dominance of higher stems that formed the overstory level, and the overstory. The large variability in height of both understory and overstory fits the large range of the distribution of stem diameters. The HEI forest stand presents small understory stems and large canopy trees (Figure 2).

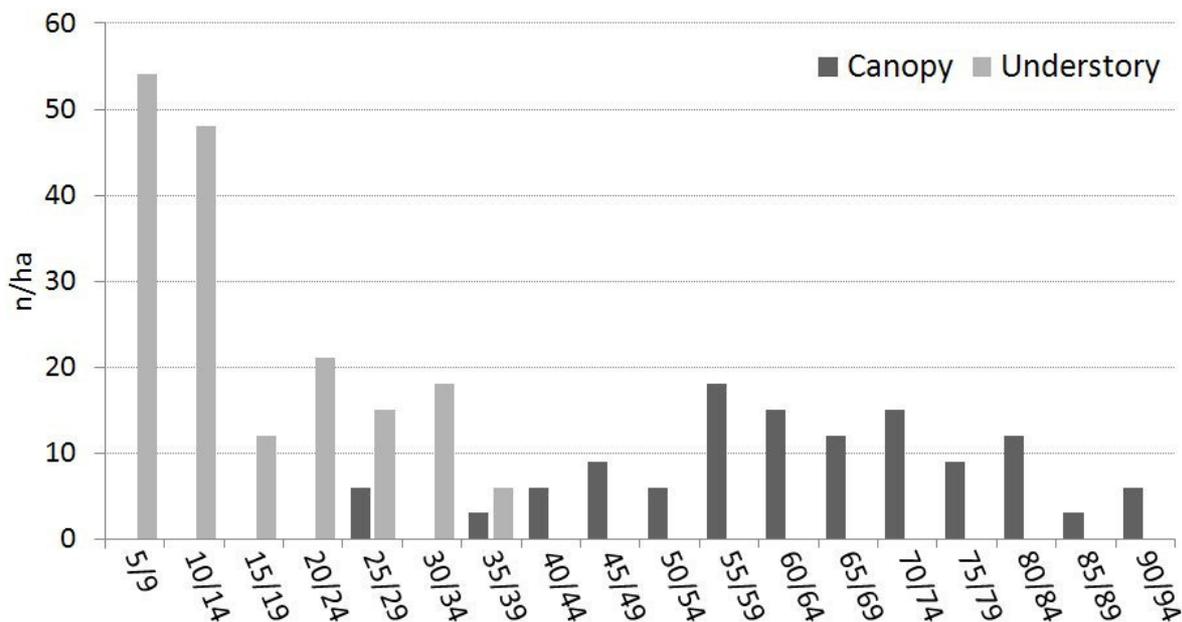


Figure 2. Diameter distribution of the Heinrichshöhe (HEI) investigation plot. Stems abundance (/ ha) per class of diameter at breast height (in cm).

Those dimensional features of stand stems correspond well to an uneven-aged stand structure (Peterken 1996, Choi *et al.* 2007). The overall abundance of stems presents a relatively high density, especially the understory level and the two smallest dbh. While, in terms of space occupancy, the overstory stems largely dominate, despite their far less abundance, as the basal area values illustrate (Table 1). This observation allows to postulate that the understory, as a global cohort, does not seem to be in high competition for space with the overstory stems.

The identified and previously described stand stems and vertical structure may indicate an important, fine spatial, natural process of patch dynamic (Pickett and White 1985, Peterken 2001, Roxburgh *et al.* 2004). Indeed, the on-site *Picea abies* regeneration established and grown, in favour of small sized gaps formed by fine scale canopy openings due to single, or small groups, tree(s) senescence, or prematurely died stems because of disturbance occurrences like beetles impact (e.g. Hughes 2002). Such fine scale stand dynamic does not fit over-stand dynamic control of occurrences, like large scale disturbances (e.g. fire event - Whitlock *et al.* 2010 – storms - Nagel *et al.* 2006).

HEI: <i>Picea abies</i>		Overstory	Understory
		relative values (%)	
Abundance (n/ha)	249	30	70
Basal area (m ² /ha)	36	80	20
Mean dhb (cm)		62	18
Mean height (m)		18	12
Regeneration:		Seeding	Sapling
Abundance (n/ha)	2738	2600	138

Table 1. Heinrichshöhe (HEI) forest stand features.

The identification of an on-site fine scale dynamic process is supported by the current spatial stems distribution. The mapping of the stand's stems allows one to observe small size groups of various dimensions in the stand (Figure 3). The CE index, with a value of 0.5, indicates a tendency to tree stem clustering (Fröhlich and Quednau 1995). That information about the forest stand spatial structure indicates that the HEI stand stems are aggregates in groups containing a small number of stems of varying dimensions. Such a spatial stem distribution patterns fits the on-site fine scale dynamics of forest disturbances and regeneration (Huth and Wagner 2006, Kathke and Bruelheide 2010).

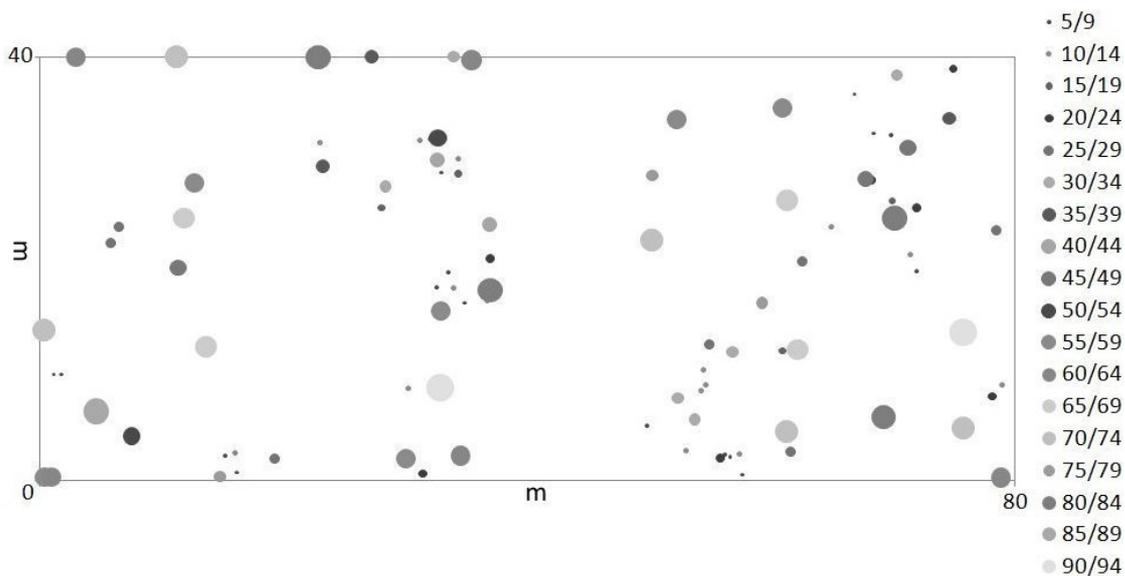


Figure 3. Forest stand spatial stems distribution of the Heinrichshöhe (HEI) investigation plot. Mapping of the trees per class of diameter at breast height (in cm), base on X and Y coordinates.

The amount and distribution of dead wood may have an important role for the stand biodiversity and regeneration by providing micro-habitats for adapted organisms and possibly having a “nursery effect” for regeneration, which would explain the clustering of stems (Motta *et al.* 2006, Bauhus *et al.* 2009). The HEI dead wood inventory indicates an important volume of dead wood, in various states of decay and consisting mainly of pieces that are standing and lying (Figure 4). Those results of the dead wood inventory fits well to the old-growth dead wood feature (Green and Peterken 1997, Aakala *et al.* 2007, Wirth *et al.* 2009), and support the previously described fine scale dynamic process by indicating fine scale openings of the stand structure. The overall characterized stand feature indicates the current importance of the natural process for the on-site forest dynamics.

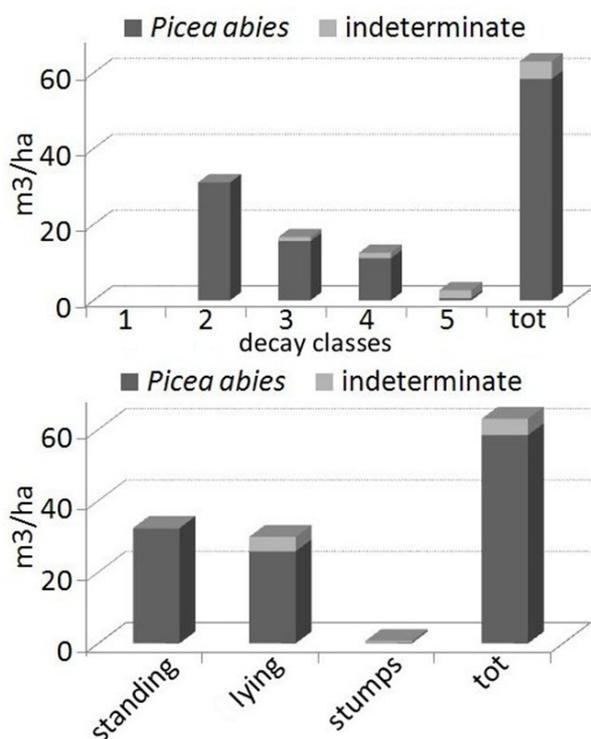


Figure 4. Dead wood inventory of the Heinrichshöhe (HEI) investigation plot. Upper graphic: dead wood volume per decay class; Downiest graphic: dead wood volume per type of piece.

The mean site chronology spans in 265 rings, from 2009 to 1744 (the common interval of the 16 tree ring series is from 2009 to 1844; Figure 5). The cross-dating of the two radii per tree, and of the tree ring series, providing by averaging the mean site chronology, presented a satisfying result (by eye and with the statistical index of Cross-Dating-Index; see Part 2, Chapter 4.2.2), without excluding any false rings or adding any missing rings. The high value of the expressed population signal (i.e. EPS: 0.961; Wigley *et al.* 1984, Biffra 1995) supports an important correlation between the measured tree ring series (Saulnier *et al.* 2011).

The calculation of the growing change (GC) proportion, at mid-frequency resolution,

indicates a fluctuating growth change pattern, with occurrences of large amplitude GC (Figures 5 and 6B), indicating release events (Nowacki and Abrams 1997, Black and Abrams 2005). Such detected release events are related to environmental changes, possibly due to fine scale disturbances occurrences. Those regular disturbance occurrences had various intensities, since they induced various amplitudes of growth change. Such fine scale forest stand dynamic change fits the patch dynamic process postulated based on the structural feature of the HEI forest plot.

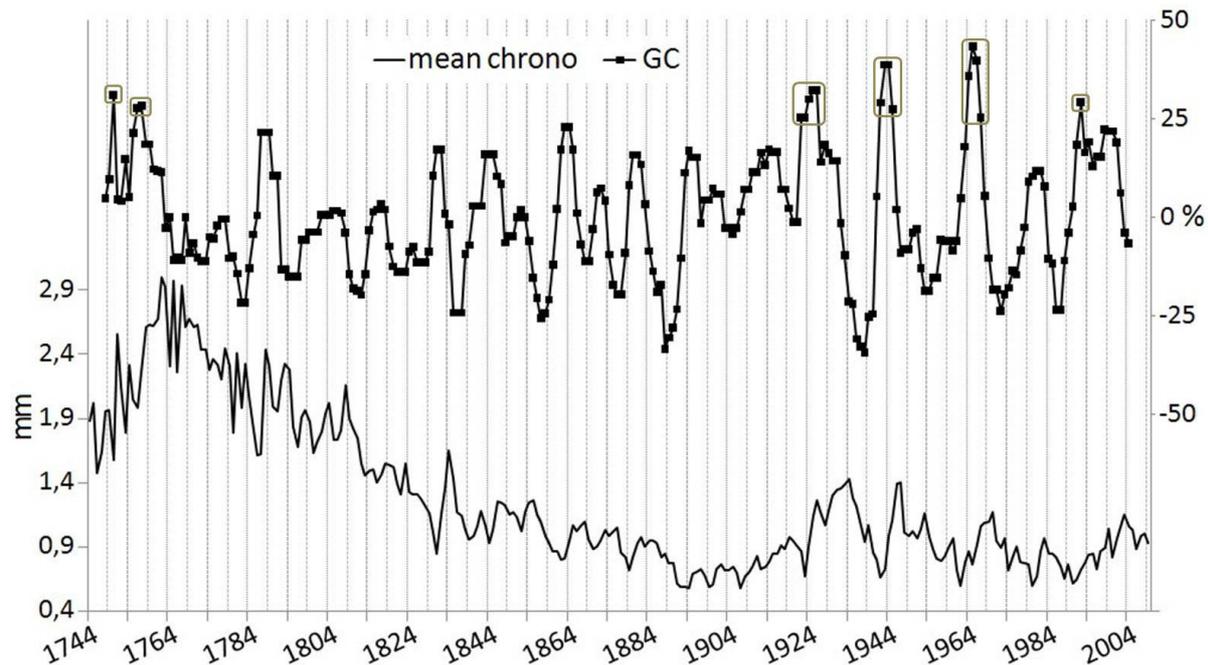


Figure 5. Tree ring signal from the Heinrichshöhe (HEI) investigation plots. Downiest curve: mean site chronology (mean chrono, in mm); Upper curve: growth change proportion (GC, in %), in the grey box are the larger amplitude GC %.

However, the high frequency signal also indicates large amplitude signal variations from year to year (Figure 6A). This is supported by the mean sensitivity, which has a relatively high value (i.e. 0.199). In terms of pointer years, this high frequency variability corresponds to the identification of 31 weak, 24 strong, and 19 extreme ring width anomalies (Neuwirth *et al.* 2007, see this Part, Chapter 5.1). Such high frequency signal indications allow to postulate that climatic control has an important influence on the growth of the stand's trees. The previously described release events might be related to large scale climatic control, as illustrated by the fact that the detected phase with significant growth changes in mid frequency signal are chronologically related to growth anomalies detected in the high frequency (Table 2).

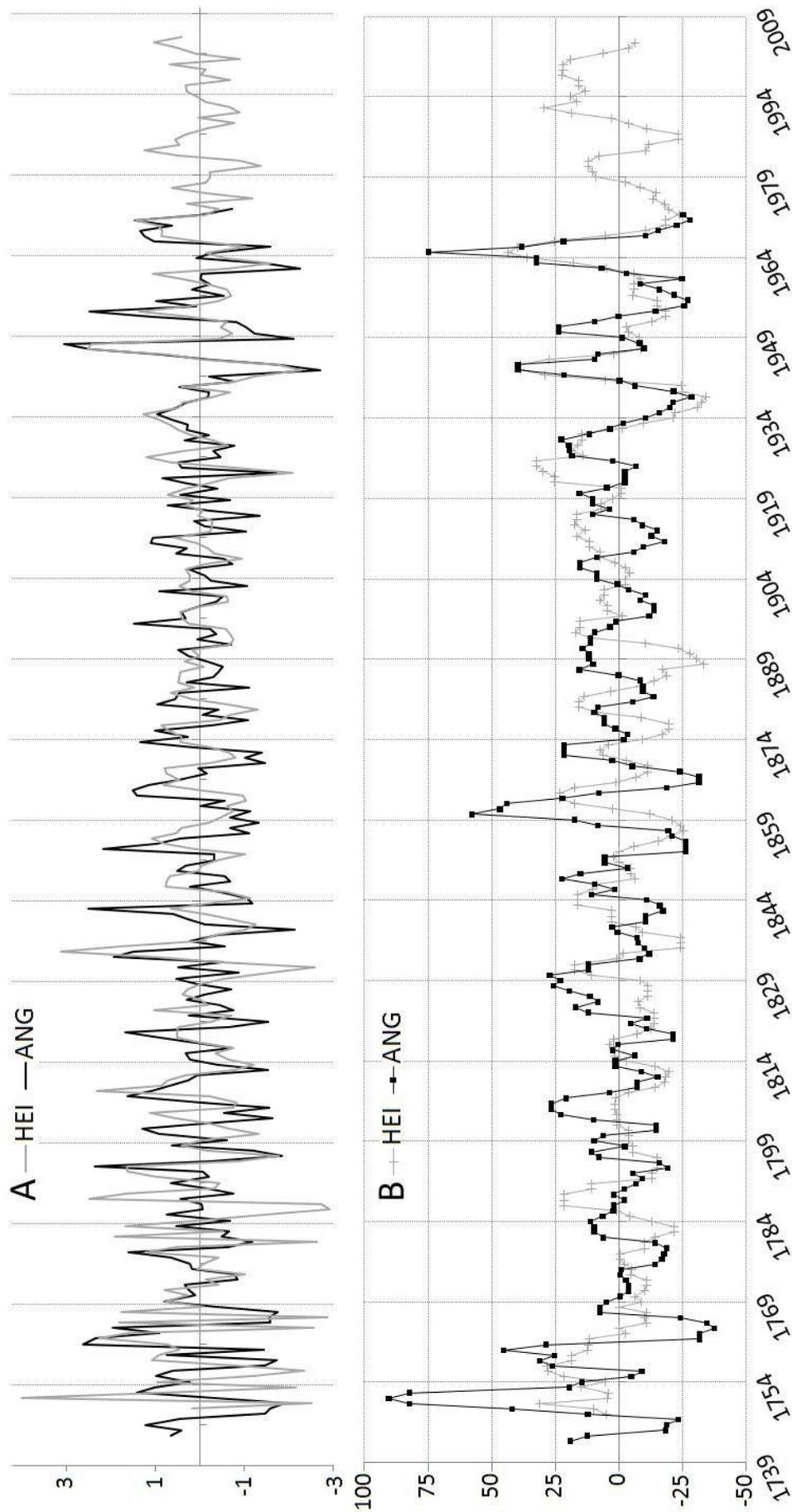


Figure 6. Comparative graphics of the standardized tree ring signals from Heinrichshöhe (HEI) and Andreasberg (AND); A: high frequency standardized tree ring signal; B: mid frequency standardized tree ring signal

To compare the HEI signals with the tree ring signals from the reference chronology AND (Figure 6), allowed the identification of regional growth pattern. The ANG reference chronology spans on 239 rings, from 1977 to 1739. The common interval with the HEI mean chronology is on 235 rings, from 1744 (i.e. the oldest ring on HEI mean chronology) to 1977 (i.e. the youngest ring on the AND chronology). The relatively high correlation between the two high chronologies (i.e. 0.41), providing a high EPS value (i.e. 0.97), supports the importance of regional control on the forest stand tree growth. To apply “response function” analysis would allow to better investigated this last aspect, but this has been not done in the current state of the data treatment.

Years	HF signal	MF signal	Years	HF signal	MF signal	Years	HF signal	MF signal
1750	-1.650	31	1862	-1.374		1940	-1.006	
1751	2.680		1863	-1.284		1941	-1.608	
1753	-1.306		1865	1.138		1942	-2.925	29
1756	-1.293	28	1867	1.036		1943	-2.295	39
1757		28	1868	1.094		1944		39
1762	1.121		1870	-1.021		1945		28
1764	-1.220		1875	1.016		1946	3.284	
1766	-1.378		1876	1.250		1947	3.116	
1780	-1.555		1879	-1.812		1953	1.876	
1781	1.190		1888		-33	1960	1.716	
1783	1.060		1889		-31	1962	-2.420	
1786	-1.839		1890		-28	1964		36
1787	-1.733		1891	-1.190		1965	-1.435	43
1788	1.583		1892	-1.366		1966		40
1789	1.062		1893	-1.232		1967	1.246	25
1793	1.026		1894	-1.100		1968	1.170	
1794	1.060		1899	-1.174		1969	1.316	
1796	-1.166		1900	-1.092		1970	1.987	
1808	1.689		1907	-1.659		1974	-1.674	
1830	-1.642		1919	1.113		1976	1.036	
1831	-2.684		1922		25	1980	-2.182	
1833	1.159		1923	-2.727	25	1981	-1.426	
1834	3.487		1924		30	1983	2.125	
1835	2.015		1925		32	1988	-1.284	
1838	-1.118		1926	1.481	32	1990	-1.512	
1839	-1.388		1933	1.018		1991	-1.176	
1844	-1.313		1934	1.367		1992		29
1852	-1.092		1936		-31	1996	-1.048	
1855	1.313		1937		-33	2000	-1.187	
1857		-26	1938		-34	2003	1.395	
			1939		-25			

Table 2. Quantitative values of the significant growth changes from Heinrichshöhe (HEI) tree ring signals in high frequency (HF, in index quantitative value) and mid frequency (MF, in growth change proportion).

Nevertheless, the high-frequency signals of both chronologies present clearly observable temporal and amplitude similarities (Figure 6A). From so distant forest stand areas, such signal synchronies must be interpreted as regional control of the growing changes (i.e. climatic control). However, observable “pointer years” asynchronies may be interpreted as being the local influence of micro and or meso-environmental control. This is supported by

the variation in mid-frequency signals indicating asynchronies in the occurrence of growth changes phases (Figure 6B). Those previous observations of on-site growth patterns are possible related to fine scale (i.e., infra-regional) of stand structure changes (e.g., forest canopy opening). Such fine scale disturbance occurrences fits the stand structure heterogeneity identified based on the forest attributes. It remains difficult to precisely identify either human or natural factors as the sources of those identified disturbances. Nevertheless, if human activities are involved in the forest stand dynamic process, it seems clear that these activities had a weak and fine scale influence, while regional climatic determinism induced a clear control of the growth patterns of the living *Picea* stems of the forest stand investigated.

Conclusion

Both approaches, forest stand characterization and tree ring series analysis, provided complementary information allowing to assess the naturalness level of the investigated forest stand, or at least to postulate a hypothesis about it. This has been done on a complementary temporal scale, in the span of the living on-site trees population.

The characterized forest stand features permit to identify a high level of stand structure complexity. This corresponds to forest stands with a high level of naturalness. Even if it was inventoried only one on-site forest species (i.e. *Picea abies*), this seems to fits with the long-term on-site investigation highlighting the *Picea* on-site dominance, and the rare occurrences of other forest trees species rare (see this Part, Chapter 6.1). Nevertheless, one can exclude that the on-site forest composition may change in the future by the establishment and the growth of other forest species (e.g. *Fagus sylvatica*), in favour of the patch dynamic process. In a biological conservation perceptive, it is interesting to highlight that the patch dynamic process seems to contribute to stand complexity on the investigated plot, and therefore must be maintained.

Tree ring series analysis allowed the occurrences of disturbance events and their temporal pattern to be detected, supporting observation from stand structural attributes. Finally, the overall comparison of HEI and AND signals highlights the co-determinism of on-site and regional control on the centennial growth condition of the HEI forest stand.

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6.4 Forest characterization and tree ring analysis of two forest stands on the south-eastern parts of the Harz Mountains (Central Germany).

Introduction

On the Harz Mountains, the ancient and strong human impact on the forest dynamics, inducing phases of drastic deforestation, have been partly documented (e.g. Beug *et al.* 1999, Voigt *et al.* 2008). This is especially the case for mining purposes (Matschullat *et al.* 1997, Monna *et al.* 2000), and the related impact of deforestation due to charcoal production (Hillebrecht 1982, von Kortzfleisch 2008), since medieval time. The long-term fire history of this mountain range has been investigated and the human influences on the past fire regime has been postulated, both on the highest elevation and on the south-eastern parts of the Harz Mountains (see Part 3, Chapters 6.1 and 6.2).

On a relatively short temporal scale, human management of forest for resource usage induced strong changes of the forest structure (Hauhs and Lange 2000, Hauhs and Lange 2010). Such human management is still active on the Harz Mountains, except on the part of highest elevation, which is under a national park protective statue (Nationalpark Harz 2011). In the south-eastern hinterland and on the side slopes of the mountain range, many areas are intensively managed forest stands, with large areas of even-aged monospecific *Picea abies* plantation (personal observation). At the regional scale, such forest features do not present a high naturalness level. Such even-aged monospecific conifer plantations do not fit the past composition of forest trees, as the insights from long-term investigation indicate (see Part 3, Chapter 6.2). In this context, when considering these various, ancient and strong human influences on the forest systems, biological conservation and/or restoration projects, sustainable management (i.e. close-to nature forest system of management), seems to be of great interest for future management planning on the south-eastern part of the Harz Mountains (Hauhs and Lange 2000, Turner *et al.* 2007, Pressey *et al.* 2010). Such aspects of conservation and/or restoration, and of sustainable management, seem even more important when considering the global scale of on-going ecosystem changes, correlated to climate and land use changes, inducing treat on ecosystems features and components (i.e. biodiversity losing; Eppink and Bergh 2007, Federici and Galluzzi 2010, Barnosky *et al.* 2011). While to initiate sustainable management and/or conservation/restoration project, it is crucial to assess the level of naturalness of the concerned ecosystems (see Part 1, Chapter 2.4). Therefore, complementary to the long-term investigation of the south-eastern part of the Harz Mountains (this part, Chapter 6.2), an investigation of the current state characteristics and short-term

forest dynamics is presented. Indeed, here it is presented an attempt to assess the human impact on the short-term and current state of two forest stands. For this, the forest stand features and tree ring series analysis of the two selected sites were investigated.

Due to the distance between, and the various environmental contexts of, those two selected sites, the results of the investigation are not compared directly. In this chapter, the data and discussion are presented separately for each site. Nevertheless, general insights from both sites are compared at a global scale.

Investigations sites

The two investigated forest site are Siebengemeindewald (SIE) and Das Große Holz (DGH), both on the south-eastern part of the Harz Mountains range (Fig. 1), and both managed by the federal land forestry service. The Harz Mountains range is presented in several parts of this document (see Part 2, Chapter 3.2), and the two selected sites of investigations are presented in detail in Part 3, Chapter 6.2, of this document. Soil and climatic features are also presented in Appendixes 3 and 4.

At the landscape level, the investigated forest stands are part of a mosaic of forest stands dominated by such species as *Fagus sylvatica* and a plantation of *Larix kaempferi* or *Picea abies* and agricultural land use.

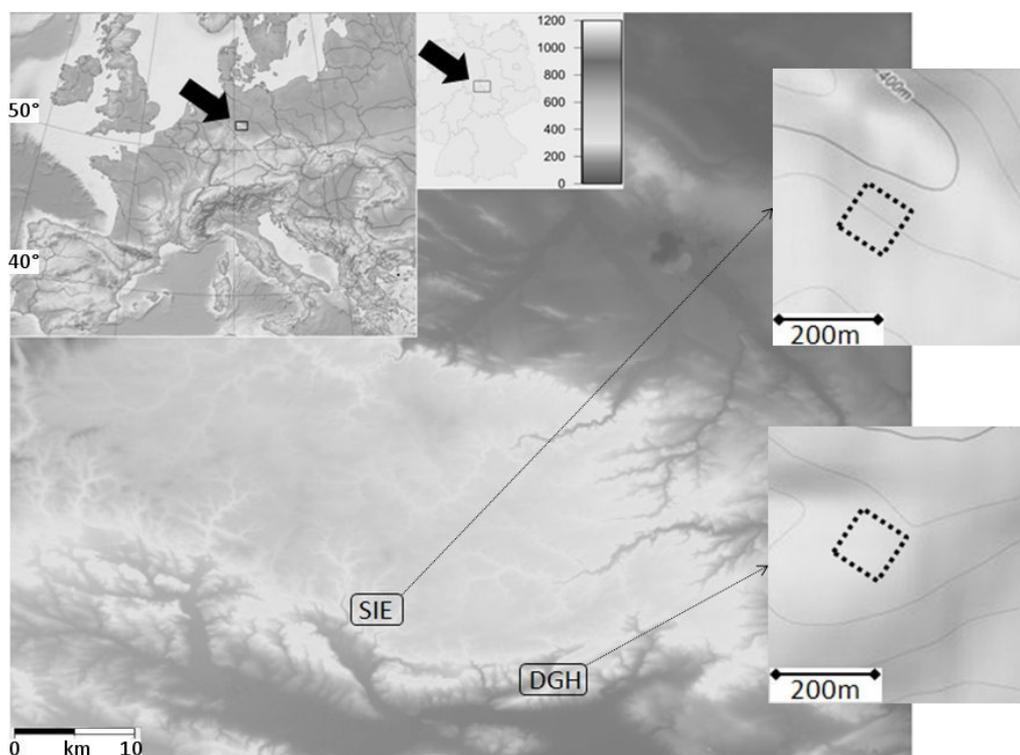


Figure 1. Maps of localization of the two studied sites, SIE (Siebengemeindewald) and DGH (Das Große Holz), on the Harz Mountains range (Topographical maps of the investigated sites with a rough representation of the investigated plots (dotted line squares)).

Methods

On both sites a similar protocol in terms of inventories, measurement and sampling, for forest stand characterization and tree ring series analysis were used.

The main methodological aspects of the forest stand characterization are described in Part 2, Chapter 4.2.1, and in Chapter 4.2.2 for the tree ring series analysis (see also Part 3, Chapters 5.1 and 5.2). Only specific aspects of the methodological protocol that are intended to fit local characteristics and issues are presented in this chapter.

On both sites one area for inventories, measurement and sampling was defined, corresponding to a square plot of ca. 4800 m² (80*60m). In each of those plots, the composition of the tree species and the stems distribution per class of diameter at breast height (dbh), per identified vertical forest level, were recorded. The dead wood volume per identifiable species and decay class was quantified. On sub-sampling plots (i.e. 100 m² in total), the forest regeneration per species (seedling and sapling abundance) was recorded. The spatial structure of the two investigated forest stands was assessed by the Clark-Evans index, based on the measurement of nearest-neighbour distance (Clark and Evans 1954).

For tree ring series analysis, 15 stems of *Fagus sylvatica* were cored on SIE and 14 of *Quercus* spp. on DGH, providing the analyzed radii sets per site.

Once the laboratory processes were completed (i.e. radii preparation and tree ring series measurements), and the measured tree ring series cross-dated (see Part 2, Chapter 4.2.2 and Part 3, Chapters 5.1 and 5.2), the mean chronology per site was obtained. The tree ring series were standardized by detrending methods using the ARTSAN program (Cook and Holmes 1996). The site high-frequency signal was obtained by averaging, providing information about the annual variation in tree growth with, moreover, the mean sensitivity and the 1st order autocorrelation coefficient, as statistical indicators of the year-to-year growth variability (e.g., Haneca *et al.* 2005).

To assess the mid-frequency growth patterns of the two forest stands investigated, the change in the growth rate of the measured tree ring series was calculated in successive temporal windows of 10 years. This was done by running median analysis methods (see Part 2, Chapter 4.2.2; Nowacki and Abrams 1997, Rubino and McCarthy 2004). This provides information about the change in the rate of growth related to changes in environmental condition, notably the occurrences of disturbances (Schweingruber 1996, Rubino and McCarthy 2004).

Results and discussion of the investigation of the site DGH

The stand structure of the investigated plot DGH has a medium abundance of stems per /ha, especially for the overstored level, which presents 194 stems per hectare. The mean dbh of the canopy level is of 33 cm. This, combined with the medium density of stems, explained the relatively small basal area estimated for the forest stand. Only one level of understory trees was identified on-site, forming a relatively simple vertical forest structure. This understory level of vegetation presents, as the canopy level, a small number of stems /ha, with a relatively small means dbh (Table 1, Fig. 2). The simple vertical structure of the forest stand fits the measured mean of the nearest neighbour distance of 4.6 m, indicating a distribution of loose stems. Moreover, the Clark-Evans index, with a value of 0.5, indicates a tendency to an aggregate tree spatial distribution (Pretzsch 1997, Laar and Akça 2007). Such a distribution of loose and clustered tree stems may indicate more or less recent events of “canopy opening” in fine scale patches (i.e. within the stand scale; Pickett and White 1985, Roxburgh *et al.* 2004, Podlaski 2008).

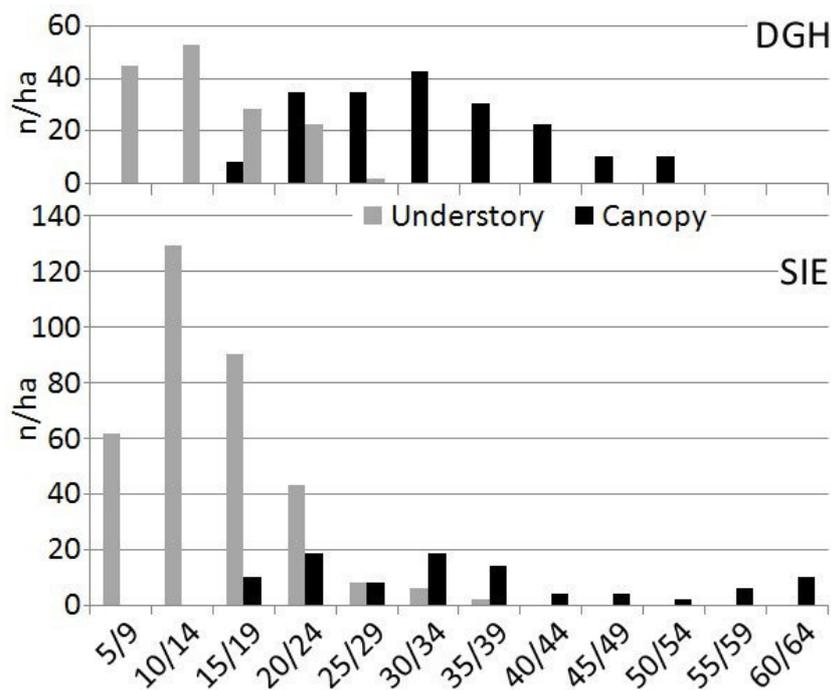


Figure 2. SIE (Siebengemeindewald) and DGH (Das Große Holz), diameter at breast height (dbh), number of stems per dbh classes (cm), per ha.

The data from the DGH forest stand structure indicates a relatively small amount of forest biomass and a relatively open canopy level, at the stand scale, with a simple and homogenous vertical and horizontal structure. That may be explained by the recent past human influences on the stand structure due to forest management (Larsen 1995, Liira *et al.* 2007).

Species	Trees density (n/ha)	Relative tree density (%)	Understory relative tree density (%)	Basal area (m ² /ha)	Relative basal area (%)	Understory relative basal area (%)
----- DGH -----						
<i>Quercus</i> spp.	239	69	41	9	69	12
<i>Tilia cordata</i>	65	19	38	2	19	11
<i>Fagus sylvatica</i>	18	5	67	0	3	33
<i>Carpinus betulus</i>	22	7	73	1	7	71
Totals	345	100	44	13	100	13
----- SIE -----						
<i>Carpinus betulus</i>	335	77	91	4	38	91
<i>Fagus sylvatica</i>	23	5	73	1	5	36
<i>Betula pendula</i>	16	4	25	1	9	5
<i>Quercus</i> spp.	60	14	21	6	64	7
<i>Sorbus aucuparia</i>	4	1	100	0	3	100
Totals	438	100	78	10	100	39

Table 1. SIE (Siebengemeindewald) and DGH (Das Große Holz) investigated forest stand characterization of the abundance and composition.

The current aggregate stems stand distribution may correspond to a past coppice management that has been abandoned or voluntary transformed to a “high trees” forest stand, since such characteristic forest structure is not visible nowadays (Fig. 3). However, the on-site “single” stems may have grown-up from a “coppice stumps”.



Figure 3. DGH (Das Große Holz) forest stand pictures. A: *Quercus* spp. lying pieces of dead wood (the largest of the inventoried plot). B: The relatively clear stand forest allowing light to enter.

The forest stand composition also presents a relatively simple pattern with only four tree species inventoried (Table 1). The abundance of stems and basal area value indicates that the canopy level is dominated by light-demanding species, especially by *Quercus* spp. This fits with the long-term indication from the taxonomical analysis of soil charcoal assemblages, also dominated by *Quercus* charcoal pieces (see this Part, Chapter 6.2).

Despite the relatively “open” canopy of the forest stand, the understory level differs from the canopy by consisting of mainly shade-tolerant species (i.e. *Fagus sylvatica* and *Carpinus betulus*). In contrast to the understory level, the forest stand regeneration indicates an important abundance of light-demanding species seedlings and saplings (Table 2).

Species (n/ha)	Seedling	Sapling
DGH		
<i>Fagus sylvatica</i>	0	10
<i>Sorbus aucuparia</i>	1400	38
<i>Quercus</i> spp.	4200	56
<i>Tilia cordata</i>	0	22
<i>Carpinus betulus</i>	0	16
tot	5600	142
SIE		
<i>Quercus</i> spp.	3200	6
<i>Fagus sylvatica</i>	480	18
<i>Carpinus betulus</i>	165	23
tot	3845	47

Table 2. SIE (Siebengemeindewald) and DGH (Das Große Holz) investigated forest stand results of the forest regeneration inventory.

Such a type of forest regeneration might have been promoted by the currently relative loose and open forest stand structure. Moreover, the significant presence of shade-tolerant species in all the vertical levels of the forest stand, including sapling classes, indicates that this, the identified current relatively loose and open forest stand structure, is due to recent changes, allowing the shade-tolerant species to develop and the light-demanding to become established, over which the previously established-light demanding species are dominating. This alternation of stand dominance by light-demanding and shade-tolerant species is a “classical succession process” of natural forest dynamics, following the “abandonment” of land after human management (Peterken 1996, Harmer *et al.* 2001).

The recent impact of human management on the forest stand dynamics is supported by the small amount of inventoried dead wood at the stand scale, with ca. 6 m³, corresponding to the dead wood volume of “managed, semi-natural stands” (Green and Peterken 1997). Moreover, the dead wood inventory indicates a simple and homogenous type and state of dead wood pieces (e.g. dead wood volume mainly from pieces lying on the ground, with only one species identified; Table 3, Fig. 3 and 4). Meanwhile, an important volume and heterogeneous type and state of dead wood is a significant component of the natural forest structure and the related forest stand biodiversity (Gilg 2004, Christensen *et al.* 2005, Oheimb *et al.* 2005).

DGH		type of piece (%)				decay class (%)					
Species	Ly.	Sta.	Stu.	Tot.	1.	2.	3.	4.	5.	Tot.	
<i>Quercus</i> spp.	63	84	28	62	0	89	17	0	0	62	
indet.	37	16	72	38	0	11	83	100	100	38	
Total (m3/ha)	4.9	0.3	0.5	5.8	0	3.6	1.9	0.2	0	5.8	
SIE		type of piece (%)				decay class (%)					
Species	Ly.	Sta.	Stu.	Tot.	1.	2.	3.	4.	5.	Tot.	
<i>Carpinus betulus</i>	39	2	2	42	8	28	7	0	0	42	
<i>Betula pendula</i>	16	13	0	28	0	15	9	5	0	28	
<i>Fagus sylvatica</i>	1	0	0	1	0	1	0	0	0	1	
indet.	45	6	2	53	0	6	25	21	1	53	
Total (m3/ha)	7.4	1.5	0.3	9.2	0.6	3.7	3	1.9	9	9.2	

Table 3. SIE (Siebengemeindewald) and DGH (Das Große Holz) investigated forest stand results of the dead wood volume measurement, in relative values. [Ly.: lying; Sta.: standing; Stu.: stumps; Tot.: totals].

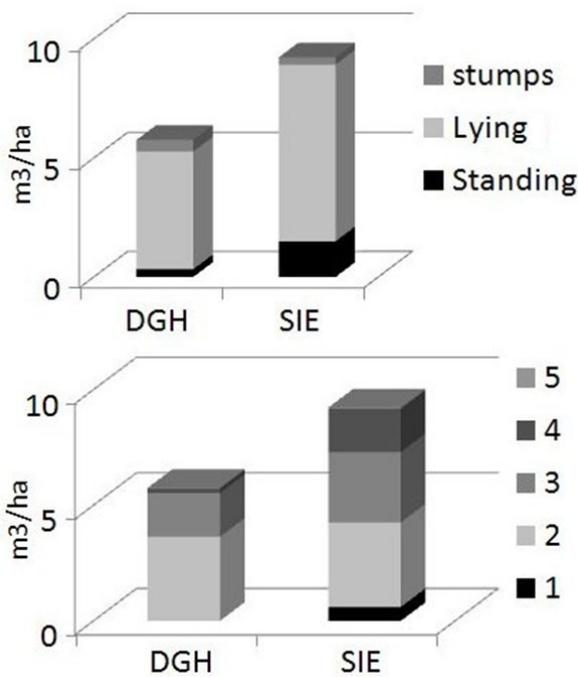


Figure 4. SIE (Siebengemeindewald) and DGH (Das Große Holz), dead wood volume, per type of piece (up graphic) and per decay class (down graphic), following the classes of dead wood defined in Part 2, Chapter 4.2.1, Table 3.

The 28 radii gathered from the 14 cored *Quercus* spp. provide data sets for tree ring analysis. The overall cross-dating presented satisfying results either by eye or using the Cross-Dating-Index (Rinn 2003). The mean site chronology spans 129 years (1880-2009), the common interval of the 14 tree ring series is 83 years (1926-2009). The low value of the standard deviation of the ring width of the mean site chronology (i.e. 0.68) indicates a relatively homogenous growth pattern at the stand scale (Schweingruber 1996). The mean site chronology indicates two global phases in the growth pattern (Fig. 5A). The oldest phase,

from 1880 to ca. 1920, presents a relative cyclicality in the ring width change, over the yearly scale. The high-frequency signal also indicates this oldest phase with some large amplitude change of ring width, from year-to-year, before ca. 1920 (Fig. 5B). Later, the high-frequency signal presents more homogenous patterns, with small amplitude ring width changes. This fits the values of the mean sensitivity (ms) and 1st order autocorrelation (ac). For the overall span of the analyzed chronology, the relatively small ac and ms values (i.e. 0.58 and 0.14 respectively) indicates a low correlation between the year-to-year ring width, and external growth control, like climate variability (Schweingruber 1996, Haneca *et al.* 2005, Saulnier *et al.* 2011). Such indications support the importance of on-site process on the forest dynamics and tree growth.

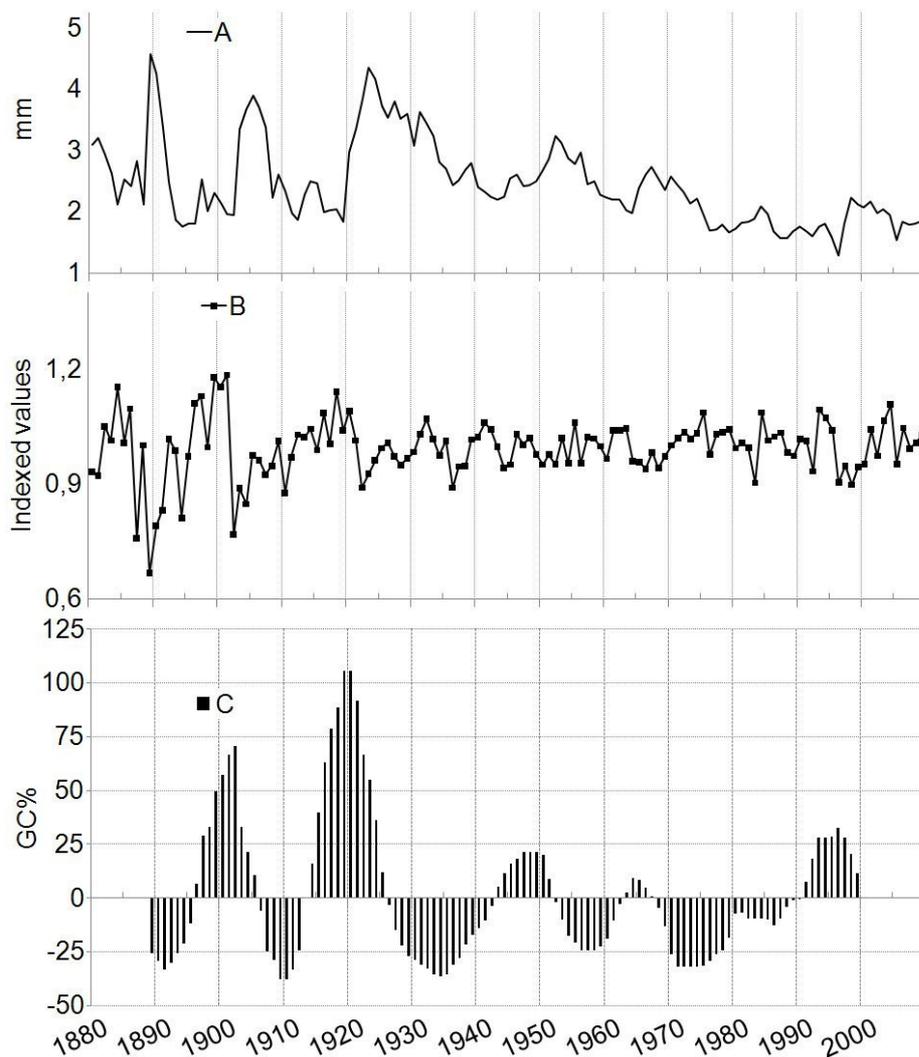


Figure 5. DGH (Das Große Holz) mean site chronology (A), high-frequency standardized signal (B), and mid-frequency standardized signal (C).

The calculated mid-frequency signals fits the two main growth phases observed in high-frequency (Fig. 5C). Two release phases have been identified before 1925, about 1902 and 1920, with a major amplitude release vent (i.e. over 50 % of growth changes, Fig. 6; Abrams

1992, Rubino and McCarthy 2004). Those are certainly indicative of severe canopy opening (Abrams 1992, Nowacki and Abrams 1997). Between the occurrences of those release events was a period of about 20 years. After 1925, no more release events occurred until a phase in about 1995, with the recording of a minor release event (Figs. 5C and 6). During these last ca. 70 years, the growth change pattern is relatively stable.

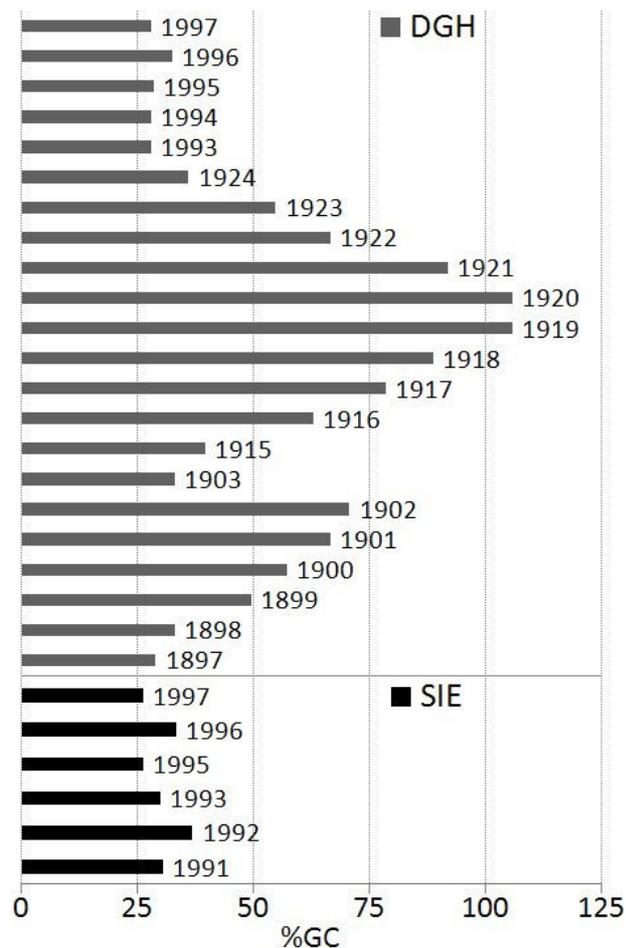


Figure 6. SIE (Siebengemeindewald) and DGH (Das Große Holz) release events based on the growth change calculation on 10-year temporal windows.

Both high- and mid-frequency signals seem to indicate a change in the forest stand dynamics about 80 years ago. Before this period, the investigated forest stand was probably under coppice management, or at least regular and severe harvesting. Then, no more severe canopy openings occurred later than 1925, either from human or natural factors. This last point does not mean that no change in the canopy structure occurred. As was indicated by the forest stand characterization, “weak” forests stand opening that induce weak changes in the growth pattern that are observable both on the measured mean site chronology and in the mid-frequency signal (Fig. 5A and 5C) may still occur, probably due to human stems harvesting.

Results and discussion of the investigation of site SIE

The investigation plot of SIE presents a small canopy tree abundance (96 stems /ha), although there is a dense understory forest level (342 stems /ha; Table 1). The understory vegetation is included in only one vertical level. Therefore, the vertical forest stand structure is simple (McElhinny *et al.* 2005). The canopy level shows a “bimodal” dbh distribution, with several stems of relatively large dimension. Overall, the horizontal structure is heterogeneous, with a relatively large range of dbh distribution (Fig. 2). In term of space occupancy, either the canopy or the understory level represent a small basal area, meaning a small biomass amount on-site (Table 1). This fits with the small overall forest level mean dbh of 22 cm. The on-site forest vegetation consists mainly of small-dimension, understory trees. The dense understory forest level provides a relatively small mean site nearest neighbour distance (i.e. 3 m), indicating a relatively closed forest structure. However, the Clark-Evans index calculated for the plot was 0.4, indicating a tendency to an aggregate tree spatial distribution (Pretzsch 1997, Laar and Akça 2007). The stems distribution, at the stand scale, is not homogeneous, as some fine scale patches may have more or less dense tree stems (Fig. 7). Therefore, the occurrence of fine scale disturbances can be postulated (Roxburgh *et al.* 2004).



Figure 7. SIE (Siebengemeindewald) forest stands pictures. A: forest canopy gap, presenting more light available, with ferns and mixed *Fagus sylvatica*, and *Quercus* spp. regeneration; B: aggregate *Fagus sylvatica* and *Quercus* spp. stems.

In regards to forest composition, there is a clear “bipolar” stand composition. Shade-tolerant species strongly dominate the understory forest level (mainly *Carpinus betulus*), and light-

demanding species dominate the canopy level. This is true in terms of stems abundance and basal area, as well (Table 1). This “bipolar” stand composition might result from the process of stems competition for light, inducing more favourable growth condition for shade-tolerant species, under the canopy cover. However, when looking at the forest regeneration inventory, it is interesting to observe that, in parallel to the relatively important number of shade-tolerant seedlings and saplings, there is a significant abundance of light-demanding seedlings (i.e. *Quercus* spp.; Table 2). Even if *Quercus* spp. may have become established and grown with relatively weak light availability (Rameau *et al.* 1993, Rameau 1996), this observation fits the previous identification of the aggregates trees spatial distribution, indicated by the CE index. Such a spatial stems distribution allows the establishment of oak regeneration, in favour of more light availability within the small surface open patches. This may indicate the importance of a fine scale patches dynamic process (Pickett and White 1985, Roxburgh *et al.* 2004, Podlaski 2008).

Based on the previous observations for SIE, it can be postulate comparable hypothesis than based on the observation done concerning DGH. It seems that the current stand feature of SIE results, as DGH, from past human management. Indeed, the past human influence on the forest stand dynamic seems relevant to explain the relatively simple stand structure, the small on-site basal area, and the aggregate horizontal structure, which fit past coppice management. This also fits with personal observation on-site of coppice stumps. Moreover, the postulated SIE stand human management seems to be have finished a longer time ago than on DGH, explaining the denser understory forest level, the less dense canopy level, and the greater dimension of some trees still present as overstored (Fig. 2). The dead wood inventory supports the fact that past human management on SIE ended for a longer period than on DGH. Indeed, there is more dead wood volume on SIE than on DGH (Fig. 3). Nevertheless, the SIE volume of dead wood remains small (Table 3).

From the 15 *Fagus sylvatica* twice cored, providing 30 radii, only 29 radii have been included in the analyzed ring series, since one of the radii was excluded because the measurement results did not fit the other data set sufficiently for the cross-dating process. Once the cross dating was finally done, the mean site chronology was calculated (Fig. 8A). This one spans 86 years, from 2009, with a common interval from 2009 to 1959. This relatively short span of analyzed tree ring series makes it difficult to identify past human management. Nevertheless, some global observation from the growth patterns might be pointed out based on the standardized signals (Figs. 8B and 8C). The high-frequency signal indicates large variability of the width ring, especially in the period of 1985-2003. Such

growth patterns might indicate an important influence of climatic variability on the trees' radial growth. This is supported by the high value of mean sensitivity for the overall site chronology (i.e. 0.299) and, especially, by the ms of the period 1985-2003 (i.e. 0.387). The mid frequency signal indicates only one significant growth change phase (Fig. 8C), with release events (Fig. 7), from 1991. This allows one to postulate the absence of a strong canopy opening event, at the stand scale. Therefore, it is assumed that the abandonment of the forest coppiced forest management, previously identified, was at least 86 years ago.

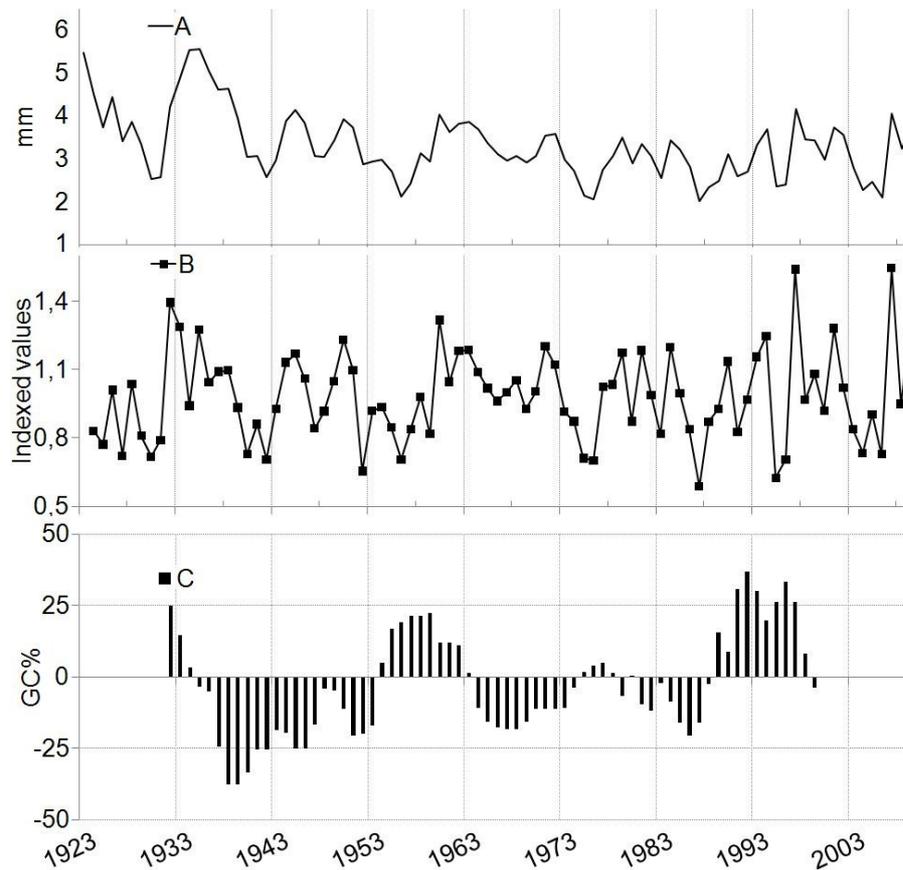


Figure 8. SIE (Siebengemeindewald) mean site chronology (A), high-frequency standardized signal (B), and mid-frequency standardized signal (C).

Conclusion

Despite the difficulty to compare two widely separated sites, many different site features and global common trends can be identified and pointed out.

Both investigated stands provide evidence of an ancient (i.e. at the temporal scale of the two tree ring series analyzed), and, by phases, intensive human impact on the forest dynamics and on the current state of the forest structure and composition. This was especially reliably identified in the stand plot of DGH where local evidence allowed us to postulate past coppice forest stand management. However, on both investigated sites, the abandonment, or at least the change to “less impacting”, human practices allowed the natural processes to “re-start”, or

at least to increase in importance as factors of stand dynamic “drivers”. Therefore, both stands currently present a relatively high level of naturalness.

Those naturalness levels should be, at least, maintained and, even better, increased by conservation/restoration or sustainable management planning. Therefore, it would be interesting to promote the factors that increase forest stand heterogeneity relevant for the area, like the identified fine scale canopy opening, allowing fine scale, species composition and stand structure changes. Indeed, stand heterogeneity is one the identified off-reserve conservation measures for forest biodiversity conservation (Lindenmayer *et al.* 2006). Those stand observations also seem very interesting and important for forest planning at the landscape level, in regards to stand heterogeneity within the landscape mosaic. Such “forest pockets” with natural, or even semi-natural, forest feature are needed for biological conservation, on a global scale.

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*RECONSTRUCTION OF FIRE AND FOREST HISTORY ON
SEVERAL INVESTIGATION SITES IN GERMANY, BASED ON
LONG AND SHORT-TERM INVESTIGATIONS - MULTIPROXY
APPROACHES CONTRIBUTING TO NATURALNESS ASSESSMENT
ON A LOCAL SCALE*

Part 4.

Synthesis and Conclusion

Reconstruction of fire and forest history on several investigation sites in Germany, based on long and short-term investigations - Multiproxy approaches contributing to naturalness assessment on a local scale

Synthesis and Conclusions

The various types of environmental indicators used in the research presented here (see Part 3) provided a large and heterogeneous data set that is relevant mainly at a local spatial scale (i.e. forest stand scale) and in various temporal scales (see Appendix 1). When considering, moreover, the investigation site distances, within and between the two large study areas and the sites context feature heterogeneity (see Part 2, Chapter 1), macro-scale data synthesis and interpretation are difficult. However, by comparing the main insights from the on-site investigations and the data set from “site to site”, it is possible to detect convergent and divergent aspects (e.g. events synchrony and asynchrony), possibly relevant on a macro-scale, or at least do a comparative overview of the on-site insights. Nevertheless, the identification of such common trends and global scale patterns must be done with care, keeping in mind the previously described aspects.

Short term dynamics of the investigated forest plot were reconstructed. A process of forest stand disturbance has been identified that corresponds to the well-described “patch dynamic process” (Pickett and White 1985, Roxburgh et al. 2004, Podlaski 2008). For example, the occurrences of fine spatial scale forest stand disturbances have been identified on the investigation sites of the Riesewohld forest (RIES and RIEN; see Part 3, Chapter 5.2), thanks to the detection of forest stands feature differences. On those investigation sites, dynamic processes have been identified at stand scale and even at a finer scale, nearly at stem-to-stem scale. On several investigated sites, the patch dynamic process has been identified thanks to the detection of tree growth patterns asynchronies, from either on-site (see Part 3, Chapters 5.1 and 6.3) or “site to site” (see Part 3, Chapters 5.2, and 6.4), tree ring series signals comparison. Based on large scale site comparisons, both local and regional control of the on-site tree growth have been identified (see Part 3, Chapter 6.3). Such trees growth patterns are comparable at macro-scale using the high frequency standardized signals, “skipping” the individual trees and on-site environmental control of the growth (see Part 2, Chapter 4.2.2). The overall mean site ring series standardized in high-frequency are presented in Figure 1. High-frequency signal convergences and divergences can be observed in Fig. 1,

especially between the Stodthagener Wald (STO) and Westensee (WES) signals. A better macro-scale regional comparison, at regional and supra-regional scale, could have been done by comparing high-frequency signals from the various sites investigated, to climatic records (e.g., Andreassen et al. 2006).

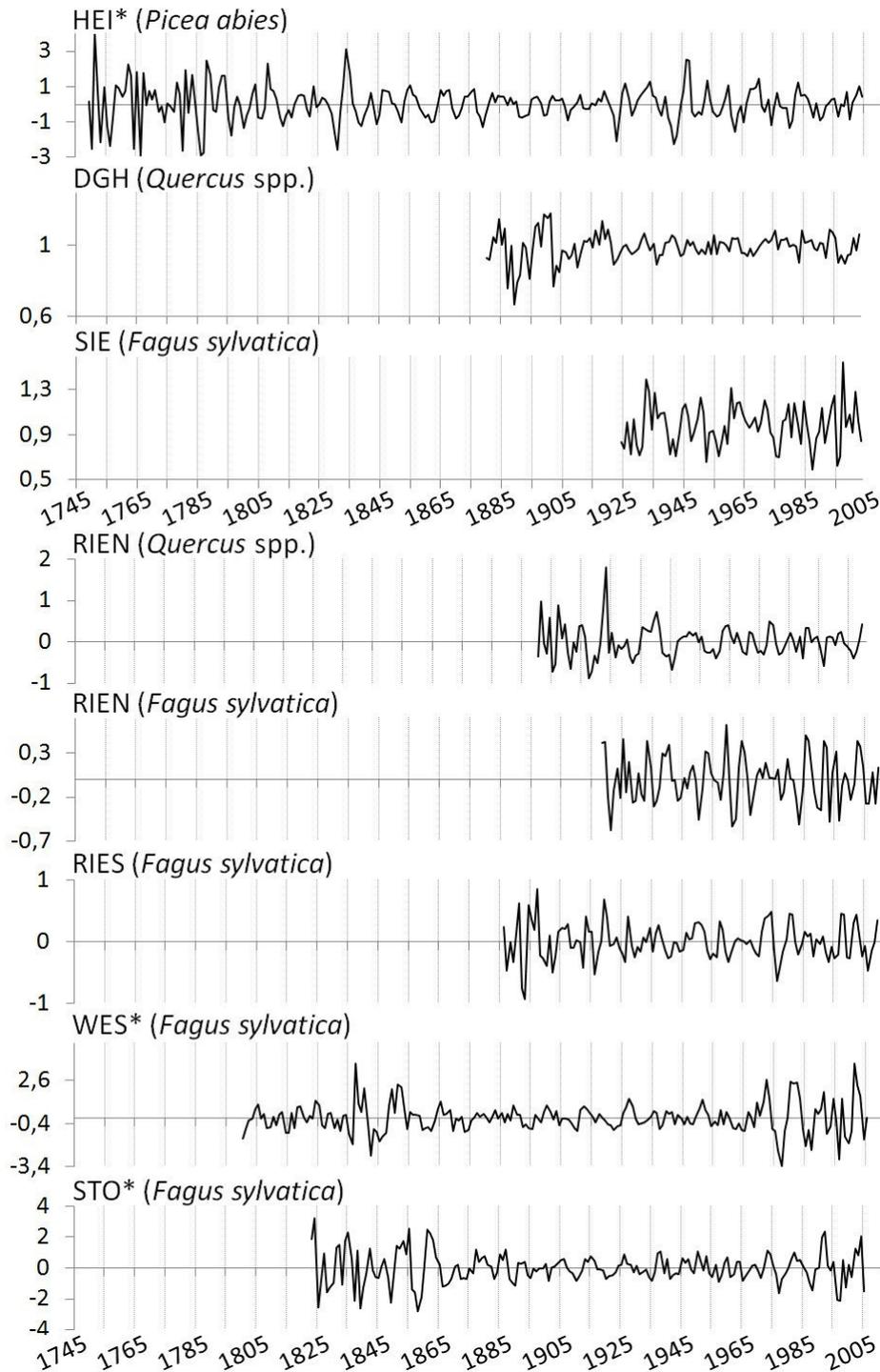


Figure 1. High-frequency standardized signal of the tree ring series gathered from the investigated forest sites. [*: “running windows” method of standardization].

However, this is not the focus and, therefore, not the approach used in the overall research presented in this document. However, the human influence on past forest dynamics remains difficult to assess and even more difficult to quantify, either on a long or short temporal scale. Nevertheless, the influences of human activities, as sources of fine scale disturbances, related to the previously described processes of stand scale dynamics (i.e. anthropogenic disturbances; see Part 1, Chapter 2.3) has been often postulated (e.g. past coppice management of the Siebengemeindewald (SIE) and Das Grosse Holz (DGH) sites; see Part 3, Chapter 6.4). Moreover, at several investigation sites, long-term fire event occurrences, and related forest stand disturbances were detected. Their fine spatial scale of occurrence was discussed, as being possibly due to human ignition and control (see Part 3, Chapter 5.3, 6.1, 6.2).

From the overall investigations it seems clear that it is difficult to define a fix, “static natural state of reference”, which allows to assess the naturalness degree by comparison (see Part 1, Chapter 2.4). It seems much more relevant to assess forest stand naturalness by two dimensional gradual scales, based on a combination of insights from the various indicators and analysis made for the naturalness assessment of the sites considered. A two-dimensional plotting of the nine investigation sites, along two x-axis and y-axis, is proposed to assess the overall naturalness/hemeroby degree of each single site and to identify a hierarchy within the investigated sites. For this plotting several important indicators have been selected, presenting information from one or more data sets, and allowing a global quantification. This quantification, enabling the positioning of the sites along the axis, is made of one to five grades (i.e. degrees), from low level of naturalness/high level of hemeroby, to high level of naturalness/low level of hemeroby for each selected criterion (Fig. 2).

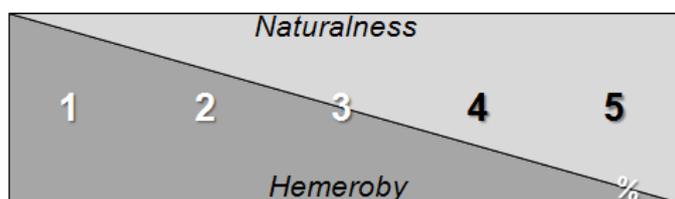


Figure 2. Quantified levels of the indicators selected for the Naturalness and Hemeroby assessment.

This quantification, while very simple, appears to be relatively subjective. However, due to the qualitative aspect of several indicators used, it appears to be inevitable to use a subjective approach to quantify them. The selected indicators were grouped on two dimensional aspects of the naturalness/hemeroby assessment- the long term insights and the short term insight. Those global insights represent respectively the x-axis and the y-axis. The four global

indicators that provide insights into the long-term scale are (1) the correlation between the past and present forest stand species composition, (2) the correlation between the past and present dominant tree species, (3) the evidence for abrupt events of biotic changes (e.g. soil charcoal concentration) and (4) the evidence for abrupt events of abiotic changes (e.g. soil erosion). The four global indicators that provide insight about the short-term scale are (1) the state of the on-going forest stand dynamics (e.g. forest regeneration), (2) the dead wood feature (e.g. volume), (3) the forest heterogeneity and (4) the presence of recent management evidence. Using the five grades scale, each investigation site was assessed by accumulating its values for long and short insights. This two-dimensional gradual hierarchy of the nine investigation sites allow the identification of various levels of naturalness (vs. levels of hemeroby). From Figure 3, it seems clear that the investigation site HEI presents the higher level of naturalness. This observation fits the detailed on-site investigation (See Part 3, Chapters 6.1 and 6.4). For example the short-term investigation of HEI, indicating the high level of stand heterogeneity, the species composition, etc., and based on the long term investigation, the old occurrences of fire and the related ancient forest trees composition support a high level of naturalness. This is especially true in regards to the others sites investigated, notably STO and WES, which present a lower level of naturalness. For those two sites, the relatively recent human management seems to have had an important influence on the naturalness level, despite their statue of area under conservation. For example, the simple stand structure, which does not fits with the long term insights, strongly reduces the values of the indicators on the two axes for those two sites (see Part 3, Chapters 5.1 and 5.3). The sites, RIES and RIEN, present similar levels of naturalness from a long-term insight, but differ on the short-term insight axis. This fits with the on-site observation of notably much higher stand heterogeneity on RIES (see Part 3, Chapter 5.2). The sites SIE and DGH, also compared to RIEN and RIES, seem to present relatively similar levels of naturalness, while they differ a bit on long-term insight, due mainly to the important correlation of the past and present species composition and dominance (see Part 3, Chapters 6.2 and 6.3). Those observations illustrate that it is important to consider that the naturalness assessment is not relevant if using only one, or a few indicators (see Part 1, Chapter 2.4). In that case the site positioning would be very different.

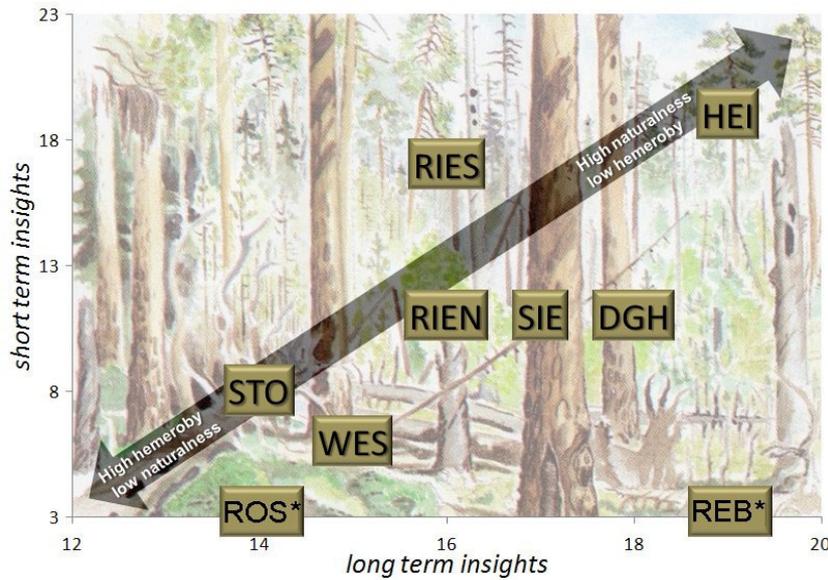


Figure 3. Overall naturalness assessment of the investigated sites on a two-dimensional graphic. STO: Stodthagener Wald, WES: Westensee, RIEN: Riesewohld North; RIES: Riesewohld South, HEI: Heinrichöhe, REB: Renneckenberg, ROS: Rosentalskopf, SIE: Siebengemeindewald, DGH: Das Grosse Holz. [*: naturalness assessment based only on long-term insights].

The two-dimensional plotting is based on a multi-variable approach. This is supported by the multivariate cluster analysis (Fig. 3). This analysis indicates the similarities between the nine investigated sites based on the correlation matrix of the eight indicators that were selected for the previously described two-dimensional plotting. This analysis indicates that the site HEI and, secondly, the site RIES are isolated from the other sites, probably because of their high degree of naturalness (at least compared to the others investigated sites). STO and ROS are the two next isolated sites. This fits with long- and short-term similarities observed between those two sites. This latter observation also fits the two next isolated sites, WES and REB. Finally, the sites RIEN, SIE, isolated from DGH, also presented global convergences based on the indicators used.

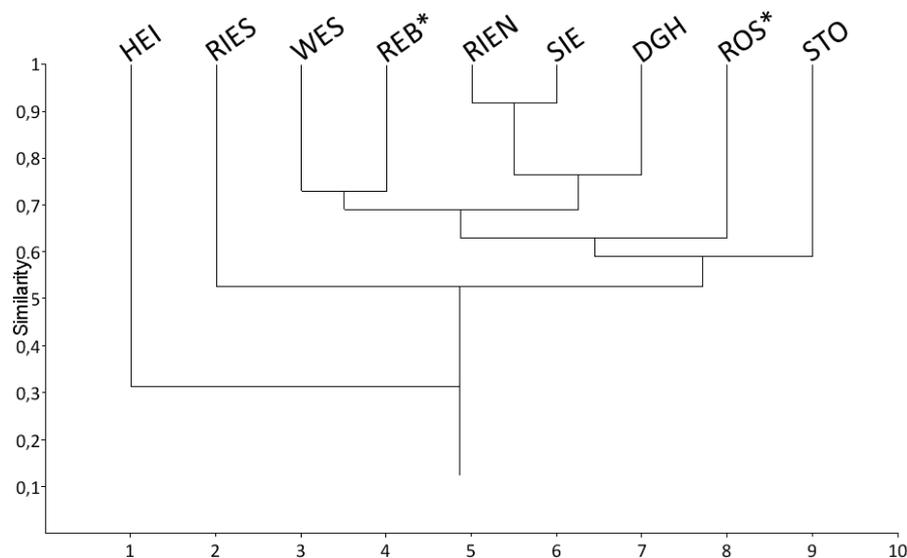


Figure 4. Cluster analysis, based on the correlation distances matrix of eight parameters (i.e. indicators).

From the overall observations about the naturalness assessment it seems clear that the approaches used in the research presented here can greatly contribute to the assessment of the current degree of naturalness at the stand scale. It also appears difficult to propose a specific and detailed management intervention to conserve/restore the degree of naturalness. Such interventions are part of forest management planning. Therefore, this is under the purview of forest managers. Nevertheless, the approaches presented here provide global and detailed insights allowing one to guide the forest planning. For example, every intervention that contribute to an increase in the level of stand heterogeneity (in terms of vertical, horizontal, taxonomic, etc., structure) during the short-mid-long term future would be applied in conservation/restoration planning. Also, any intervention that contributes to closer correlation between the long- and short-term insights, e.g. the stand species composition (i.e. not viewed as a fixed state), must be included in forest conservation/restoration planning.

In addition, interesting macro-scale insights about the human role on past forest dynamics are provided by the data set of the charcoal pieces radiocarbon dating. The chronological distribution of the 71 dated charcoal pieces (one date excluded because it was dated from the full-glacial phase, Fig. 5), independent of the sampling site origin or taxonomic identification or the stratigraphy assessment indicates many more fire events since the beginning of the Neolithic period (i.e. one fire event dated every ca. 107 years) than before (i.e. one fire event dated every ca. 486 years), and even more after the Bronze Age (i.e. one fire event dated every 73 years) than earlier (i.e. one fire event dated every 343 years). Of course, the fire frequency presented in this paragraph do not indicate “real” and exhaustive fire frequency occurrences, because the dated charcoal pieces come from a large geographical area and not strictly from chronological stratified palaeo-archives (see part 2, Chapter 4.1.1). The fire frequency presented represents an overall assemblage of the single-dated fire events from the investigated sites. Nevertheless, the temporal distribution of the 71 dated charcoal pieces indicated a nearly continual “fire occurrences” in two phases. The older phase was during the late Pleistocene/early Holocene period, ranging from 13285 to 9032 years cal BP, with one dated fire event every 304 years. The younger phase covers from the mid-Holocene period to modern times, from 4437 to 1919 years cal BP, with one dated fire event every 47 years. Between those two phases, a period from 9032 to 4437 years cal BP presented only three dated fire events, indicating one fire event every 1532 years. Moreover, it should be noted that such charcoal dating pattern that is identified with a large scale data set is also observable with on-site data set, presenting similar “fire phases” for the late Pleistocene/early Holocene and late Holocene periods (see e.g. Part 3, Chapter 6.2).

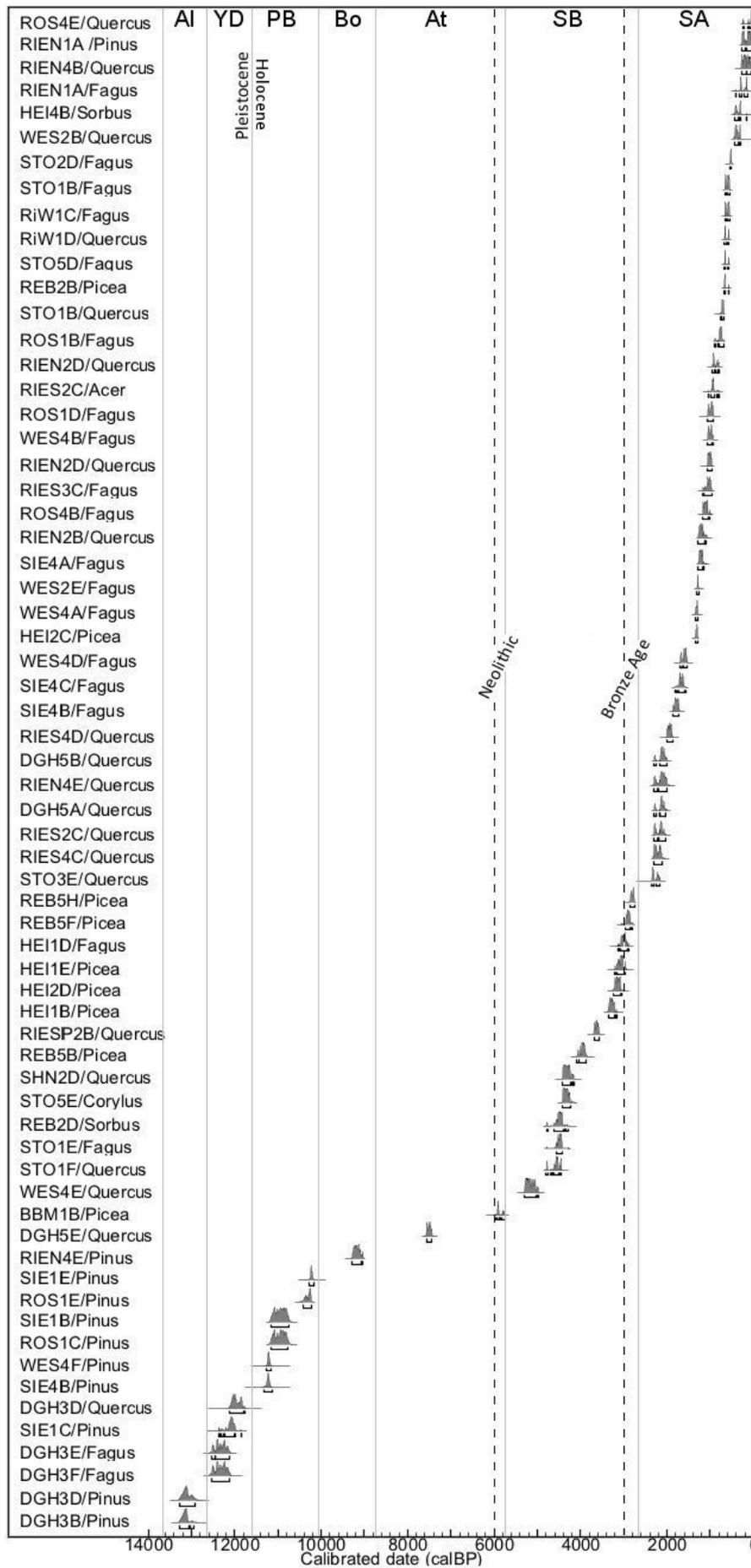


Figure 5. Chronological distribution of the radiocarbon-dated charcoal pieces (63 from soil samples and 2 from peat sequences). AI: Allered; YD: Younger Dryas; PB: Preboreal; Bo: Boreal; At: Atlantic; SB: Subboreal; SA: Subatlantic. Radiocarbon age calibrate with 2σ confidence interval, using Oxcal 4.1.56 program and the IntCal09 dataset.

However, other possible sources of charcoal formation than forest fire, also recorded in the analyzed and dated charcoal assemblages, must be considered. This especially concerns the younger records (this is developed in some chapters of Part 3, dealing with the interpretation of soil charcoal records). Nevertheless, the information from the overall data set of the single dated charcoal pieces enables one to infer that, during the late Pleistocene – early Holocene periods, fire occurred with a relatively high frequency, probably correlated to natural determinism, under climatic control (i.e. wildfire). This fits to the type of forest composition and structure of this period, just after the glacial phase, mainly consisting of pioneer forest/woodlands, which provide easy, flammable fuel. Then, a phase with weak fire frequency occurred, during the early/mid Holocene period, which corresponds to the Holocene climate amelioration and vegetation change to the establishment of temperate broadleaf forests, forming a not-so-easy flammable fuel as previously. The third phase showed a high fire frequency from the beginning of the Neolithic period and increasing with human development. It is postulated that human activities and usage of fire were main determinism of fire control for this period. Indeed, when considering the late Holocene mesophile temperate broadleaf forest type in Central Europe, it seems reliable to postulate anthropogenic controls for the high fire frequency identified. Even in regards to the recently postulated cyclicity of abrupt event of climatic deterioration during the Holocene period (Bond et al. 1997, Bond et al. 2001, Wanner et al. 2008, Severinghaus et al. 2009), human control seems to be the main factor contributing to fire occurrences since the Neolithic period, at least.

The macro-charcoal fire signal gathered from the analyzed peat sequences fits the macro-scale interpretation of the dated charcoal pieces, at least concerning the Neolithic period (Fig. 6). Indeed, those peat macro-charcoal accumulation patterns, correlated to depth/age models, indicate more fire events, and are related to higher fire frequency from the Neolithic period onwards.

These hypotheses of the long-term fire history and determinism factors are also postulated by large scale synthesis (Carcaillet et al. 2002, Marlon et al. 2008, Power et al. 2008, Marlon et al. 2010). However, those analyses, concerning Europe, are only based on Mediterranean, Alpine and Boreal areas. In this regards, the fire history based on charcoal records from both soil and peat sequences that is presented here constitutes the first large-scale, and one of the first fine-scale, indications of long-term fire history inferred from palaeo-records of the natural archives in Central Europe.

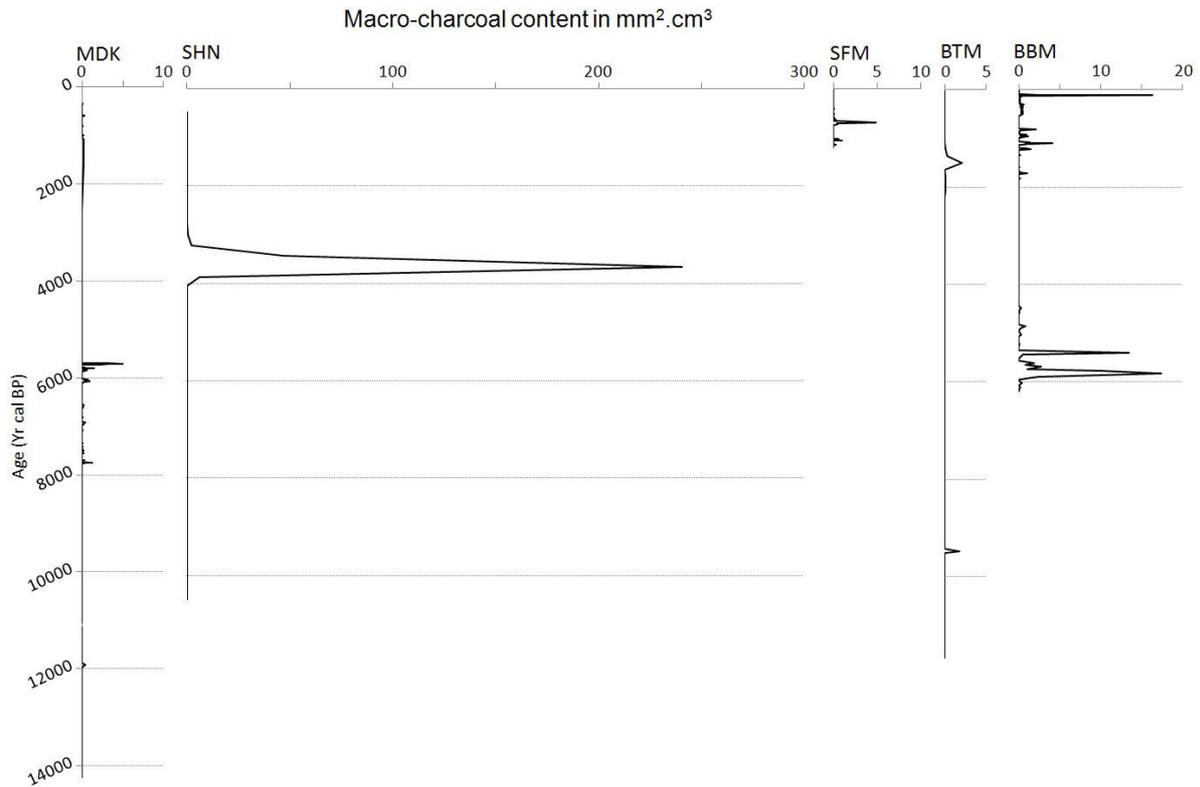


Figure 6. Macro-charcoal signal gathered from the analyzed and dated peat sequences. MDK peat sequence correlated to Westensee; SHN peat sequence correlated to Stodthagener Wald; SFM peat sequence correlated to Riesewohld South; BBM peat sequence correlated to Heinrichöhe; BTM peat sequence correlated to Renneckenberg.

Both soil and peat sequences charcoal records indicate large signal heterogeneity in chronological and quantitative indication. From soil charcoal assemblages such, large heterogeneities are observable between (Fig. 7) and within the sampling sites (Fig. 8).

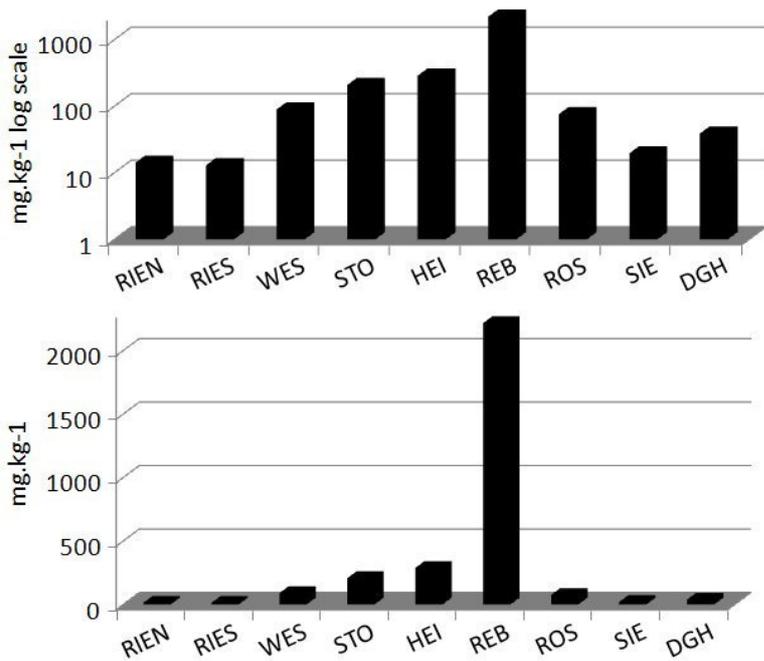


Figure 7. Total soil charcoal concentration for investigated sites. STO: Stodthagener Wald, WES: Westensee, RIEN: Riesewohld North; RIES: Riesewohld South, HEI: Heinrichöhe, REB: Renneckenberg, ROS: Rosentalskopf, SIE: Siebengemeindewald, DGH: Das Grosse Holz.

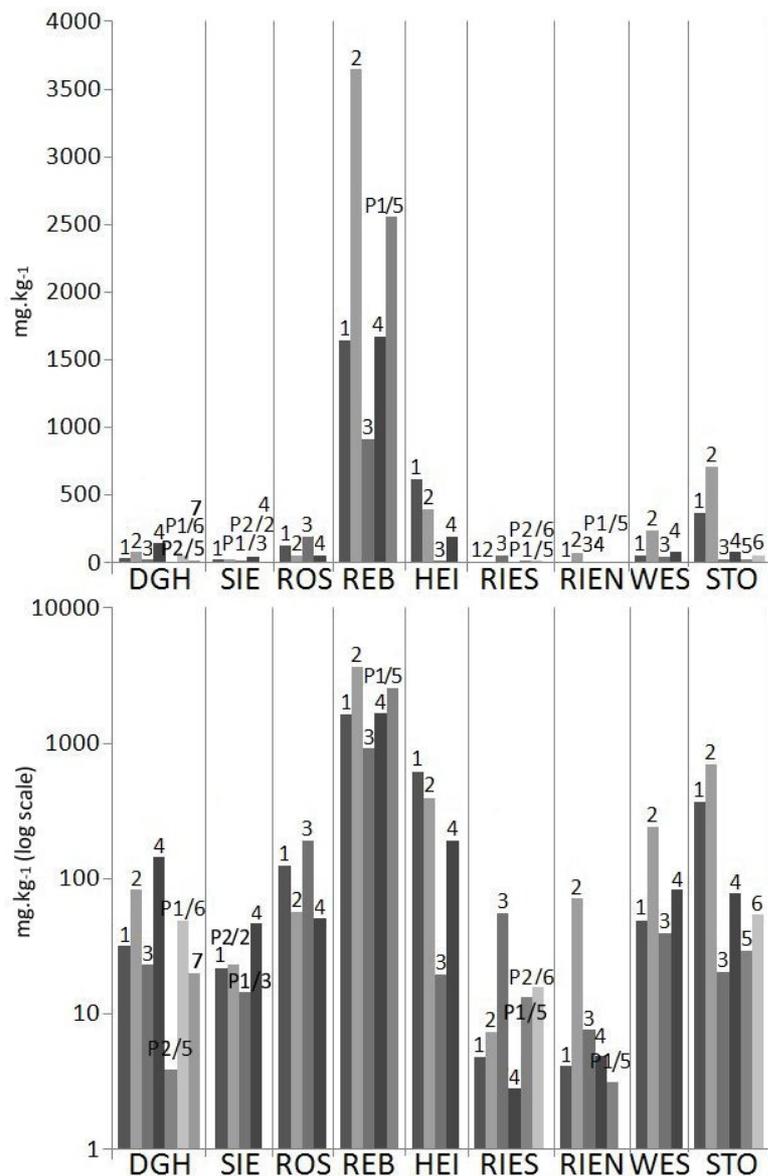


Figure 8. Total soil charcoal concentration per sampled soil profile of the investigated sites. STO: Stodthagener Wald, WES: Westensee, RIEN: Riesewohld North; RIES: Riesewohld South, HEI: Heinrichöhe, REB: Renneckenberg, ROS: Rosentalskopf, SIE: Siebengemeindewald, DGH: Das Grosse Holz.

These observations may be interpreted as indication of fine scale fire regime variability, even if fire disturbance is mostly a large scale disturbing process (Bowman et al. 2009, Whitlock et al. 2010). This might be one more indication for the high level of human usage of fire, inducing high variability of a fire regime, at the stand scale. These human uses of fire, inducing man-made fire events and anthropogenic past fire regimes, allow one to investigate past events of forest disturbances. Thus, the history of the forest dynamics and, therefore, charcoal analysis contributes to naturalness assessment through a long temporal scale.

Finally, we conclude by pointing out some global aspects and perspectives. The drawing of global research conclusions and the data comparison have been made easier by using indicators with comparable spatial scale (i.e. the forest stand scale). In this regard, soil charcoal analysis is a “precious scientific tool”, which provides a great deal data that is

suitable for on-site detection of forest change events. This spatial scale of long term investigation enabled us to identify stand heterogeneities, possibly fitting the scale of human management and of anthropogenic influence occurrences. Therefore, to investigate past human influence on forest dynamic it seems relevant to use soil charcoal analysis, to obtain fine scale insights. Such a scale of investigation is also relevant in dealing with the “patch dynamic process”. Obtain large scale patterns is possible by increasing the number of data-gathering sites, and so enlarging the scale of investigation.

Further, it can be noted that the historical approach is of great importance for naturalness assessment. Moreover, the applied interdisciplinary research was very complementary and so presents relevant and interesting perspectives for future research. Indeed, even if no direct temporal connection between the various indicators used was strictly possible, by interpreting the temporal data through two temporal “poles”, which are long- and short-term data, it has been possible to draw some interesting conclusions that contribute to a naturalness assessment.

For future investigations, a comparable protocol of investigation might be applied, with also the integration of complementary information from written sources and oral history. This would increase the investigation’s relevance from the biological point of view, including also more anthropologic and archaeological considerations.

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*RECONSTRUCTION OF FIRE AND FOREST HISTORY ON
SEVERAL INVESTIGATION SITES IN GERMANY, BASED ON
LONG AND SHORT-TERM INVESTIGATIONS - MULTIPROXY
APPROACHES CONTRIBUTING TO NATURALNESS ASSESSMENT
ON A LOCAL SCALE*

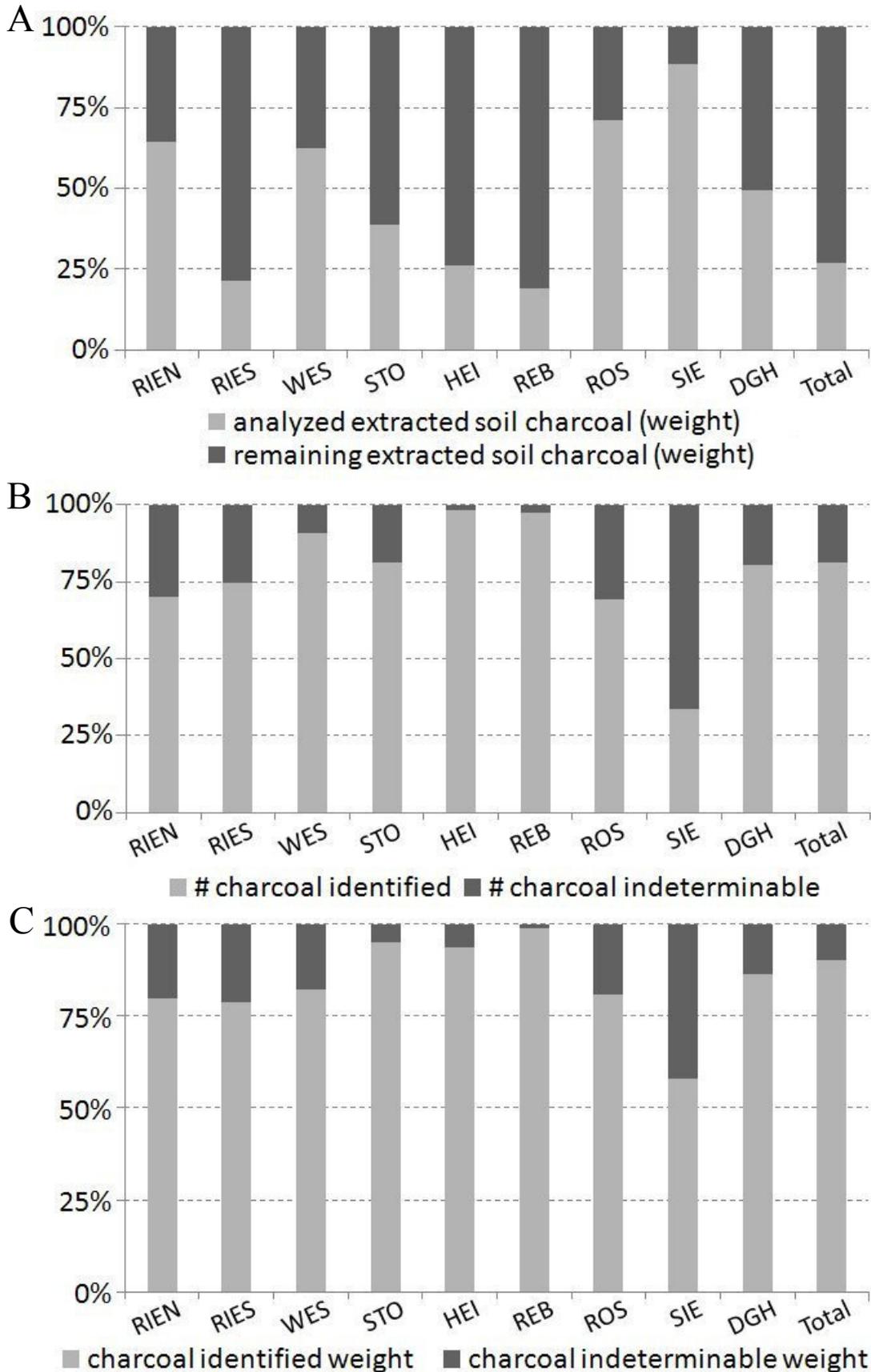
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Overview table of the soil charcoal samples and analyzed data set. (#: number).

Investigation area	Sampling sites	# soil profile	# soil trench	Mean number of soil horizons / profiles	Mean number of sampling layer / profiles	Sample weight (kg)	Weight of extracted charcoal (g)	Weight of analyzed charcoal pieces (g)	# charcoal analyzed
Northern Germany (Schlewig-Holstein)	RIEN	4	1	3	6	202.6	2.9	1.85	580
	RIES	4	2	5	6	283	3.7	0.78	460
	WES	4	∅	3	6	168	15.1	9.37	1758
	STO	6	∅	4	5	236	38.8	18.9	1922
Central Germany (Harz Mountains)	HEI	4	∅	2	5	60	17.3	4.49	1071
	REB	5	∅	2	5	103	228.4	43.75	2181
	ROS	4	∅	2	5	98	7.4	5.28	1174
	SIE	2	2	2	5	124	2.4	2.15	982
	DGH	5	2	4	7	258	10	4.95	1608
	Total	38	7	27	51	1533	326	91.51	11736

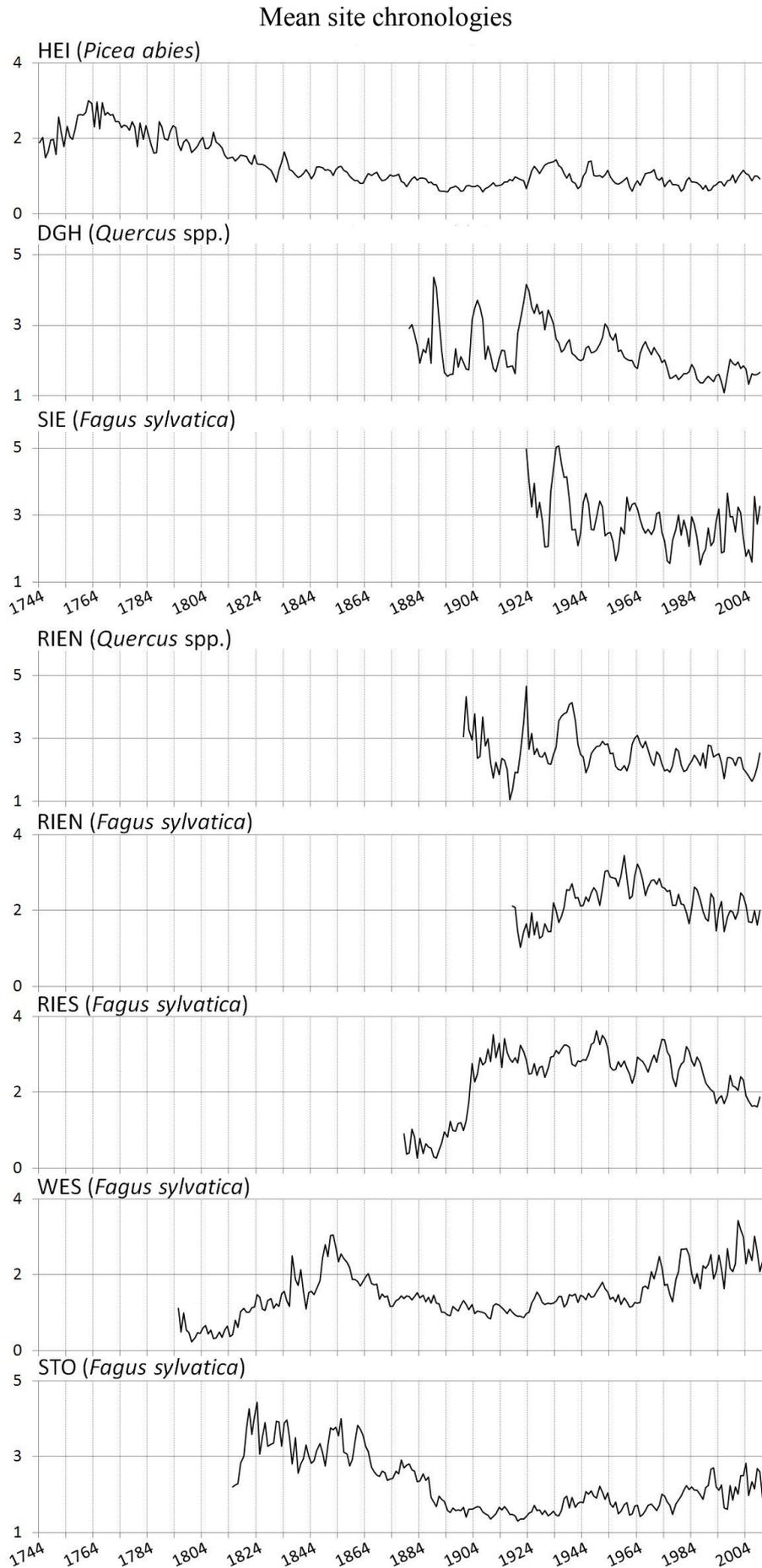
Overview figures of analyzed data set: A – proportion of analyzed and remaining soil charcoal weight; B – proportion of identified and indeterminable charcoal in number of pieces (#: number); C - proportion of identified and indeterminable charcoal in weight.



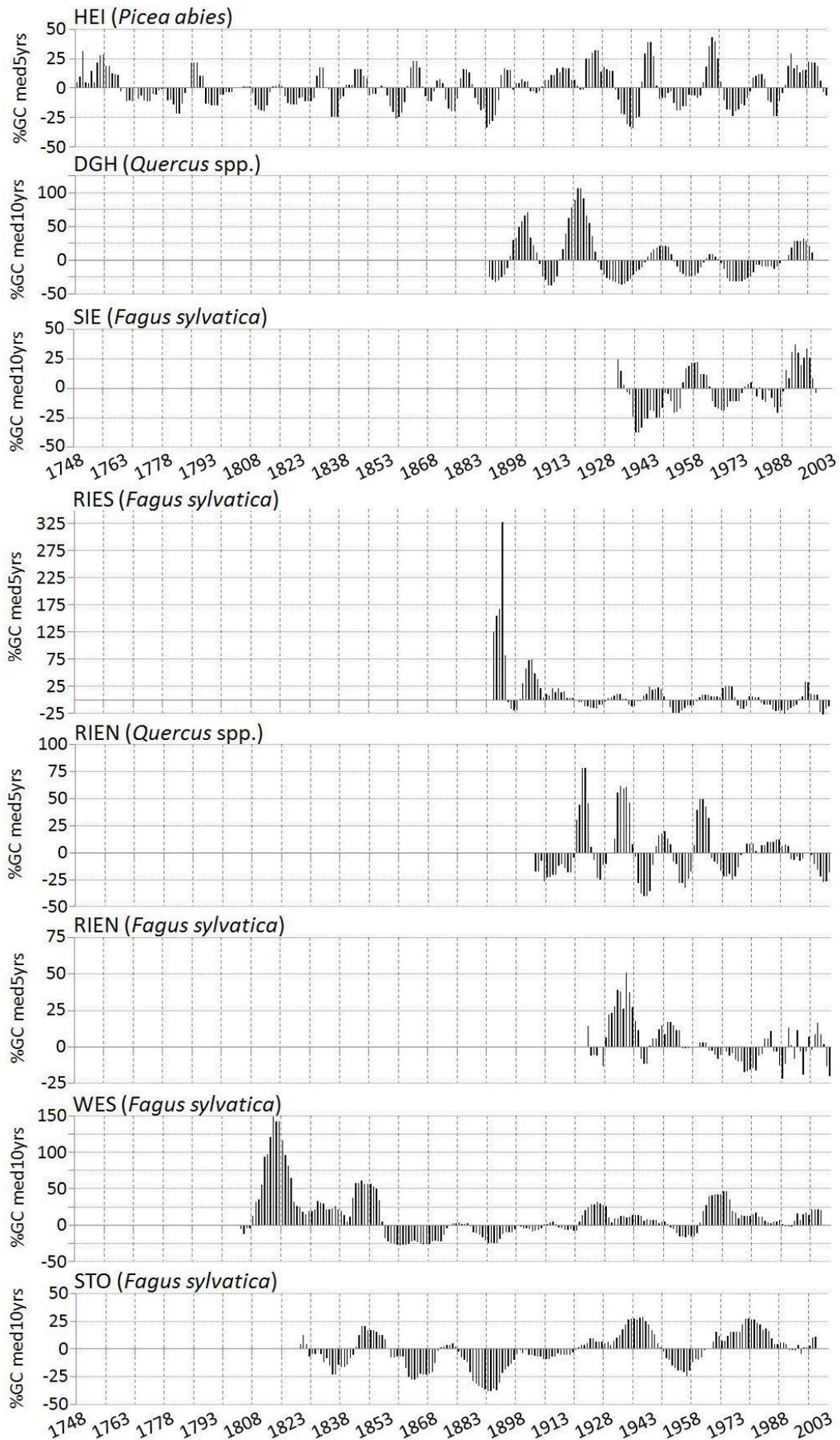
Investigation area	Peat sequence	Nearest soil sampling site	Depth (m)	Number of samples	Number of samples with macro-charcoal	Temporal resolution (yrs.cm ⁻¹)
Northern Germany (Schleswig-Holstein)	SHN	STO	2.18	181	15	48
	MDK	WES	5.56	510	106	26
	SFM	RIES	1.28	128	12	9
Central Germany (Harz Mountains)	BBM	HEI	2.53	253	92	25
	BTM	REB	1.57	151	11	74
	OEB	SIE	1.14	114	29	∅
	ROM	ROS	0.92	92	37	∅

Synthesis table of the sampled and analyzed tree ring series per investigated sites.
 [#: number; sd: standard deviation; ac 1st order: Autocorrelation coefficient of first order; ms: mean sensitivity].

Investigation area	Sampling sites	# radius	# cored trees	Sampled tree species	Coring date	Ending date	Commun interval ending date	Radius				Ring width (mm)				ac 1 st ord	ms	Developed in part 3, chapter:
								with max rings #	with min rings #	ending date	interval ending date	max	min	mean	med			
Northern Germany (Schlewig-Holstein)	RIEN	20	10	<i>Quercus</i> spp.	2009	1900	1913	110	97	3.45	2.21	1.03	1.13	0.51	0.8	0.147		
		10	5	<i>Fagus sylvatica</i>	2009	1918	1930	92	79	4.37	0.76	2.23	2.19	0.62	0.7	0.153	5.2	
	RIES	30	15	<i>Fagus sylvatica</i>	2009	1886	1946	124	64	4.02	0.23	2.52	2.66	0.72	0.9	0.158		
	WES	30	15	<i>Fagus sylvatica</i>	2010	1794	1871	216	139	3.43	0.24	1.49	1.41	0.62	0.71	0.276	5.1	
	STO	28	14	<i>Fagus sylvatica</i>	2010	1815	1890	195	120	4.13	1	1.98	1.77	0.76	0.77	0.249	app. 2/e	
Central Germany (Harz Mountains)	HEI	32	16	<i>Picea abies</i>	2009	1744	1844	265	165	3	0.58	1.28	1.06	0.58	0.85	0.199	6.3	
	SIE	30	15	<i>Fagus sylvatica</i>	2009	1923	1959	86	50	5.06	1.52	2.83	2.64	0.79	0.54	0.299	6.4	
	DGH	28	14	<i>Quercus</i> spp.	2009	1880	1926	129	83	4.07	0.78	1.95	1.81	0.68	0.58	0.141		
	total	208	104															

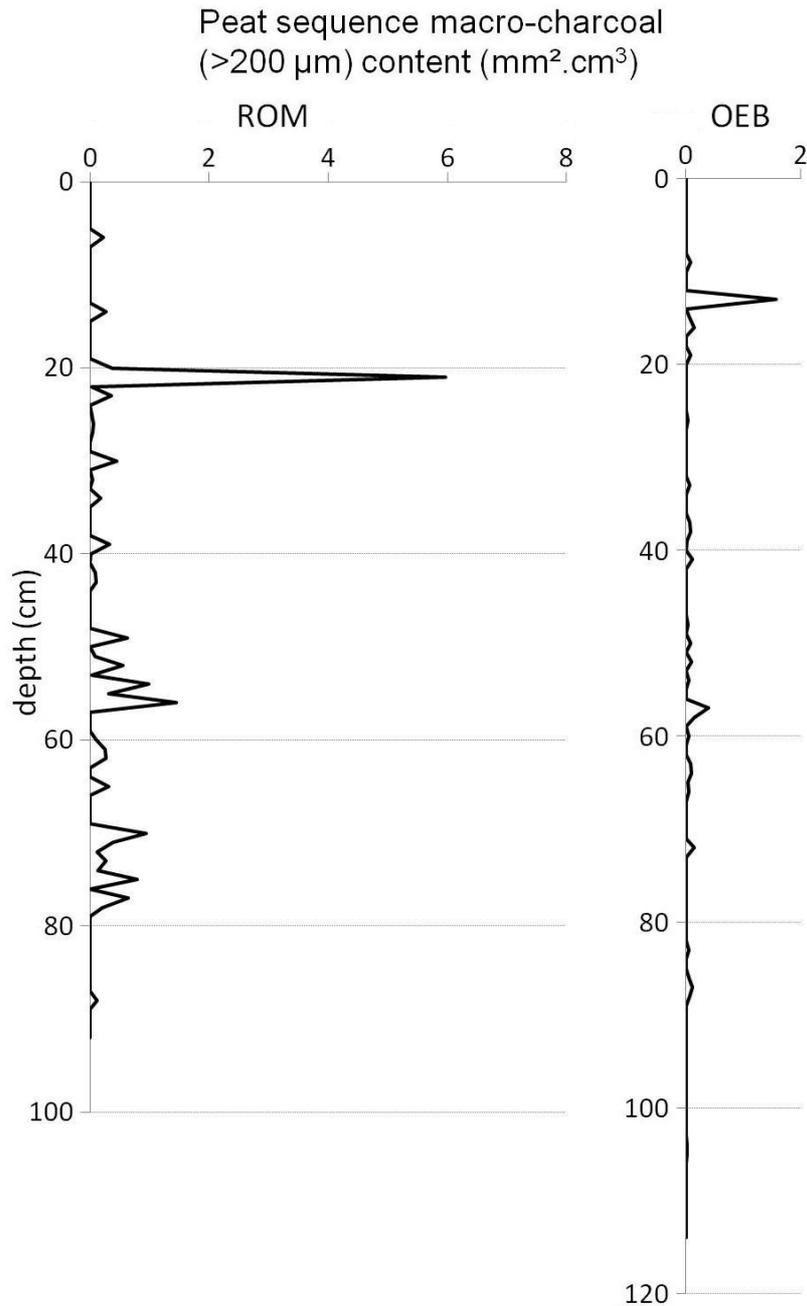


Growth change calculation

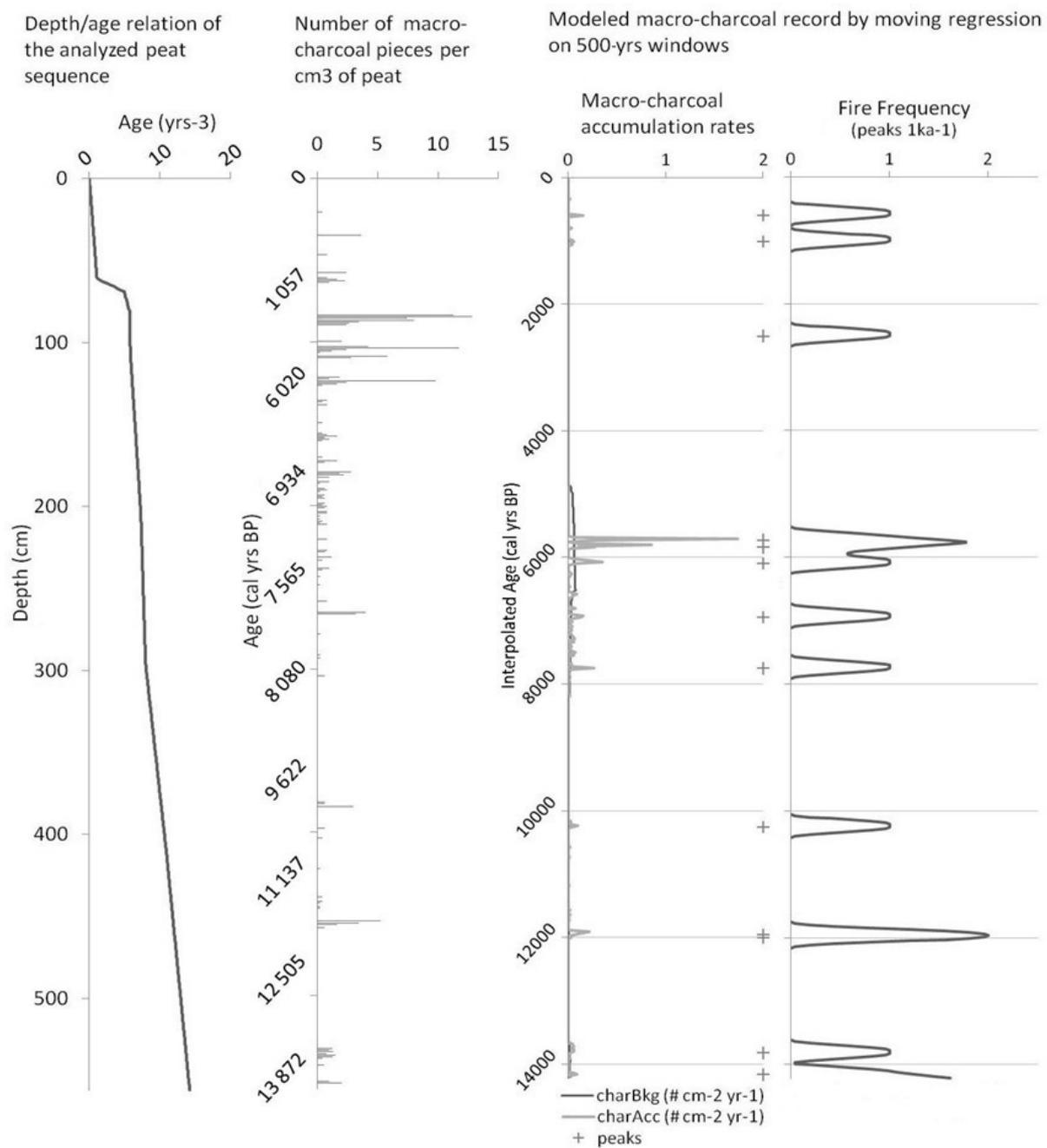


Overview table of the forest sites characterization on the two investigation areas
 (#: number; CE: Clark Evans Index; DW: Dead Wood).

Investigation area	Forest plot	# tree species	Basal area (m ² /ha)	Abundance (#/ha)	# vertical levels	CE	DW volume (m ³ /ha)	Regeneration abundance (#/ha)
Central Germany (Harz Mountains)	HEI	1	36	249	2	0.51	63	2738
	SIE	5	10	438	2	0.3	9.2	5847
	DGH	4	13	345	2	0.49	5.8	5742
Northern Germany (Schleswig-Holstein)	WES	1	20	66	1	2.52	∅	2194
	RIES	7	30	280	2	0.56	20.6	160 000
	RIEN	8	13	564	2	0.27	2.52	62 400



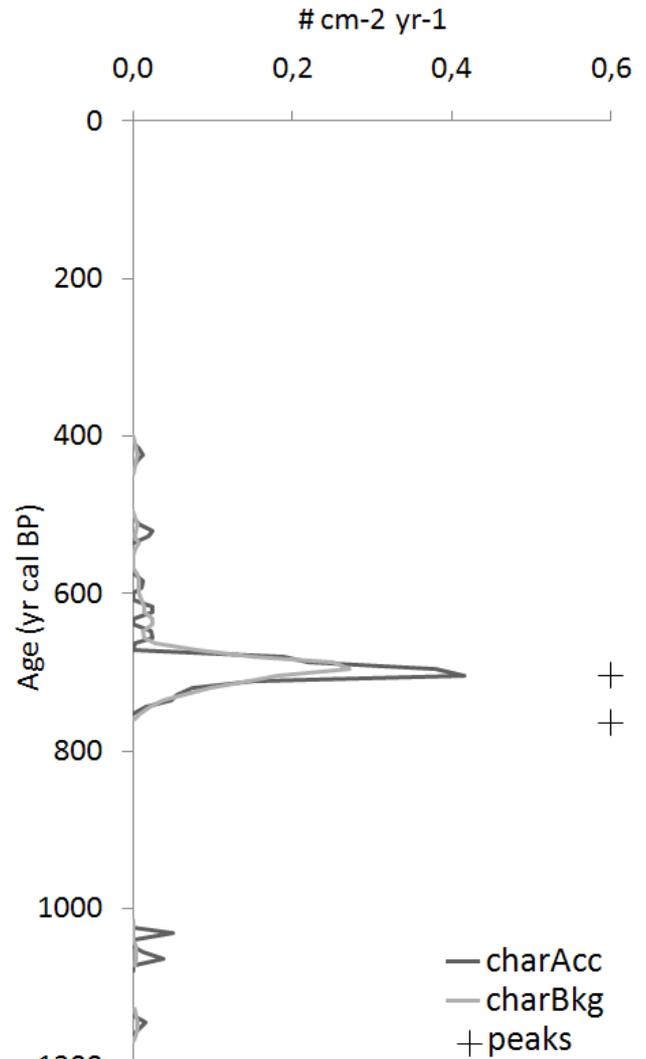
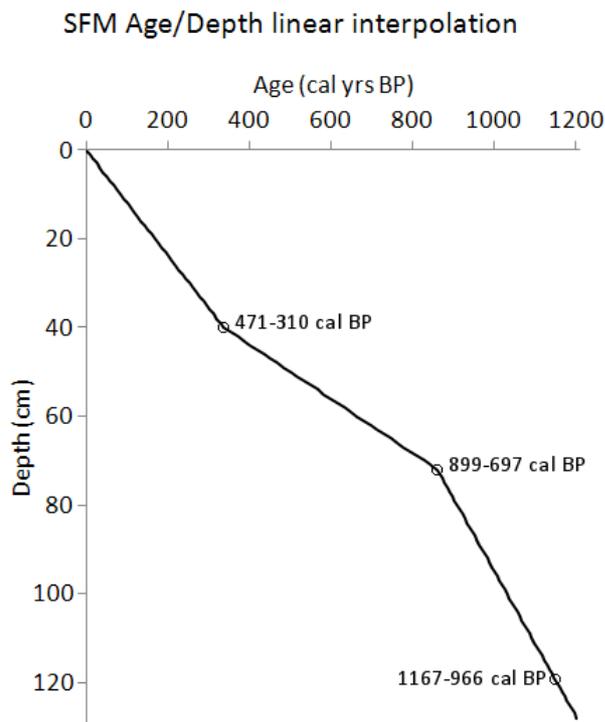
In the southeastern area of investigation of the Harz Mountains, the more continental climatic part (cf. Part 2, Chapter 3.2, and Part 3, Chapter 6.2 and 6.4), two “short” peat sequences were cored and sampled following the methods used for macro-charcoal analysis (see Part 2, Chapter 4.1.2). The age / depth model of both cores have not been estimated since no radiocarbon dating has been obtained so far.



The coring and the analysis of this peat sequence follow the methods and protocols that are described in Part 1, Chapter 4.1.2 and in several chapters of Part 3.

A peat sequence of 128 cm has been cored, spanning about 1200 yrs BP.

On the 130 samples analyzed, 12 contained macro-charcoals. All of those macro-charcoal records are younger than 400 yrs BP. Three macro-charcoal records have been identified as being older than 1000 yrs BP. A phase with more continuous macro-charcoal records has been identified at ca. 45 to 65 cm of the peat sequence, and a phase of much richer macro-charcoal records has been identified at ca. 60 to 65 cm of the peat sequence (i.e. about 700 yrs BP).



A long-term multiproxy investigation has been conducted of the Stodthagen Forest (Northern Germany). The details of it are presented in Part 3, Chapter 5.3.

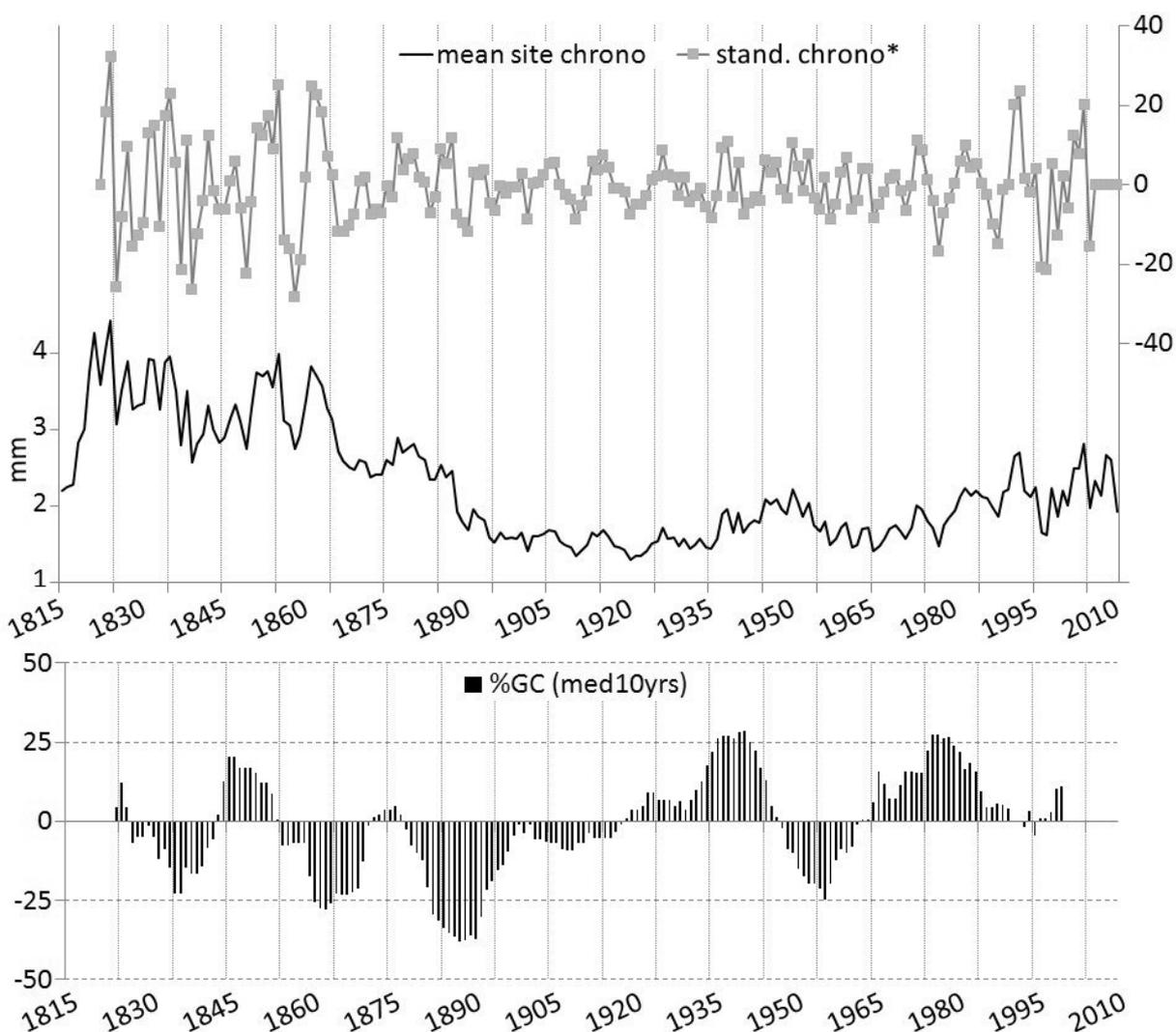
A short term investigation has also begun. For this investigation, 14 *Fagus sylvatica* trees have been sampled and analyzed following the protocol that is presented in several chapters of the main document.

Here are the main results of the measurement of the tree rings series and data treatment.

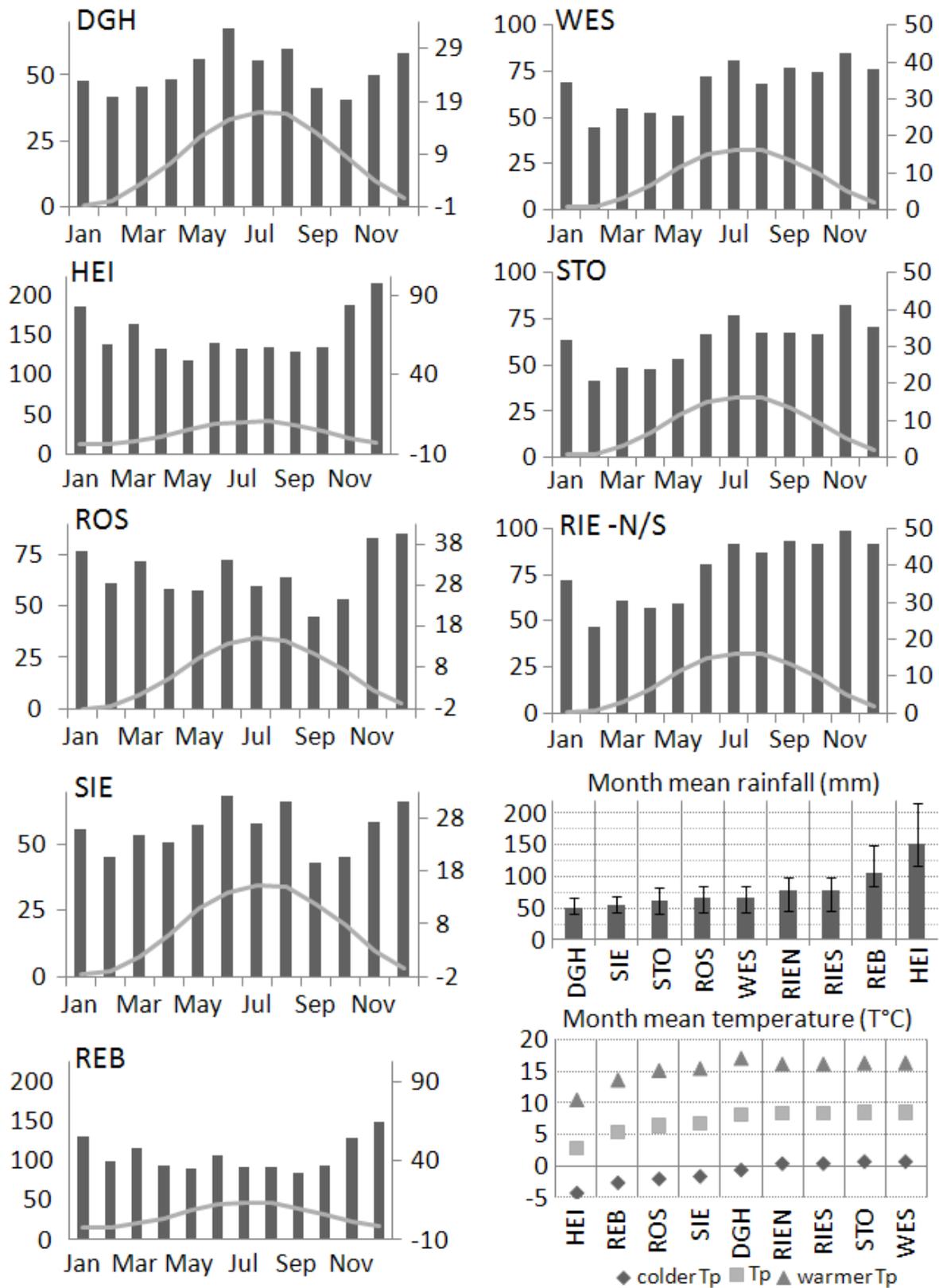
STO mean chronology feature:

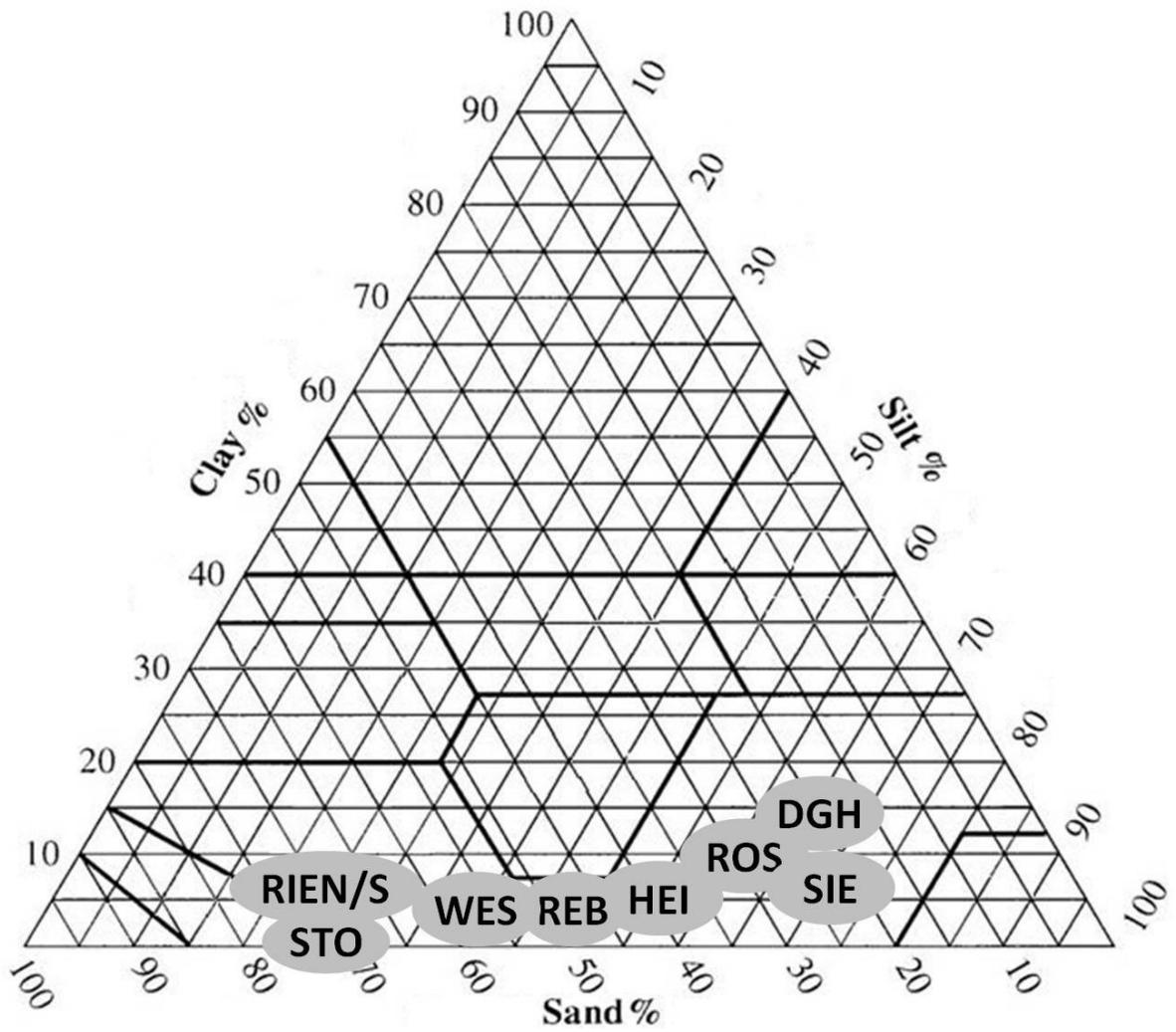
Sampling sites	Coring date	Ending date	Commun interval ending date	Radius with max rings #	Radius with min rings #	Ring width (mm)				sd	ac 1st ord	ms
						max	min	mean	med			
STO	2010	1815	1890	195	120	4.13	1.197	1.98	1.77	0.76	0.77	0.25

[#: number; sd: standard deviation; ac 1st order: Autocorrelation coefficient of first order; ms: mean sensitivity]



[*standardized site chronology calculated by the 'pointer years' methods; GC: Growth Change]





POINT ON THE ANATOMICAL DISTINCTION OF *LARIX* AND *PICEA* WOOD CHARCOAL PIECES, BASED ON THE ANATOMICAL ANALYSIS OF EXPERIMENTAL AND PALAEOBOTANICAL DATA SETS

INTRODUCTION

During the last decades an increasing number of palaeoecological investigations based on soil wood charcoal analyses have been done, notably in boreal and alpine regions (*e.g.* Talon *et al.* 1998; Carcaillet & Brun 2000; Ohlson & Tryterud 2000; Carnelli *et al.* 2004; Talon *et al.* 2005; Talon 2010). Such relatively new palaeobotanical approaches allow us to reconstruct the forest dynamic and the fire history for a long temporal resolution (*e.g.* Sümegi & Rudner 2001; Haesaerts *et al.* 2010) and at the local scale (*e.g.* Touflan & Talon 2009), based on the quantification of wood charcoal pieces in soil, per samples and/or per identified taxa, thanks to the fact that the wood anatomy is fossilized by carbonization (Thinon 1992; Carcaillet & Thinon 1996). However, the relevance and the reliability of the soil wood charcoal data are strongly dependent on the level of taxonomic identification. This taxonomical resolution might be limited because of the condition of conservation (*i.e.* taphonomical aspects; *e.g.* Scott *et al.* 2000; Braadbaart & Poole 2008; Scott & Damblon 2010) and / or because of the wood anatomical structure itself (*i.e.* limits of wood anatomical distinction; *e.g.* Figueiral & Carcaillet 2005).

In the case of soil wood charcoal assemblages from boreal and alpine areas of investigation the limitation of the taxonomical resolution concerning the *Larix* and *Picea* genus - since their wood anatomy is very similar- is a big issue. These wood anatomy similarities explain the often use of the common taxonomical type *Larix/Picea* or *Picea/Larix* (*e.g.* Talon 2010; Touflan *et al.* 2010). Nevertheless, to distinguish between those genres might be particularly interesting, as far as their occurrence in soil wood charcoal assemblages might indicate and provide different and important data for the reconstruction of forest history. Indeed, the distinction between *Larix* spp. and *Picea* spp. of different biomes (*e.g.* *Picea mariana*, *Larix sibirica* in boreal forests and *Larix decidua*, *Picea abies* in alpine forests) would be very interesting to better understand their receptive Holocene dynamics. On a broad spatial scale the global patterns of the long term history of the different species of the genus *Larix* and *Picea* are well described by a considerable amount of palaeobotanical studies, especially by palynological investigations (*e.g.* Penalba & Payette 1997; Bradshaw & Lindbladh 2005; Latalowaa & Knaap 2006), but this is not so clear for the fine spatial scale. The pollen types of these genres probably contribute to explain this unclarity. Indeed, *Picea* spp. pollen grains

are transported over a long distance, making that genus difficult to precisely assess at the local scale, while the *Larix* spp. pollen grains are transported over a short distance (*i.e.* “heavy” pollen grain), making it hardly recorded in the sediment sequences, even if it is present in the catchment area. However, thanks to the fact that the palaeobotanical signal from soil charcoal assemblages is interpretable locally (Dutoit *et al.* 2009, Touflan *et al.* 2010), an improvement of the possibilities to distinguish wood charcoal pieces of *Larix* spp. and *Picea* spp. may provide important knowledge for a better understanding of the history of Holocene boreal and alpine forest systems.

In this paper we present and discuss the results of ‘blind identification tests’ based on a wood anatomical criterion identified by previous anatomical studies: the shape of the bordered pits of the ray tracheid walls (Bartholin 1979; Anagnost *et al.* 1994; Talon 1997). We tested the use of that anatomical criterion on two types of data sets: an experimental data set (*i.e.* wood charcoal pieces produced from collected wood pieces) and a data set from a palaeobotanical investigation in a low mountain range in central Germany (*i.e.* data set from ‘real’ soil charcoal assemblages).

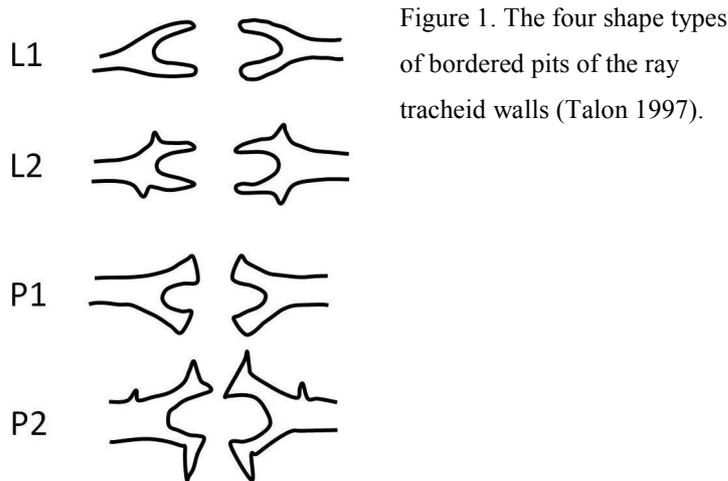
MATERIAL AND METHODS

Anatomical distinction of Larch and Spruce wood

Larix spp. and *Picea* spp. have a quite similar wood anatomy. Their microscopic wood anatomy characteristics are well described in several wood anatomy atlases and identification keys (*e.g.* Jacquiot 1955; Schweingruber 1990a; Schweingruber 1990b). Those two wood types are two conifer genera, therefore they both have softwood wood anatomical features (notably a homogenous anatomical structure, longitudinal and radial tracheids, and bordered pits with scalloped tori on tracheids walls). Moreover, they both have resin canals, piceoid pits on cross-fields, and heterocellular rays. There are also exciting wood anatomical differences which distinguish *Larix* spp. and *Picea* spp., as those used by Marguerie *et al.* (2000) to distinguish *Larix laricina*, *Picea glauca* and *Picea mariana* wood anatomy. However, most of the described anatomical criteria are difficult to observe on wood charcoal material (*e.g.* heartwood color), especially working with wood charcoal material from soil samples (*e.g.* earlywood / latewood transition). Moreover, those criteria are often based on relative observations (*e.g.* the number of areole pit rows on the tracheids border is frequently noted as two for *Larix* and mostly one for *Picea*). This subjective quantification does not allow a strict distinction of the wood charcoal type as present/absence criteria would allow one to do. However, the work of Bartholin (1979) allows us to define the use of the shape of

the bordered pits of the ray tracheid walls as explicit criterion for the *Larix* spp. and *Picea* spp. wood distinction. Schweingruber (1990a) described the shape of the bordered pits as variable from a smooth shape for *Larix* to an angular shape for *Picea*. That method has been used by Anagnost *et al.* (1994) which identified three types of bordered pit shapes based on wood from archaeological contexts. Talon (1997), on wood charcoal pieces, reaches four different ‘degrees’ of bordered pit shapes from smooth (bordered pit type Larix1 –L1– and Larix2 – L2) to angular shapes (bordered pit type Picea1 – P1– and Picea2 – P2; Fig. 1).

We used these ‘degrees’ of bordered pit smoothing in the following anatomical work.



Anatomical analysis of the experimental data set

The wood material for the experimental analysis has been collected on formally identified alive trees. To include possible wood anatomical variation due to local morphotype we collected material from different specimens, in different geographic areas. Thus, two pieces of wood of *Larix decidua* and two pieces of wood of *Picea abies* have been collected from two different specimens in the south west of the Harz Mountain (central Germany). Two other wood pieces of *Larix decidua* and *Picea abies* have been collected from two different specimens in the Southern French Alps (Table 1). All the collected and used pieces of wood were pieces of branches, between 5 and 15 cm in diameter. We did not take into consideration possible differences between branches and trunk wood.

Pair 1	<i>Picea abies</i> – specimen Harz 1 <i>Larix decidua</i> - specimen Harz 1
Pair 2	<i>Picea abies</i> – specimen Harz 2 <i>Larix decidua</i> – specimen Harz 2
Pair 3	<i>Picea abies</i> – specimen Southern Alps 1 <i>Larix decidua</i> - specimen Southern Alps 1
Pair 4	<i>Picea abies</i> – specimen Southern Alps 2 <i>Larix decidua</i> – specimen Southern Alps 2

Table 1. Pairs of the coupled tree specimens used for the ‘blind identification test’ series in the experimental wood charcoal data sets and their respective geographical origin.

The wood charcoal experimental material has been produced from the collected wood in laboratory under a controlled carbonization setting. We used an electric oven (Heraeus M110) with the same setting for all the material: 45 minute of carbonization at 400°C.

After carbonization the charcoal material has been fragmented by hand and passed through a column of sieves to get charcoal assemblages per classes of size: 1 to 2 mm; 2 to 5 mm; bigger than 5 mm.

For every series of identification, 100 wood charcoal pieces of *Larix* and *Picea* have been randomly selected in variable proportion, coupled by pair or geographical origin (Table 1). We analyzed four series of identification (*i.e.* four pairs) per class of size, meaning that we analyzed 400 wood charcoal pieces per class of size (*i.e.* 1200 wood charcoal pieces in total). Every single piece of wood charcoal has been put into a numbered box. The taxa (*i.e.* *Larix* or *Picea*) of the wood charcoal piece in every box have been previously recorded by a person other than the charcoal analyzer. Then, every piece of charcoal has been taxonomically analyzed (*i.e.* one box at a time). To do this, the charcoal pieces were prepared using a binocular (Nikon SMZ 1500, magnification 10 to x100). The taxonomical identification has been done using an episcopic microscope (Nikon ME600, magnifications x100, x200, x500), and the result of the identification (*i.e.* *Larix* or *Picea*) corresponding to each box number has been noted. The identification of every single charcoal piece has been compared to the original input. Moreover, during the microscopic analysis of every single charcoal piece the type of shape of the bordered pit used for a distinction has been noted. The results of the experimental identification (*i.e.* proportion of correct or wrong identifications) have been compiled and analyzed by size class and/or per type of shape pits used for the distinction.

Anatomical analysis of palaeobotanical data set

In the framework of on-going palaeobotanical research about the fire and forest long term history in central Germany (Graduate School “Human Development in Landscapes”, Christian-Albrecht University of Kiel), several soil profiles have been sampled in the Harz Mountains for soil charcoal analysis purpose. In the part at the highest elevation (*i.e.* up to 700 m a.s.l.) of this low mountain range, two study sites in a *Picea abies* woodland have been investigated providing six different soil charcoal assemblages. Since the laboratory protocol of the soil charcoal analysis provides, per soil samples, charcoal assemblages per class of size of 1 to 2 mm; 2 to 5 mm; and bigger than 5 mm (*i.e.* the same size classes as the experimental data set), we did the taxonomical analysis using as an anatomical criterion for the *Larix* and *Picea* distinction the shape of the bordered pits, per class of size of the soil samples of the six

soil profiles of this palaeobotanical investigation. To do this we used the same technical staff as for the experimental data set analysis.

RESULTS AND DISCUSSION

Analysis of the experimental data set

On the set of 1200 *Larix* and *Picea* wood charcoal pieces analyzed (in a random and an unequal proportion) 1045 were correctly distinguished, while 155 were wrong. That means the ratio of correct distinction between *Larix* and *Picea*, using their respective shape type of bordered pits of the ray tracheid was 87 %. This ratio changes considerably if we look for it per size classes of wood charcoal pieces (Fig. 2).

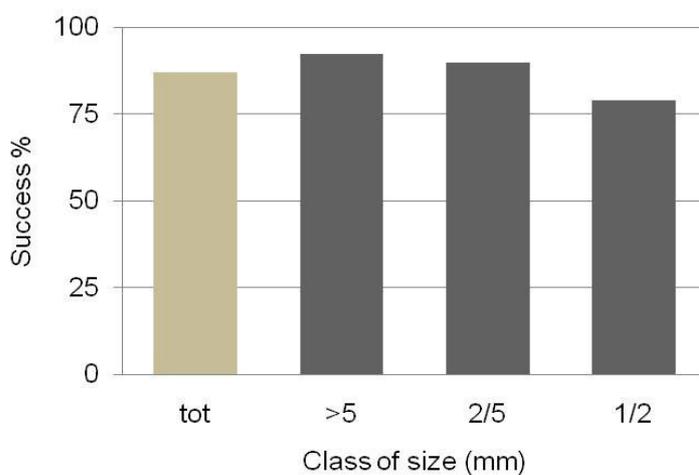


Figure 2. Proportion of successful *Larix* and *Picea* distinction in the experimental wood charcoal data sets. All classes of size cumulatively (tot) and per class of size.

The set of the 400 bigger charcoal pieces (*i.e.* > 5mm) allows us to get correct distinctions of 92 % (*i.e.* 369 pieces correctly identified). The charcoal pieces from 2 to 5 mm have been correctly distinguished at 90 % (*i.e.* 360 correct distinctions). The smaller size of charcoal pieces (*i.e.* 1/2 mm) provides a lower proportion of correct distinctions, with ‘only’ 79 % of correct distinctions (*i.e.* 316 correct distinctions). These results confirm the ‘size dependence’ of the larch and Spruce distinction pointed out by Talon (1997). Indeed, the lower level of correct *Larix* and *Picea* distinctions have been obtain on the smaller size class. This is supported by the correlation of the number of wrong distinctions to the size class of wood charcoal pieces analyzed ($R^2 = 0.93$; Fig. 3).

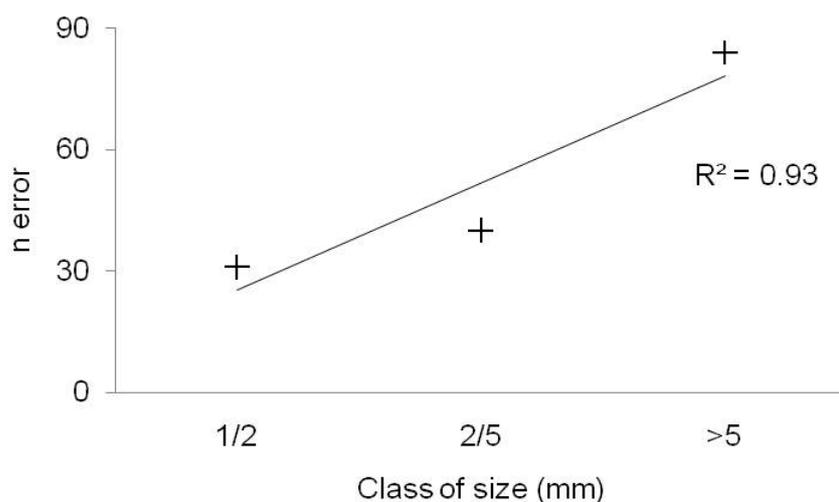


Figure 3. Correlation of the number of wrong *Larix* and *Picea* distinction (n error) and the three classes of size of wood charcoal pieces analyzed in the experimental data sets.

However, even the bigger size class of wood charcoal pieces does not allow one to reach 100 % correct *Larix* and *Picea* distinction. This indicates that even for the ‘big’ wood charcoal pieces the distinction between *Larix* and *Picea* stays delicate. Based on our data set, the distinction between *Larix* and *Picea* stays at best with a minimal incertitude of 8 % for the wood charcoal pieces bigger than 5 mm and of 13 % for all classes of size added together. This incertitude may be explained by the wrong or correct identification of the shape type of the bordered pit of the ray tracheid used for the taxonomical distinction (*i.e.* diagnostic criteria). This means that the use of the shape of the bordered pit of the ray tracheid as an absolute diagnostic criterion is a subjective criteria. However, the use of different types of shapes of the bordered pit of the ray tracheid might be helpful to makes this criteria more exhaustively observable.

Indeed, the results of the ‘blind test identification’ per type of shape of bordered pit showed that (Fig. 4): 1.1 % of wrong distinctions have been done using the shape type L1 (13 errors of identification), 4.7 % with the shape type L2 (56 errors of identification), 6.2 % with the shape type P1 (73 errors of identification), and 1.1 % with the shape type P2 (13 errors of identification). These results indicate that the shape type of bordered pit L1 and P2 allow better *Larix/Picea* distinction than the shape type L2 and P1.

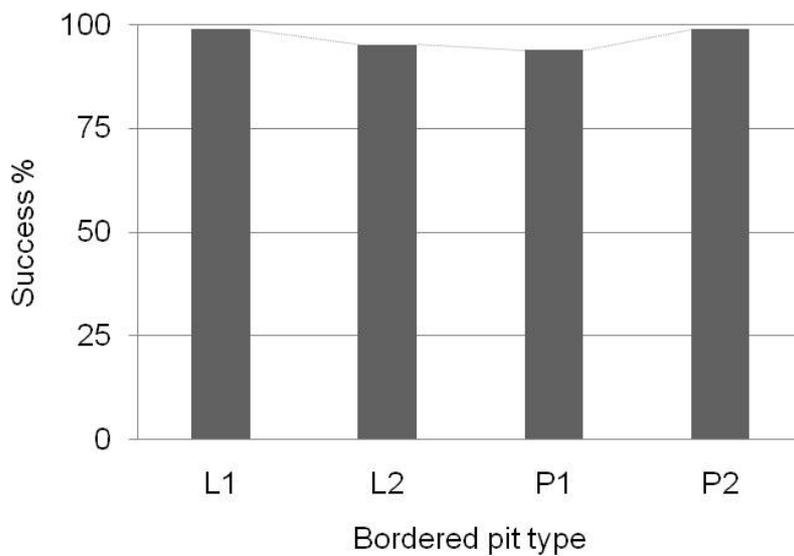


Figure 4. Proportion of successful *Larix* and *Picea* distinction per type of shape of bordered pits of the ray tracheid walls in the experimental wood charcoal data set.

The shape type of bordered pit P1 is even more delicate to use than the shape of bordered type L2, since the rate of wrong distinction is higher. This may be explained by the fact that from the shape type L1 to P2 the anatomical structure of the bordered pit switches to a more recognizable and visible degree of angularity. There is a ‘gradient of angularity’ of the shape of the bordered pit of the ray tracheid walls from L1 (i.e. smooth shape) to P2 (i.e. angular shape), making these two last ‘opposite’ bordered pits easier to distinguish than the two intermediate shape types of bordered pit L2 and P1 (Fig. 5).

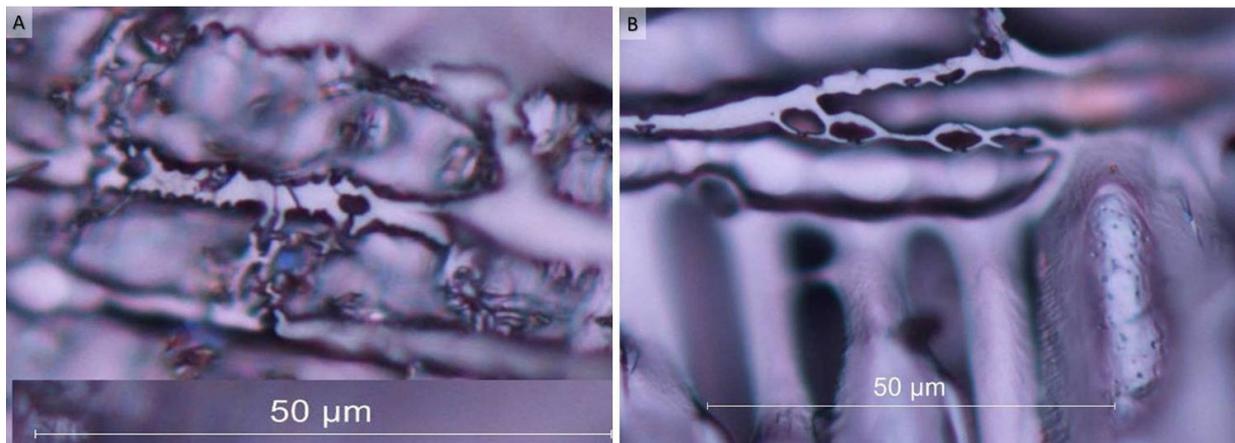


Figure 5. Picture of characteristic shape of bordered pits of the ray tracheid walls. A: shape type P2; B: shape type L1. Taken with microscope camera Nikon Digital Sight DS-U1, on a microscope Nikon SMZ 1500, with a x500 magnification.

Observing the results of the anatomical distinction test using the different type of bordered pit shapes per size class (Fig. 6), we note that the two bigger rates of wrong *Larix* and *Picea* distinction occur with the wood charcoal set from 1 to 2 mm using the shape type of bordered

pit L2 (7 % of wrong identification) and with the shape type of bordered pit P1 (10 % of wrong identification).

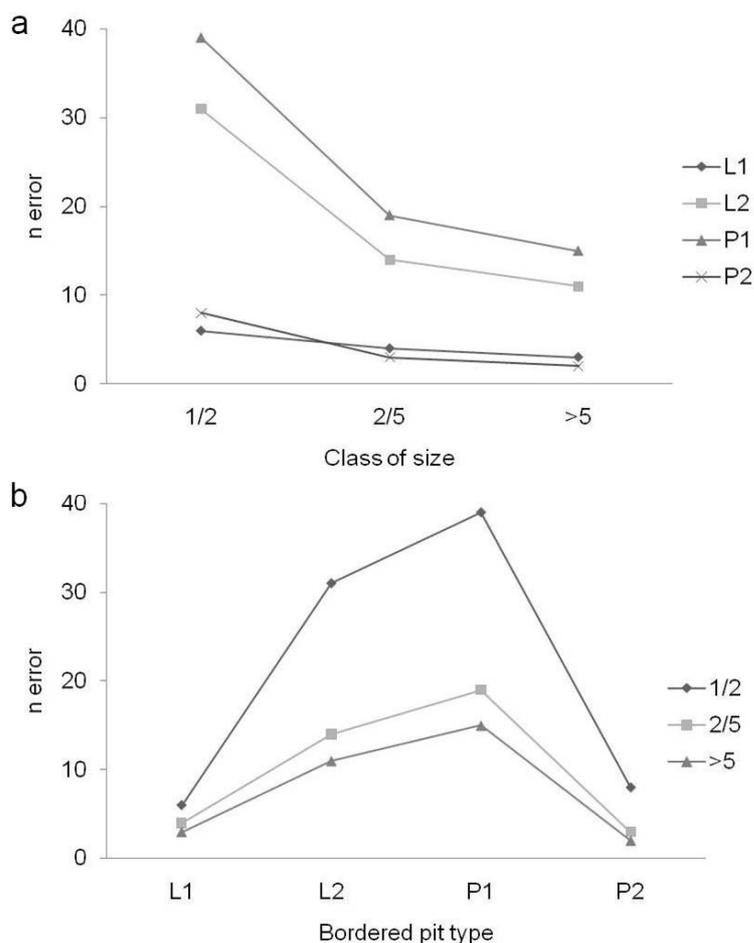


Figure 6. Number of wrong *Larix* and *Picea* distinction, (a) per the class of size for the four types of shapes of bordered pits of the ray tracheid walls, and (b) per the different type of shapes of bordered pits of the ray tracheid walls for the class of size (b).

The two bigger rates of correct distinction have been obtained with the shape of bordered pit type L1 and P2, with more than 98 % of correct distinction for the wood charcoal pieces from 1 to 2 mm, and more than 99 % for the wood charcoal pieces bigger than 2 mm (*i.e.* 99.3 % and 99.5 % for respectively the charcoal pieces from 2 to 5 mm and bigger than 5 mm; Table 2). This indicates that the distinction of *Larix* and *Picea* wood charcoal pieces of the experimental data set has been influenced by the size class and the type of bordered pit used as diagnostic criteria.

Class of size	Bordered pit type			
	L1	L2	P1	P2
1/2	98.5	92.3	90.3	98
2/5	99	96.5	95.3	99.3
>5	99.3	97.3	96.3	99.5

Table 2. Proportion of successful *Larix* and *Picea* distinctions in the experimental wood charcoal data sets for the four types of shapes of bordered pit of the ray tracheid walls per class of size.

Because we did not record the absolute number of bordered pits which we observed for our identification, we are not able to provide a minimal number of bordered pits which we need to observe a distinction between *Larix* and *Picea* wood. However, based on our experience we may say that the number of bordered pits needed to be observed to distinct *Larix* and *Picea* wood charcoal pieces is highly variable from piece to piece, and from a microscope view to another one, on the same single charcoal piece. This support that one single observation of one bordered pit type L1 or P2 might be enough to formally identify a *Larix* or a *Picea* wood charcoal piece, while the observation of many bordered pit types L2 or P1 might still not be enough to formally distinguish *Larix* from *Picea*. The validity of the identification depends not so much on the number of but on the observation of diagnostic bordered pit types L1 or P2. However, the bigger the number of observed bordered pits, the bigger is the probability of observing at least one bordered pit type L1 or P2. And the bigger the number of bordered pits observable, the bigger is the number of ray tracheid walls observable, and the bigger is the size of the charcoal piece, explaining the better identification of the bigger charcoal pieces.

Analysis of the palaeobotanical data set

A total number of 2506 pieces of charcoal have been identified as wood anatomical type *Picea/Larix* (the other taxa present in the assemblages are not relevant for this paper). Using the insights from the analysis of the experimental data set, the taxonomical analysis of the palaeobotanical data set allows for a distinction between *Picea* and *Larix*, or more precisely to distinguish *Picea* from a *Picea/Larix* common wood charcoal type. Indeed, when it was possible to formally discriminate *Picea* from *Larix*, it was always *Picea* which has been identified. However, the *Picea* and *Larix* distinction was not possible every time possible, as was the case for the analysis of the experimental data set. In the case of no distinction between *Picea* and *Larix* wood charcoal pieces, we retained the name of the common anatomical type *Picea/Larix*. From the six soil profiles sampled it is clear that the formal identification of *Picea* charcoal pieces using the shape of the bordered pits type P2 have been much more successful on the bigger size class (*i.e.* in total 1.6 % of identified *Picea* for the size class 1/2 mm, 21.8% for the size class 2/5 mm and 66.3 % for the size class > 5 %; Fig. 7).

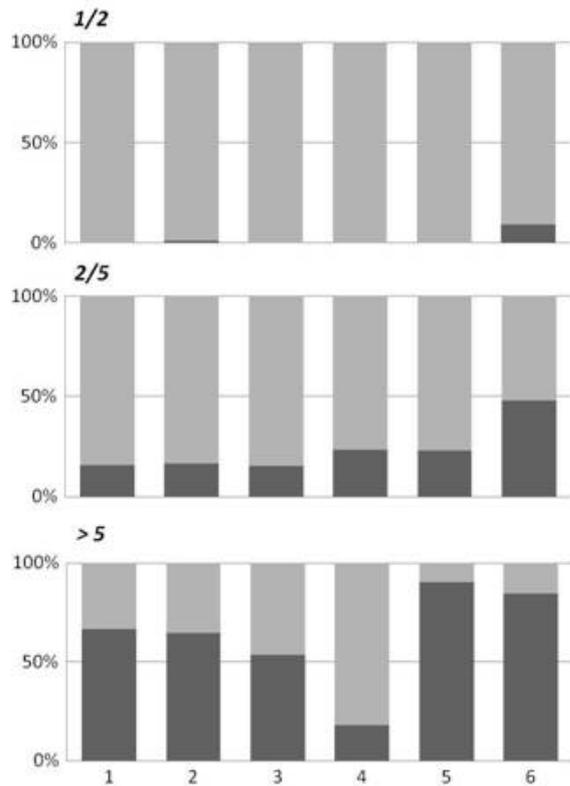


Figure 7. Proportion of *Picea* (■) and *Picea/Larix* (◻) identification in the six palaeobotanical data sets per classes of size.

CONCLUSIONS

The experimental anatomical test, based on previous research, does not provide absolute anatomical diagnostic criteria to always distinguish *Larix* wood/charcoal types from *Picea* wood/charcoal types. However, we confirm in this anatomical study the ‘size dependence’ of the *Larix/Picea* anatomical distinction. This ‘size dependence’ seems to be directly correlated to the observable surface of the analyzed material: correlate to the size of this surface, is the chance of seeing relevant diagnostic criteria, which are the shape of the bordered pits of the ray tracheid walls. A greater surface size heightens chances for observing diagnostic criteria. This is supported by the results of the anatomical analysis of the soil charcoal assemblages from the palaeobotanical investigation.

If this ‘blind identification test’ does not provide an absolute possibility to distinguish more precisely between *Larix* and *Picea* than in previous studies, we pointed out the ‘border’ of the possibility to use the different type of shapes of the bordered pits of the ray tracheid walls.

This information may be important to guide and help the formal identification of wood charcoal pieces especially for a radiocarbon dating strategy. Indeed, for the soil charcoal analysis the dating of charcoal pieces is especially important to get the chronological framework of the palaeo-record and to draw the past history of the trees recorded in the charcoal assemblages. For that reason, the type of shape of the bordered pits of the ray

tracheid walls used, especially for big charcoal pieces, seems quite relevant and reliable to formally identify the single pieces of wood charcoal pieces which we need to date.

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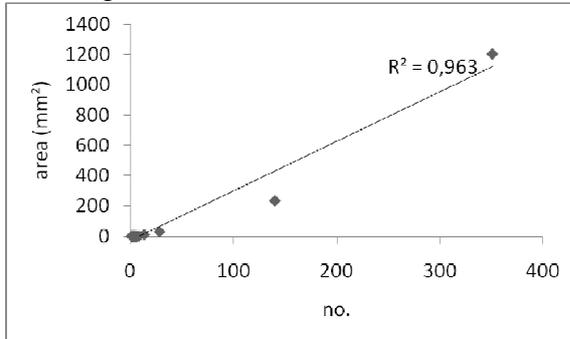
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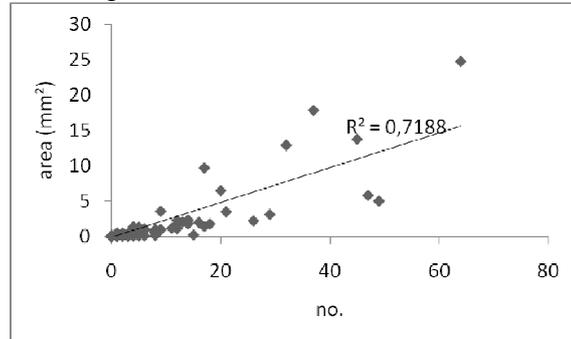
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Linear correlation of the number of macro-charcoal pieces and the corresponding macro-charcoal area per sample of peat sequence (1 cm³).

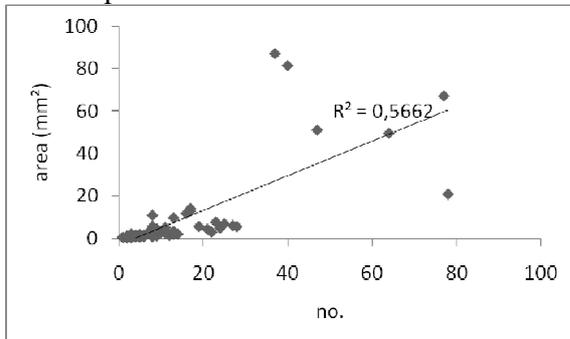
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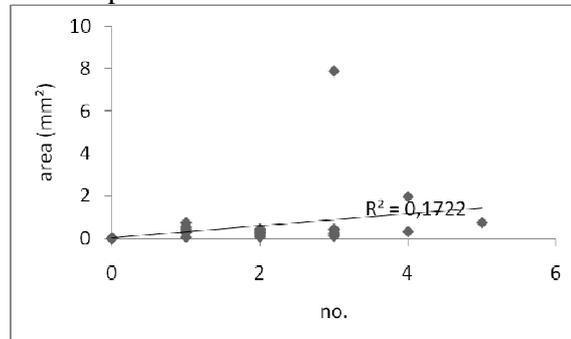
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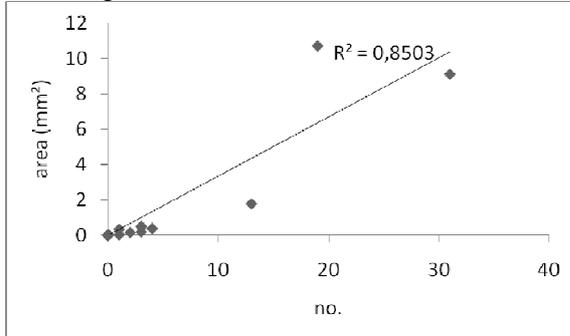
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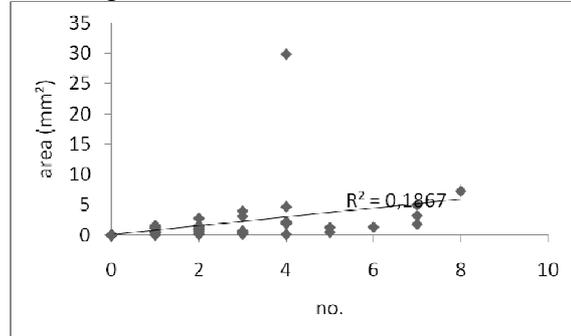
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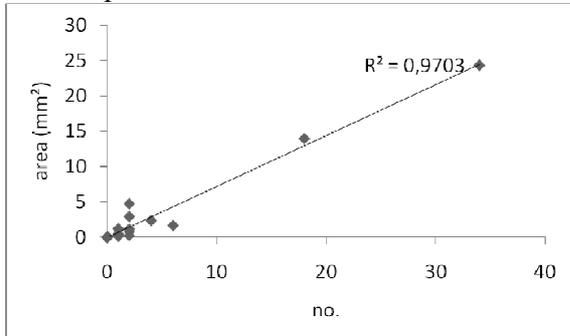
Peat sequence BTM



Peat sequence ROM



Peat sequence SFM



Lab. ref.	Site / Peat sequence	Sampled material	Depth (cm)	Identified taxa	Age conv. & error (\pm) BP	Age cal. BP	Age cal. med. BP	Age cal BC/AD
KIA37285	RIEN1A	Charcoal	5	<i>Pinus</i>	115 \pm 30	270-11	116	1680-1939 AD
KIA37284	RIEN1A	Charcoal	5	<i>Fagus</i>	230 \pm 30	420-0	206	1530-1955 AD
KIA40582	RIEN2B	Charcoal	15	<i>Quercus</i>	1255 \pm 30	1279-1083	1210	672-867 AD
KIA38764	RIEN2D	Charcoal	35	<i>Quercus</i>	1115 \pm 25	1066-961	1013	885-989 AD
KIA40583	RIEN2D	Charcoal	35	<i>Quercus</i>	985 \pm 25	958-797	910	993-1154 AD
KIA41183	RIEN4B	Charcoal	15	<i>Quercus</i>	145 \pm 35	283-0	147	1667-1950 AD
KIA38763	RIEN4E	Charcoal	45	<i>Pinus</i>	8210 \pm 30	9280-9032	9177	BC 7331-7083
KIA40584	RIEN4E	Charcoal	45	<i>Quercus</i>	2130 \pm 50	2309-1991	2115	BC 360-42
KIA40585	RIES2C	Charcoal	25	<i>Acer</i>	1020 \pm 30	1048-802	941	902-1048 AD
KIA40586	RIES2C	Charcoal	25	<i>Quercus</i>	2155 \pm 30	2307-2043	2152	BC 358-94
KIA40587	RIES3C	Charcoal	25	<i>Fagus</i>	1140 \pm 30	1169-968	1033	781-982 AD
KIA41184	RIES4C	Charcoal	25	<i>Quercus</i>	2185 \pm 30	2314-2120	2238	BC 365-171
KIA41185	RIES4D	Charcoal	35	<i>Quercus</i>	1990 \pm 30	1998-1977	1939	BC 79-49 AD
KIA43762	RIESP2B	Charcoal	20	<i>Quercus</i>	3385 \pm 25	3692-3572	3630	BC 1743-1623
KIA37282	RiW1C	Charcoal	25	<i>Fagus</i>	640 \pm 30	668-554	598	1283-1396 AD
KIA37283	RiW1D	Charcoal	35	<i>Quercus</i>	675 \pm 25	676-561	650	1275-1389 AD
KIA40242	SFM117	Peat block	117	Ø	1135 \pm 25	1167-966	1024	783-984 AD
KIA40240	SFM40	Peat block	40	Ø	335 \pm 25	471-310	387	1479-1640 AD
KIA40241	SFM72	Peat block	72	Ø	860 \pm 25	899-697	763	1053-1253 AD
KIA42505	SHN173	Peat block	173	Ø	8740 \pm 45	9892-9558	9716	BC 7943-7609
KIA42502	SHN19	Peat block	19	Ø	760 \pm 25	728-669	689	1223-1281 AD
KIA41186	SHN50	Peat block	50	Ø	1570 \pm 25	1526-1404	1466	425-546 AD
KIA42503	SHN58	Peat block	58	Ø	1330 \pm 30	1303-1180	1271	647-770 AD
KIA38762	SHN63	Charcoal	63	<i>Quercus</i>	3880 \pm 35	4419-4161	4320	BC 2470-2212
KIA41187	SHN81	Peat block	81	Ø	485 \pm 30	545-499	521	1406-1451 AD
KIA42504	SHN99	Peat block	99	Ø	5215 \pm 40	6176-5906	5968	BC 4227-3957
KIA41179	STO1B	Charcoal	15	<i>Fagus</i>	630 \pm 25	662-554	597	1288-1397 AD
KIA37431	STO1B	Charcoal	5	<i>Quercus</i>	810 \pm 20	763-682	715	1187-1269 AD
KIA37433	STO1E	Charcoal	45	<i>Fagus</i>	4030 \pm 30	4572-4422	4485	BC 2623-2473
KIA41180	STO1F	Charcoal	55	<i>Quercus</i>	4065 \pm 30	4799-4437	4550	BC 2850-2488
KIA37434	STO2D	Charcoal	35	<i>Fagus</i>	505 \pm 20	543-510	526	1407-1441 AD
KIA38760	STO3E	Charcoal	45	<i>Quercus</i>	2280 \pm 35	2352-2158	2303	BC 403-209
KIA38759	STO5D	Charcoal	35	<i>Fagus</i>	680 \pm 20	675-565	657	1276-1386 AD
KIA41181	STO5E	Charcoal	45	<i>Corylus</i>	3895 \pm 30	4418-4243	4336	BC 2469-2294
KIA38761	STO5F	Charcoal	45	<i>Juniperus</i>	39130 \pm 1130 / -990			
KIA43761	WES2B	Charcoal	15	<i>Quercus</i>	305 \pm 20	437-302	392	1513-1648 AD
KIA43760	WES2E	Charcoal	45	<i>Fagus</i>	1355 \pm 20	1306-1266	1289	645-685 AD
KIA42905	WES4A	Charcoal	5	<i>Fagus</i>	1405 \pm 25	1348-1287	1311	603-663 AD
KIA42906	WES4B	Charcoal	15	<i>Fagus</i>	1090 \pm 25	1058-938	997	893-1013 AD
KIA42907	WES4D	Charcoal	35	<i>Fagus</i>	1695 \pm 25	1693-1538	1596	257-413 AD
KIA42908	WES4E	Charcoal	45	<i>Quercus</i>	4485 \pm 35	5395-4980	5167	BC 3346-3031
KIA42909	WES4F	Charcoal	55	<i>Pinus</i>	9790 \pm 45	11267-11150	11215	BC 9318-9201

Lab. ref.	Site / Peat sequence	Sampled material	Depth (cm)	Identified taxa	Age conv. & error (\pm) BP	Age cal. BP	Age cal. med. BP	Age cal BC/AD
KIA41043	BBM147	Peat block	147	Ø	1905 \pm 25	1924-1741	1852	26-209 AD
KIA41044	BBM19	Peat block	19	Ø	145 \pm 20	283-5	151	1668-1945 AD
KIA41182	BBM245	Charcoal	245	<i>Picea</i>	5135 \pm 30	5985-5753	5902	BC 4036-3804
KIA41042	BBM67	Peat block	67	Ø	985 \pm 20	955-798	916	996-1153 AD
KIA43778	BTM148	Peat block	148	Ø	9905 \pm 40	11592-11218	11296	BC 9643-9269
KIA43776	BTM21	Peat block	21	Ø	465 \pm 25	536-496	514	1414-1454 AD
KIA 43777	BTM76	Peat block	76	Ø	7400 \pm 30	8323-8172	8249	BC 6374-6223
KIA44619	DGH2B	Charcoal	15	<i>Quercus</i>	1995 \pm 25	1995-1887	1944	BC 46-64 AD
KIA44620	DGH2F	Charcoal	55	<i>Quercus</i>	4030 \pm 30	45724422	4485	BC 2623-2473
KIA44621	DGH3A	Charcoal	5	<i>Quercus</i>	2230 \pm 25	23342154	2227	BC 385-205
KIA43770	DGH3B	Charcoal	15	<i>Pinus</i>	11235 \pm 40	13285-12956	13147	BC 11336-11007
KIA42898	DGH3D	Charcoal	35	<i>Quercus</i>	10240 \pm 45	12126-11769	11987	BC 10177-9820
KIA43772	DGH3D	Charcoal	35	<i>Pinus</i>	11215 \pm 60	13277-12910	13122	BC 11328-10961
KIA43771	DGH3E	Charcoal	45	<i>Fagus</i>	10435 \pm 40 / -35	12529-12956	13147	BC 10580-10171
KIA42899	DGH3F	Charcoal	55	<i>Fagus</i>	10435 \pm 45	12531-12118	12325	BC 10582-10169
KIA44622	DGH3F	Charcoal	55	<i>Fagus</i>	10310 \pm 45	12386-11972	12113	BC 10437-10023
KIA43773	DGH5A	Charcoal	11	<i>Quercus</i>	2140 \pm 25	2300-2009	2128	BC 351-60
KIA43774	DGH5B	Charcoal	41	<i>Quercus</i>	2130 \pm 30	2299-2001	2111	BC 350-52
KIA43775	DGH5E	Charcoal	80	<i>Quercus</i>	6610 \pm 35	7566-7438	7502	BC 5617-5489
KIA44623	DGH5E	Charcoal	80	<i>Quercus</i>	3610 \pm 35	40703834	3919	BC 2121-1885
KIA37286	HEI1B	Charcoal	15	<i>Picea</i>	3055 \pm 30	3360-3170	3285	BC 1411-1221
KIA37432	HEI1D	Charcoal	35	<i>Fagus</i>	2875 \pm 30	3140-2883	3000	BC 1191-934
KIA37287	HEI1E	Charcoal	45	<i>Picea</i>	2910 \pm 35	3206-2953	3052	BC 1257-1004
KIA 43757	HEI2C	Charcoal	25	<i>Picea</i>	1415 \pm 20	1346-1293	1316	604-657 AD
KIA38767	HEI2D	Charcoal	35	<i>Picea</i>	2965 \pm 25	3247-3040	3144	BC 1298-1091
KIA42900	HEI4B	Charcoal	15	<i>Sorbus</i>	280 \pm 25	435-158	373	1516-1793 AD
KIA43765	REB2B	Charcoal	15	<i>Picea</i>	700 \pm 25	686-566	665	1264-1385 AD
KIA43766	REB2D	Charcoal	35	<i>Sorbus</i>	4010 \pm 50	4789-4297	4486	BC 2840-2348
KIA43767	REB5B	Charcoal	15	<i>Picea</i>	3635 \pm 30	4080-3860	3946	BC 2131-1911
KIA43768	REB5F	Charcoal	55	<i>Picea</i>	2795 \pm 25	2961-2802	2897	BC 1012-853
KIA43769	REB5H	Charcoal	75	<i>Picea</i>	2700 \pm 25	2850-2757	2796	BC 901-808
KIA42896	ROS1B	Charcoal	15	<i>Fagus</i>	860 \pm 25	899-697	763	1052-1253 AD
KIA42897	ROS1C	Charcoal	25	<i>Pinus</i>	9610 \pm 45	11165-10771	10941	BC 9216-8822
KIA 43763	ROS1D	Charcoal	35	<i>Fagus</i>	1075 \pm 35	1057-931	982	894-1020 AD
KIA38768	ROS1E	Charcoal	45	<i>Pinus</i>	9140 \pm 40	10415-10225	10288	BC 8466-8276
KIA43764	ROS4B	Charcoal	35	<i>Fagus</i>	1180 \pm 25	1175-1009	1108	775-942 AD
KIA38769	ROS4E	Charcoal	45	<i>Quercus</i>	50 \pm 25	255-31	61	1695-1919 AD
KIA42902	SIE1B	Charcoal	15	<i>Pinus</i>	9600 \pm 50	11161-10756	10940	BC 9212-8807
KIA43758	SIE1C	Charcoal	25	<i>Pinus</i>	10300 \pm 35	12378-11848	12083	BC 10429-9899
KIA38765	SIE1E	Charcoal	45	<i>Pinus</i>	9070 \pm 40	10280-10180	10228	BC 8331-8231
KIA44624	SIE2A	Charcoal	5	<i>Fagus</i>	1120 \pm 35	1168938	1020	782-1013 AD
KIA43759	SIE4A	Charcoal	5	<i>Fagus</i>	1260 \pm 20	1275-1146	1220	675-804 AD
KIA42904	SIE4B	Charcoal	15	<i>Fagus</i>	1850 \pm 25	1865-1715	1783	85-235 AD
KIA42903	SIE4B	Charcoal	15	<i>Pinus</i>	9810 \pm 55	11331-11137	11226	BC 9382-9188
KIA38766	SIE4C	Charcoal	25	<i>Fagus</i>	1765 \pm 25	1806-1573	1667	144-378 AD

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Schlüsselwörter

Natürlichkeit, Multiproxy, zeitliche und räumliche Skalen, Umweltveränderungen, menschlicher Einfluss, Baumring-Analyse, Waldcharakterisierung, Boden-Holzkohle-Analyse, Torf-Holzkohle-Analyse

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Mots clés

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