Peatland initiation through time and space

Cindy Quik

Propositions

1. Incomplete descriptions of sample taphonomy are the main limitation for reconstructing peat initiation.
(this thesis)

2. Current peat remnants offer sufficient options to validate peatland reconstructions.
(this thesis)

3. It is outdated that FAIR datasets are not credited for the PhD degree.

4. Open review is the best peer-review strategy to enhance scientific quality.

5. It is inconceivable that bags of garden compost are certified organic when they contain peat-based products.

6. Compulsory use of carbon credits in research projects is needed to reduce environmental impact of international travel for scientific conferences.

Propositions belonging to the PhD thesis, entitled

Peatland initiation through time and space

Cindy Quik
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Peatland initiation through time and space

Cindy Quik

Thesis committee

Promotor
Prof. Dr Jakob Wallinga
Professor of Soil Geography and Landscape
Wageningen University & Research

Co-promotors
Dr Roy van Beek
Associate professor, Soil Geography and Landscape and Cultural Geography
Wageningen University & Research

Dr Ype van der Velde
Associate professor, Faculty of Science, Earth and Climate
Vrije Universiteit Amsterdam

Other members
Prof. Dr Gerlinde de Deyn, Wageningen University & Research
Dr Minna Väliranta, University of Helsinki, Finland
Prof. Dr Michael Dee, University of Groningen
Dr Kim Cohen, University of Utrecht

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Chapter 1

General introduction

1.1 Wetlands and peatlands

Wetlands are a distinctive landscape type, and can be characterized as areas where the mineral substrate is water-saturated or inundated. Consequently the substrate is poorly aerated, and the period that the water table is near or above the surface is of such duration that the prevalent vegetation and other organisms are adapted to life in water-saturated soil conditions (Charman, 2002c: 4; Joosten and Clarke, 2002: 24; Rydin and Jeglum, 2013c: 2–3). A minimum depth of 30 cm of peat is required to classify a wetland area as a peatland (Charman, 2002c: 4; Joosten and Clarke, 2002: 24; Rydin and Jeglum, 2013c: 4). Peat is organic material that accumulated as a result of a positive production-decay balance. It consists of the (partially) undecomposed remains of plant and animal tissues, which accumulated under more or less water-saturated conditions (Rydin and Jeglum, 2013c: 4). Peatlands comprise 50 – 70% of all global wetlands, making them the most prevalent wetland type (Joosten and Clarke, 2002: 6). As peatland terminology is not fully refined and standardized (Joosten and Clarke, 2002: 9), and several terms are used interchangeably (Rydin and Jeglum, 2013c: 13), I have included a glossary with definitions as used in this thesis (Textbox 1.1).

Peatlands exist in a diversity of conditions. As a result, they are present on all continents, covering a wide latitudinal range and occurring at altitudes varying from sea level to alpine zones (Joosten and Clarke, 2002: 6; United Nations Environment Programme, 2021). Since the 1800s (and regionally earlier), the extent of peatlands has decreased, with an estimated reduction in their global surface area of 10 to 20% (Joosten and Clarke, 2002: 7). For Europe, the loss in peatland area is much greater. Joosten and Clarke (2002: 32) estimated that over 50% of the European peatland area was lost in the period between 1952 and 1992. For the Netherlands, only 1% of the former peatland area is left today (Joosten and Couwenberg, 2001: 407).

Peatlands form natural archives of past environmental changes. Through the preservation of in-situ plant remains, pollen, spores, and animals, and capture of air- and waterborne pollen, spores and other particles, peat deposits contain a record of changes over time that provides information not only about peatland development itself but also about the paleoenvironmental conditions in which these developments took place (Rydin and Jeglum, 2013b: 107). As such, the remains embedded in peat deposits are called the peat archives (Godwin, 1981). In addition, peat deposits contain cultural heritage with a degree of preservation that is unparalleled in dryland environments, including bog bodies, wooden trackways, and a range of other finds (e.g. Glob, 1969; Casparie, 1987; Coles and Lawson, 1987; Van der Sanden, 1996).

The information contained in the peat archives is of unprecedented relevance. Key areas of research include (1) understanding of peatland functioning and development (Tuittila *et al.*, 2013; Hilbert *et al.*, 2017), (2) interpretations of allogenic drivers of change such as climate and sea level rise (Morris *et al.*, 2018), (3) consequences for ecosystem services provided by peatlands (Parish *et al.*, 2008b; Kimmel and Mander, 2010; Rotherham, 2020), such as carbon dynamics (e.g. Yu *et al.*, 2011; Ratcliffe *et al.*, 2021), and (4) to contextualize long-term human-landscape interactions (e.g. Gearey and Everett, 2021). The tremendous losses in peatland surface area as discussed above, related losses in peat thickness, and ongoing threats to their existence in Europe and elsewhere (e.g. Bragazza *et al.*, 2006; Swindles *et al.*, 2019) pose the urgency to accumulate the knowledge that is contained in the peat archives, and the need to protect the areas that are left. In addition, understanding the past is principal for navigating the future, for which dynamic scenarios need to be envisioned and management must be guided towards resilience and adaptivity to change (Gillson *et al.*, 2021).

The peat archives are generally studied intensively to answer questions stemming from various research fields. However, one of the biggest changes recorded in the peat archives, the transition to peat growth itself, is underexposed in scientific research. Recent research indicated that relatively dry forests (with high biomass, high water use, and a thin organic soil) and peat-forming wetlands (with few and/or small trees, relatively low biomass, low water use, and a thick organic soil) may form alternative stable states. Each of these stable states holds a degree of resilience to changes in climate or hydrology, but when thresholds are crossed a persistent shift between these states may occur (Van der Velde *et al.*, 2021). The transition from dryland to wetland (and to peatland) represents a huge landscape change, with major impacts for landscape functioning, ecosystem services and human-landscape interactions.

1.2 From dryland to wetland to peatland

1.2.1 A transition in time and space

During the transition from dryland to wetland and to peatland, peat initiation may occur through (a combination of) three processes, which are briefly outlined in Textbox 1.2. In the course of time, the peat layer accumulates vertically and the peatland may reach a point where the surface grows above the groundwater level. Subsequent isolation from groundwater and full dependence on precipitation leads to ombrotrophication, a process known as the fen-bog transition (Charman, 2002a; Rydin and Jeglum, 2013d). In addition to vertical accumulation of peat, the peatland may expand laterally. Poor drainage adjacent to the peatland may lead to paludification of surrounding soils. This is an autogenic process (Charman, 2002a), but the extent and rate of lateral expansion are influenced by allogenic factors such as climate and topography of the mineral soil (Korhola, 1994; Loisel *et al.*, 2013).

1.2.2 Reconstructing peat initiation and lateral expansion

Reconstructing the period, pace and pattern of peat initiation and lateral expansion requires dating the bottom of peat deposits overlying mineral sediment, often called the *basal peat*. Because of the organic composition of peat, radiocarbon (^{14}C) dating is the best suited method to connect peat stratigraphies to an absolute time scale. Radiocarbon dating is based on the radioactive decay of ^{14}C. This isotope is produced in the upper atmosphere as a result of cosmic radiation. It is subsequently oxidized to $^{14}CO_2$, which becomes incorporated in the tissues

Textbox 1.1: *Definitions and classification as used in this thesis*

Definitions

Wetland[1]	An area where: ▪ The water table is close to or above the surface; ▪ As a result, the substrate is poorly aerated; ▪ The period that the water table is near or above the surface is of such duration that the prevalent vegetation and other organisms are adapted for life in water-saturated soil conditions.
Peat[2]	A substance that consists of the (partially) undecomposed remains of plant and animal tissues, which accumulated under more or less water-saturated conditions. In this thesis material with an organic matter percentage of 40 or more is considered as peat.
Peatland[3]	An area where 30 cm of peat or more naturally accumulated.
Mire[4]	A wetland dominated by active peat-forming vegetation.
Fen or minerotrophic peatland[5]	Mire or peatland that in its present state receives water that has been in contact with mineral soil (groundwater, surface runoff). As a result, fens are often characterized by more alkaline conditions and higher nutrient availability (in comparison to bogs).
Bog or ombrotrophic peatland[5]	Mire or peatland that in its present state receives water and nutrients solely from precipitation. As a result, bogs are often characterized by more acidic conditions and low nutrient availability (in comparison to fens).
Minerogenous or geogenous versus ombrogenous[5]	Referring to the trophic status (as in minerotrophic and ombrotrophic) during peat initiation (i.e., not the present state).

Classification

Six basic hydromorphological mire types[6] can be distinguished based on the shape of the peatland and its mineral substrate, and the hydrological situation of the peatland:

- Raised mire (bog)
- Blanket mire (bog)
- Basin mire (fen)
- Valley mire (fen)
- Floodplain mire (fen)
- Sloping mire (fen)

[1] Charman, 2002c: 4; Joosten and Clarke, 2002: 24; Rydin and Jeglum, 2013c: 2–3
[2] Rydin and Jeglum, 2013c: 4
[3] Charman, 2002c: 4; Joosten and Clarke, 2002: 24; Rydin and Jeglum, 2013c: 4
[4] Joosten and Clarke, 2002: 24; Rydin and Jeglum, 2013c: 4–5
[5] Charman, 2002c: 6
[6] Charman, 2002c: 7

Textbox 1.2: *Processes of peat initiation*

Terrestrialisation[1]	Terrestrialisation (also called infilling) refers to the process where peat develops in or at the edge of water bodies. Terrestrialisation is characterized by gyttja deposits at the base, which require a water depth of at least 0.5 m to form[2].
Paludification[1]	Paludification refers to peat formation on previously unsaturated mineral substrate, and thus reflects drowning of the landscape.
Primary mire formation[1]	Primary mire formation involves peat growth on newly exposed waterlogged substrate (e.g. after land uplift from sea). Here, peat growth starts directly on the fresh parent material.

[1] Charman, 2002a; Rydin and Jeglum, 2013d
[2] Bos, 2010

of living organisms through photosynthesis and uptake via the food chain. Upon death of the organism, the radioactive decay of ^{14}C enables to derive its age (i.e., timing of death) (Bayliss *et al.*, 2004; Walker, 2005; Ramsey, 2008b).

The methods that are used to study peat initiation and lateral expansion (mostly applied in boreal settings), can be roughly classified in three approaches. The first group includes studies where transects of basal peat dates are obtained and lateral expansion rates are inferred based on the distance between dating points (e.g. Almquist-Jacobson and Foster, 1995; Turunen *et al.*, 2002b; Anderson *et al.*, 2003; Turunen and Turunen, 2003; Peregon *et al.*, 2009; Robichaud and Bégin, 2009; Weckström *et al.*, 2010; Loisel *et al.*, 2013; Zhao *et al.*, 2014). In this group, the spatio-temporal pattern of lateral development is not visualised. This is in contrast to the second group of studies, where the spatial distribution of the obtained basal dates is manually converted to lines of equal age, so-called isochrones. These isochrones visualise the pattern of lateral development, and the rate of lateral expansion can be deduced from the distance between isochrones (Foster *et al.*, 1988; Korhola, 1994, 1996; Mäkilä, 1997; Bauer *et al.*, 2003; Mäkilä and Moisanen, 2007; Edvardsson *et al.*, 2014). A third group includes studies that make use of numerical modelling based on hydrological and ecohydrological feedbacks. In these models, vertical peat growth (age-depth) for a peat column is simulated (e.g. the Holocene Peat Model, Frolking *et al.*, 2010; the DigiBog model, Baird *et al.*, 2012 and Morris *et al.*, 2012; the coupled DigiBog-STREAM model, Swinnen *et al.*, 2021). Unfortunately, numerical models that include lateral expansion of peatlands are so far unavailable (see e.g. the discussion on peat models by Baird *et al.*, 2012).

To obtain dating information for reconstructions, one can either look back in the scientific record to build on and integrate existing information, or obtain new data from the field. Data that have been collected in the past are often referred to as 'legacy' data (Griffin, 2015; Smith *et al.*, 2015). Data rescue is an area of increasing influence in geosciences as many researchers realise both the scientific potential of reusing legacy data, and the growing threat of data loss (Wyborn *et al.*, 2015). Data loss is especially alarming in regions and landscapes where natural archives are degrading or at risk, such as peatlands.

When legacy data are synthesized through meta-analyses, new insights may develop that require a bird's-eye view to be discovered (see for example Tolonen and Turunen, 1996; Ruppel *et al.*, 2013. Meta-analyses cross the boundaries of time and place that form the limits of case studies, and are particularly useful when information can no longer be obtained from the field, or when long-term records are needed to investigate how phenomena change through time. However, this requires adequate data access and retrieval, transformation of data to current digital formats, and ways to evaluate data quality and effects of changing research methods to ensure robust meta-analyses. However, no overviews exist of factors that need to be taken into consideration for reuse of geochronological information in peat research, and standardized workflows or designs for quality assessments of peat dates are lacking.

When obtaining new information from the field for reconstructing peat initiation and lateral expansion, accurately dating *basal peat* is key. However, so far a variety of criteria has been used to define *basal peat*, which subsequently led to diverse approaches to date peat initiation. The accuracy of dates in representing the event of interest, i.e. the timing of peat initiation, may be questioned if the (possibly site-specific) definition of the *basal peat* remains implicit. To the best of my knowledge, both the mineral-to-peat transition (i.e., the stratigraphical range reflecting the timespan of the peat initiation process) and the layer called *basal peat* (i.e., the stratigraphical layer that is defined as the bottom of a peat deposit), are not universally defined.

Appropriate sampling and sample pre-treatment for radiocarbon dating are the following principal steps to obtain an accurate age of the basal peat layer. During the past decades multiple concerns were raised (and partly addressed) with the radiocarbon dating of peat (e.g. Törnqvist *et al.*, 1992, 1998; Shore *et al.*, 1995; Nilsson *et al.*, 2001; Brock *et al.*, 2011; Van der Plicht *et al.*, 2019). To overcome the majority of concerns with radiocarbon dating of peat samples, AMS dating of terrestrial plant macrofossils is generally advised (e.g. Piotrowska *et al.*, 2011). Unfortunately, this is not always possible for mineral-to-peat transitions, where the organic material may be highly amorphous and plant macrofossil content is generally low. If plant macrofossils cannot be obtained, one has little recourse but to use bulk dating. This can be problematic as bulk samples consist of a mixture of organic fractions and potentially a mixture of ages, which may yield apparent ages that are either too old or too young for the peat layer of interest (e.g. Törnqvist *et al.*, 1992). Through chemical pre-treatment, a bulk sample can be split up in fulvic, humic and humin fractions based on their solubility (Brock *et al.*, 2011; Van der Plicht *et al.*, 2019). Due to its mobility, the fulvic fraction is generally not used for dating as it may result in significantly younger ages than the humic or humin fraction from the same level (Shore *et al.*, 1995). There is no clear consensus in literature on whether humic or humin dates are most representative for dating peat layers (see e.g. the contrasting findings by Hammond *et al.*, 1991; Cook *et al.*, 1998; Waller *et al.*, 2006; Brock *et al.*, 2011; Van der Plicht *et al.*, 2019). In addition, virtually no studies focus on basal peat layers while investigating the ages of these organic fractions (with the exception of

Brock *et al.*, 2011). It therefore remains unclear which carbon fractions of basal peat layers (which might be slightly different in organic carbon composition and especially in carbon content due to admixture of the mineral substrate compared to peat samples from higher positions in peat profiles) are most representative for the time period of peat initiation.

1.2.3 The case of peat remnants

So far, the palaeogeographical development of the former extensive peat landscapes of the Northwest European mainland has received mixed scientific attention. For the Netherlands for example, current palaeogeographic reconstructions (Zagwijn, 1986; Westerhoff *et al.*, 2003; Vos, 2015b; Vos *et al.*, 2020) were created with a strong focus on the development of the delta (e.g. Berendsen and Stouthamer, 2000, 2001) and coastal area (e.g. Hijma, 2009; Cohen *et al.*, 2014; Pierik *et al.*, 2017). In contrast, the spatio-temporal development of non-coastal and non-alluvial peatlands in the coversand landscape (see Section 1.5) remains uncertain, probably as a result of their large-scale disappearance following reclamation activities in the past few centuries (Gerding, 1995) and consequent limited amount of data for these areas (Spek, 2004; Van Beek, 2009; Vos, 2015a). Consequently, steering factors for peat initiation and lateral development in these areas are not well understood. Whereas peat growth in the coastal area is strongly related to Holocene sea level rise (e.g. Törnqvist and Hijma, 2012), the influence of (the combination of) sea level rise, climate change, permeability of the mineral substrate, vegetation changes and human influence on peat growth in the coversand landscape is more debated (e.g. Casparie and Streefkerk, 1992; Van Geel *et al.*, 1996; Everts *et al.*, 2002; Jansen and Grootjans, 2019).

Due to the poor preservation of peat landscapes in the Northwest European mainland, alternative approaches to reconstruct peat initiation and lateral expansion are needed compared to regions with intact peat cover. The tremendous losses of peat landscapes in Europe and in the Netherlands in particular (see Section 1.1) call for reuse of existing data in studies on the formation, dynamics and palaeoenvironmental characteristics of these landscapes, as legacy data may contain information that can no longer be obtained from the field. Currently, existing information on the age of these former peat landscapes is not yet fully synthesized. The most complete overview is contained in the work of Vos (2015a) and Vos *et al.* (2020), but still lacks a significant part of the dating evidence on peatlands in the Dutch coversand landscape that has been collected since the start of the radiocarbon dating facility at the University of Groningen in the 1950s.

The large-scale peat losses in Northwest Europe hamper new field studies and pose the need for adapted field strategies. In areas where the peatland area is significantly reduced, the placing of transects of basal dates (see section 1.2.2) is questionable as the orientation of peat remnants within the former extensive peat landscape is often unknown. Moreover, basal peat layers might be damaged or removed as a result of peat-cutting (and locally ongoing excavation). Consequently, an adapted strategy is needed to collect field data from peat remnants. In addition, alternative methods of analysis are needed to reconstruct peat initiation and lateral expansion where uncertainty is quantified (i.e., in contrast to manual derivation of isochrones from basal age data). This is especially relevant when reconstructing a former landscape of which large parts are lost.

1.3 Problem statement and aim

Based on section 1.2 I define two key research deficits, which can be subdivided in several elements:

I. Methodological developments are needed to constrain the spatio-temporal development of peatlands more accurately.

   a. No overviews exist of factors that need to be taken into consideration for reuse of radiocarbon dates in geochronological peat research, and standardized workflows or designs for quality assessments of peat dates are lacking;
   b. The lack of a universally applicable and quantitative definition for basal peat, combined with multiple concerns that have been raised previously regarding the radiocarbon dating of peat, may result in apparent ages that are either too old or too young for the timing of peat initiation;
   c. Adapted strategies are needed to obtain field data and to model peat initiation and lateral expansion based on peat remnants.

II. Understanding of the timing, pace and pattern of the initiation and lateral development of peatlands in the coversand landscape of the Northwest European mainland is limited, and responsible steering factors are not well understood.

   a. Existing knowledge on the age of these peatlands is not synthesized in full;
   b. The development of these peatlands is not well constrained in time and space;
   c. The identification and relative influence of steering factors for peat growth in these areas is debated.

In this thesis I aim to reconstruct peat initiation and lateral expansion in the coversand landscape of the Northwest European mainland, and to develop the required methodological tools, which can be applied irrespective of the case study region.

To reach the thesis aim and contribute to resolving the above-mentioned research deficits, I defined six objectives. These objectives are addressed in Chapters 2 – 4, where each chapter focuses on elements of research deficits (I) and (II):

Chapter 2 (I)	To develop a workflow for reuse of legacy radiocarbon data in peatland studies, including rigorous quality assessment, and to propose ways for tailoring the workflow to specific research questions and case studies.
Chapter 2 (II)	To test and evaluate the proposed approach by applying it to the (former) peatlands in the coversand landscape of the northern Netherlands (see section 1.5).
Chapter 3 (I)	To formulate recommendations for dating basal peat. Issues that are specifically addressed include: ▪ Peat initiation is a process of a certain timespan rather than an event; ▪ Basal peat needs to be clearly defined; ▪ Selection of dating samples is typically challenging due to potential poor preservation of plant macrofossils in basal peat; ▪ The representativity of humic and humin dates for the age of basal peat is questionable.
Chapter 3 (II)	To obtain initial dating evidence for the period of peat development at one of the largest bog remnants of the Northwest European mainland, the Fochteloërveen (see section 1.5).
Chapter 4 (I)	To find explanatory variables within a digital soil mapping approach that enable reconstruction of the pattern of peat initiation and lateral expansion within (and potentially beyond) peat remnants.
Chapter 4 (II)	To reconstruct peat initiation ages and the pattern of lateral expansion for the Fochteloërveen peat remnant.

1.4 Approach and thesis outline

A schematic overview of the thesis is shown in fig. 1.1. Each of the six objectives (section 1.3) are aligned to one of the elements of the two identified research deficits. Chapters 2 – 4 each address two of these objectives.

In investigations of peatlands as a whole, where they are considered as landforms, peat landform units can be distinguished based on three scale levels: the microtope, mesotope and macrotope (Ivanov, 1981; Charman, 2002d). The microtope is characterized by a uniform vegetation and physical environment. The mesotope refers to individual mire massifs that originated from a single nucleus.

The macrotope is formed through the coalescence of multiple mire mesotopes. Each chapter is connected to a certain peat landform scale. The period after the Last Glacial Maximum to the present (Late Pleniglacial and Holocene) forms the temporal scope of the thesis.

In Chapter 5, I integrate the methodological developments that are presented in this thesis, and synthesize the knowledge that was gained on the initiation and lateral development of peatlands in the coversand landscape of the Northwest European mainland. Based on the latter I elaborate on drivers for peat formation and formulate a hypothesis on potential steering factors. Subsequently I discuss directions for future research and implications of the thesis results.

Chapters 2 – 4 are published open access in peer-reviewed scientific journals. The three datasets that underlie these publications are published under a CC BY license in the 4TU.ResearchData repository, where they are freely available for download (references and DOI links are included in the respective thesis chapters).

1.5 Study area

In this thesis I focus on mires and peatlands that formed on non-coastal (located above mean sea level) and non-alluvial topographic plains in the coversand landscape of the temperate Northwest European mainland. These plateaus are intersected by deep river valleys and locally dotted with pingo remnants (De Gans, 1976). In these various geomorphological settings, several hydromorphological mire types (Textbox 1.1) occur, including raised mires (bogs), basin mires (fens), and valley mires (fens).

During the Weichselian (OIS 4-2), deposition of aeolian coversands over Northwest Europe led to the formation of the European Sand Belt (Koster, 1988, 2005). In the eastern half and southern part of the Netherlands, these coversands occur at the surface and are located above sea level (fig. 1.2). The northern part of the Dutch coversand area was selected as case study region for this thesis. The Fochteloërveen peat remnant is located in this region and protected as a Natura 2000 area (fig. 1.2 and fig. 1.3, Provincie Drenthe, 2016; Douwes and Straathof, 2019). The Fochteloërveen does not fit within a single definition as it probably formed through coalescence of multiple smaller mires that developed on a topographic plain (see Chapter 4). However, the resultant composite peatland can best be described as a plateau raised bog, i.e. a peatland that in its current state only receives water and nutrients from precipitation, and with a generally flat and horizontal surface (Moen, 1985; Charman, 2002c: 8). More information on the northern coversand landscape and Fochteloërveen peat remnant is provided in subsequent chapters.

1.6 Formal embedding of this PhD thesis

This PhD-study is part of the NWO-Vidi project '*Home Turf. An integrated approach to the long-term development, cultural connections and heritage management of Dutch raised bogs*', led by Dr Roy van Beek. The project has an interdisciplinary design and consists of several interlinked project elements: landscape archaeology (by Roy van Beek), historical geography (by Maurice Paulissen), ore geology (by Aukjen Nauta), and palaeogeography (this thesis).

In addition to the objectives listed in section 1.3, I have contributed to interdisciplinary studies embedded in the *Home Turf* Project, with the aim to improve understanding of prehistoric and early historic human-landscape interactions in landscapes with plateau raised bogs and peatlands in general. Results from these research efforts are not included in this thesis but available in the following scientific papers:

- Van Beek R, Candel JHJ, Quik C, Bos JAA, Gouw-Bouman MTIJ, Makaske B, Maas GJ. 2019. The landscape setting of bog bodies: Interdisciplinary research into the site location of Yde Girl, The Netherlands. *The Holocene* 29(7): 1206–1222, https://doi.org/10.1177/0959683619838048.
- Van Beek R, Quik C, Bergerbrant S, Huisman F, Kama P. 2022. Bogs, bones and bodies. The deposition of human remains in European mires (9000 BC – AD 1900). *Antiquity* 1–21, https://doi.org/10.15184/aqy.2022.163.
- Van Beek R, Quik C, Van der Linden M. Drowning landscapes revisited. Correlating peatland expansion, human habitation trends and vegetation dynamics in the North European Plain. In preparation.

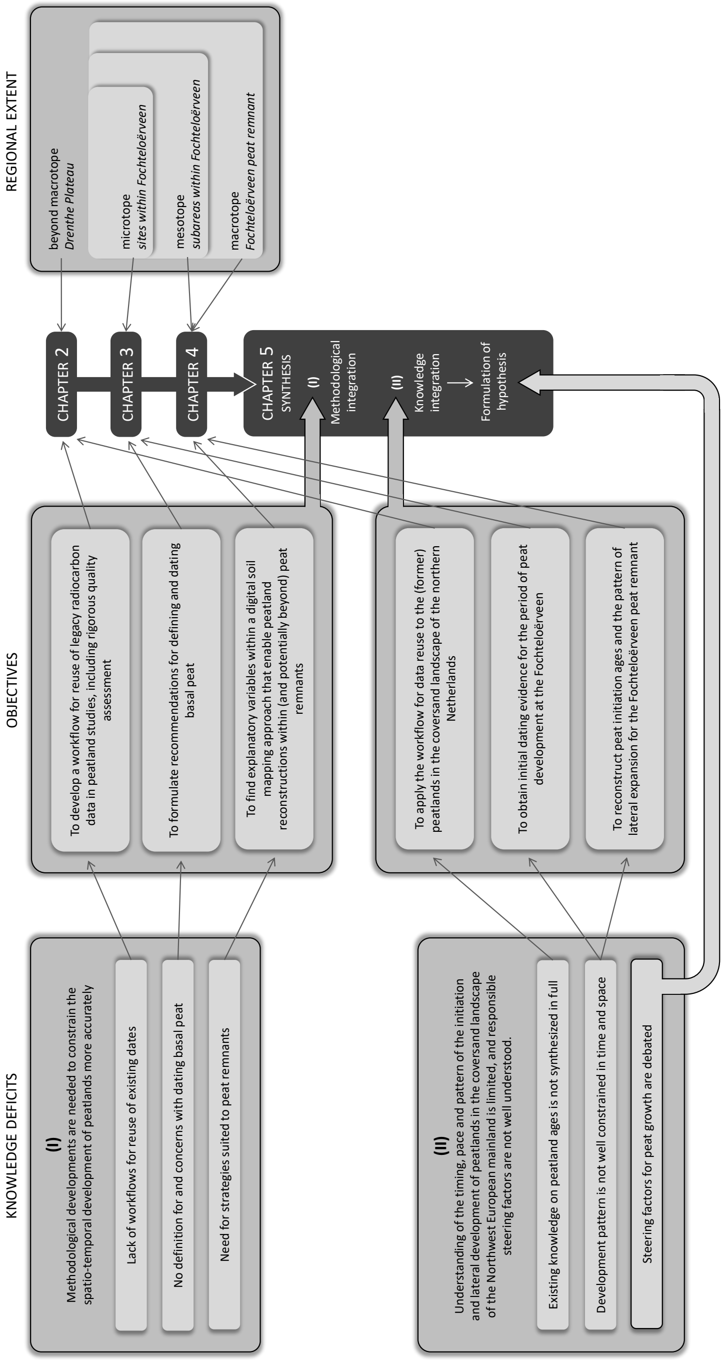

Figure 1.1: *Schematic overview of the thesis.*

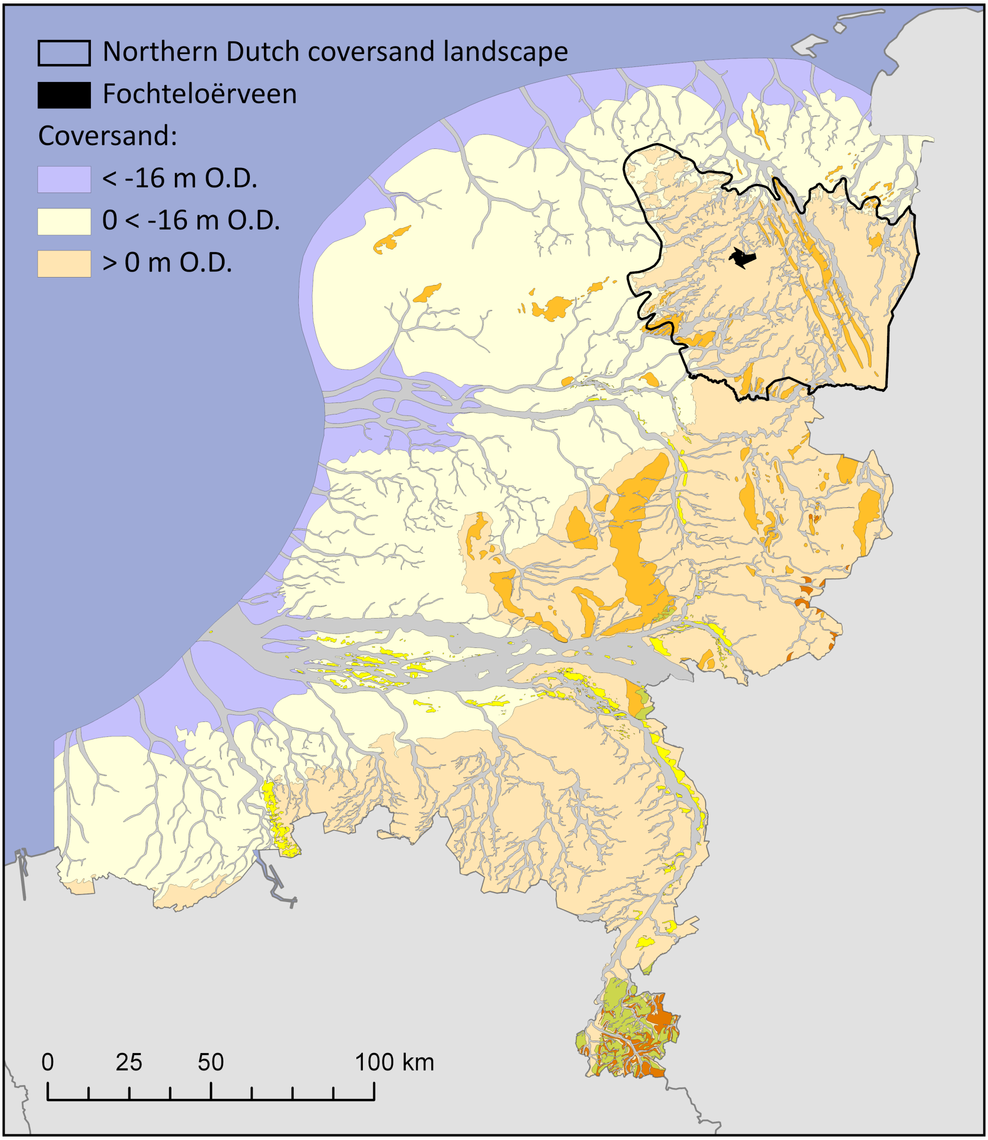

Figure 1.2: *Location of the case study region and case study peat remnant, indicated on the palaeogeographical map of the Netherlands showing the situation for 9,000 BCE (10,950 cal y BP) (Vos et al., 2020; RCE, 2022). Only map units related to the coversand landscape are indicated here. Elevation is in metres relative to Dutch Ordnance Datum (O.D. [in Dutch: NAP], roughly equal to mean sea level). Extent of the Fochteloërveen Natura 2000 area is indicated (Ministerie van Economische Zaken - Directie Natuur & Biodiversiteit, 2018).*

Figure 1.3: *Picture compilation of Fochteloërveen (upper, right and lower picture by Cindy Quik, 2019; left picture by Roy van Beek, 2020).*

Chapter 2

Using legacy data to reconstruct the past? Rescue, rigour and reuse in peatland geochronology

Cindy Quik, Ype van der Velde, Tom Harkema, Hans van der Plicht,
Jim Quik, Roy van Beek & Jakob Wallinga
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Abstract

There is a growing interest for rescue and reuse of data from past studies (so-called legacy data). Data loss is alarming, especially where natural archives are under threat, such as peat deposits. Here we develop a workflow for reuse of legacy radiocarbon dates in peatland studies, including a rigorous quality assessment that can be tailored to specific research questions and study regions. A penalty is assigned to each date based on criteria that consider taphonomic quality (i.e. sample provenance) and dating quality (i.e. sample material and method used). The weights of quality criteria may be adjusted based on the research focus, and resulting confidence levels may be used in further analyses to ensure robustness of conclusions. We apply the proposed approach to a case study of a (former) peat landscape in the Netherlands, aiming to reconstruct the timing of peat initiation spatially. Our search yielded 313 radiocarbon dates from the 1950s to 2019. Based on the quality assessment the dates –of highly diverse quality– were assigned to four confidence levels. Results indicate that peat initiation for the study area first peaked in the Late Glacial (~14,000 cal y BP), dropped during the Boreal (~9,500 cal y BP) and showed a second peak in the Subboreal (~4,500 cal y BP). We tentatively conclude that the earliest peak was mostly driven by climate (Bølling-Allerød interstadial), whereas the second was probably the result of Holocene sea level rise and related groundwater level rise in combination with climatic conditions (hypsithermal). Our study highlights the potential of legacy data for palaeogeographic reconstructions, as it is cost-efficient and provides access to information no longer available in the field. However, data retrieval may be challenging and reuse of data requires that basic information on location, elevation, stratigraphy, sample and laboratory analysis are documented irrespective of the original research aims.

2.1 Introduction

Data rescue in the geosciences is a field of rapidly growing interest (Wyborn *et al.*, 2015). Data that has been collected in the past is often referred to as 'legacy' data (Griffin, 2015; Smith *et al.*, 2015). Many researchers are realizing both the scientific potential of reusing data from past studies, and the increasing threat of data loss, particularly concerning data from the pre-digital era. Data loss is alarming, particularly in landscapes where natural archives are degrading or at risk, such as peatlands. Peatlands are under ongoing threat of excavation, drainage, pollution and climate change (e.g. Bragazza *et al.*, 2006; Swindles *et al.*, 2019).

The long-term archives of past environments contained in peat deposits are in some regions largely lost, as is evident from the relatively minute remnants of the once extensive peatlands of northwest Europe (Casparie, 1972; Vos, 2015a). Consequently, studies on the formation, dynamics and palaeoenvironmental characteristics of these landscapes could greatly benefit from data rescue, as legacy data may contain information that can no longer be obtained in the field. Additionally, access to field sites may be difficult due to strict nature conservation regulations in protected peat remnants. Furthermore, limited understanding of how representative these remnants are for the former intact landscape makes field-based studies challenging. Hence data rescue potentially offers a starting point for peatland research, may provide new insights through meta-analyses (e.g. Tolonen and Turunen, 1996; Ruppel *et al.*, 2013), and identify knowledge deficits to address with future research. However, data reuse is often challenging due to changing research methods, limited information on data quality, and difficulties regarding data access and retrieval.

Here we aim (1) to develop a workflow for reuse of legacy radiocarbon data in peatland studies, including rigorous quality assessment, and propose ways to tailor the workflow to specific research questions and case studies; (2) to test and evaluate the proposed approach by applying it to a case study of a (former) peat landscape in the northern Netherlands, for which we build a comprehensive dataset of legacy radiocarbon dates.

2.2 Background

In this section we briefly discuss the use of legacy data in geoscience, introduce processes of peat formation, review use of (legacy) radiocarbon dates in peatland research, and provide a short introduction to radiocarbon dating. In the last paragraph the case study is introduced.

2.2.1 Legacy data in geoscience

In the geosciences, legacy data may play a role to analyse landforms or processes of the past or that change through time, and to reinvestigate previous work (cf. Smith *et al.*, 2015). The distinction between 'new' and 'legacy' data is somewhat artificial, and partly the result of many practical issues such as unknown data storage locations, lack of accessibility, physically degrading storage media or unreadable data formats, and unwritten information on records that disappeared from the scientific community when researchers retired or passed away (Griffin, 2015; Wyborn *et al.*, 2015). Other important factors causing the artificial separation of legacy data include the continuous change in research methods, the technological advances to refine and develop new equipment, and ever-increasing computational power.

Data that were passed on by previous generations of scientists may potentially be used for purposes that are diverting from the original research objective for which the data collection was designed (Wyborn *et al.*, 2015). Meta-analyses based on legacy data may yield insights that require a birds-eye view on the subject matter, crossing boundaries of time and place that limit many case studies. This particularly applies when information is no longer available in the field, or when long-term records are needed to describe and quantify how systems changed through time. However, this requires adequate data access and retrieval, transformation of data to current digital formats, and ways to evaluate data quality and effects of changing research methods to ensure robust meta-analyses. To quote Griffin (2015): "[...] it is up to our community to remove [...] the artificial barriers that presently prevent the access that research requires simultaneously to *all* of its data."

2.2.2 Processes of peat formation

Peatlands form distinctive ecosystems on the verge from land and water. Their initiation is primarily dependent on the decay rate of biomass (and resulting production-decay balance), which is predominantly influenced by moisture level (Charman, 2002e). Factors that may influence moisture status and consequently peat growth potential include climate (e.g. Weckström *et al.*, 2010), changes in hydrological base level (such as sea level rise, e.g. Berendsen *et al.*, 2007) or regional groundwater changes (e.g. Van Asselen *et al.*, 2017), landforms and surface topography (e.g. Almquist-Jacobson and Foster, 1995; Mäkilä, 1997; Loisel *et al.*, 2013), impermeable deposits or resistant layers in the soil profile (e.g. Breuning-Madsen *et al.*, 2018; Van der Meij *et al.*, 2018), and anthropogenic influence (e.g. Moore, 1975, 1993). Some of these factors such as climate may act at larger spatial scales, whereas others, for instance impermeable layers, could also have more local effects.

Given favourable boundary conditions, peat initiation may occur through (a combination of) terrestrialisation (also known as infilling), paludification, and primary mire formation (Charman, 2002e; Rydin and Jeglum, 2013d). Terrestrialisation refers to the process where peat forms in or at the edge of existing water bodies. Paludification does not include a true aquatic phase, instead peat develops directly on previously dry mineral substrate, following changes in moisture status that led to waterlogging. Primary mire formation refers to peat formation on newly exposed land (as opposed to paludification, where previous vegetation was present) that has been waterlogged since initial exposure, for instance after deglaciation or land uplift from sea.

Over time, peatlands grow vertically and may reach a point where their surface rises above groundwater level. Isolation from groundwater and resulting strong dependence on rainwater leads to ombrotrophication (Charman, 2002e; Rydin and Jeglum, 2013d). These fen-bog transitions may occur at various timing (Väliranta *et al.*, 2017).

In addition to vertical growth, peatlands may expand laterally to cover larger areas. Poor drainage adjacent to the peatland may cause paludification of surrounding soils. This is referred to as an autogenic process (Charman, 2002e), but the degree to which this happens and the rate of lateral spread are dependent on allogenic factors such as climate and topography (e.g. Korhola, 1994).

Reconstructing the period of peat initiation requires dating the peat base (also referred to as basal peat, do note that this definition of basal peat is much broader than the 'Basisveen Bed' as known in Dutch stratigraphy (TNO – Geological Survey of the Netherlands, 2021b)). Peat initiation and subsequent lateral expansion are often not easily distinguished as both require basal peat dates for reconstruction. Lateral expansion can only be deduced from a series of basal dates (e.g. Mäkilä, 1997; Mäkilä and Moisanen, 2007; Chapman *et al.*, 2013), which in fact is also needed to determine which date indicates the age and location of peat initiation.

For more elaborate information on peatlands, peat accumulation and peatland ecology we refer to e.g. Frenzel (1983), Charman (2002e), Wieder and Vitt (2006), Mitsch *et al.* (2009) or Rydin and Jeglum (2013a). For spatial distribution of peatlands see e.g. Joosten *et al.* (2017b); Tanneberger *et al.* (2017), or IMCG (2021).

2.2.3 Legacy data in peatland research

Meta-analyses of composite datasets often provide new supraregional insights and may point to knowledge gaps that need to be addressed by future research. For instance, in an extensive study by Tolonen and Turunen (1996) on carbon accumulation in Finnish mires over 1000 dated peat cores were analysed, combining material from over 30 publications of various regions in Finland. Their analyses enhanced understanding on potential effects of climate warming for different mire types in Fennoscandia. Various studies include legacy dates of basal peat layers to enhance understanding of Holocene sea level rise (e.g. Berendsen *et al.*, 2007; Meijles *et al.*, 2018; Hijma and Cohen, 2019) or to increase insights in peat compaction and land subsidence (e.g. Koster, 2017). Ruppel *et al.* (2013) studied trends in peatland initiation in North America and northern Europe, through analyses of 1400 retrieved basal peat dates. Their results not only provided insights in spatiotemporal trends in peat initiation but also indicated a lack of (retrieved) data for the Northwest-European Plain. Future studies –including the research presented in this paper– may complement this image and further develop our understanding of peatlands through space and time, the influence of autogenic processes and feedbacks, and allogenic causes for changes in peatland dynamics.

2.2.4 Radiocarbon dating

For environmental reconstructions based on peat archives, radiocarbon (^{14}C) dating is the preferred method to connect stratigraphies to an absolute time scale. We provide a concise explanation of the radiocarbon method, as well as a summary of the development of its measurement techniques (fig. 2.1). This is relevant when using data obtained with techniques subject to methodological changes.

Radiocarbon dating is based on the radioactive decay of ^{14}C. This isotope is produced in the upper atmosphere by cosmic radiation. It oxidizes to $^{14}CO_2$ which is incorporated in living organisms through photosynthesis and the food chain. Upon death of the organism, the radioactive decay of ^{14}C enables to derive its age (i.e. timing of death).

Although the principle is relatively simple, complications do exist. First, changes in cosmic ray flux and geomagnetic field strength cause variations in the production rate of ^{14}C through time (De Vries, 1958). This requires ^{14}C dates to be calibrated in order to express them in calendar years. This is primarily done by ^{14}C dating of tree rings, which are dated absolutely by dendrochronology. Second, isotopic fractionation (mass dependent effects) during photosynthesis leads to depletion of the heavy isotopes ^{13}C and ^{14}C in the plants, the latter causing age aberrations for which measurements need to be corrected. Third, the half-life of ^{14}C is 5,730$\pm$40 years, where originally a value of 5,568 years was used by Libby *et al.* (1949) who developed the ^{14}C method.

In its early days, ^{14}C dates were reported in BP (Before Present, defined as 1950), using the natural ^{14}C content as a reference. It soon became clear that

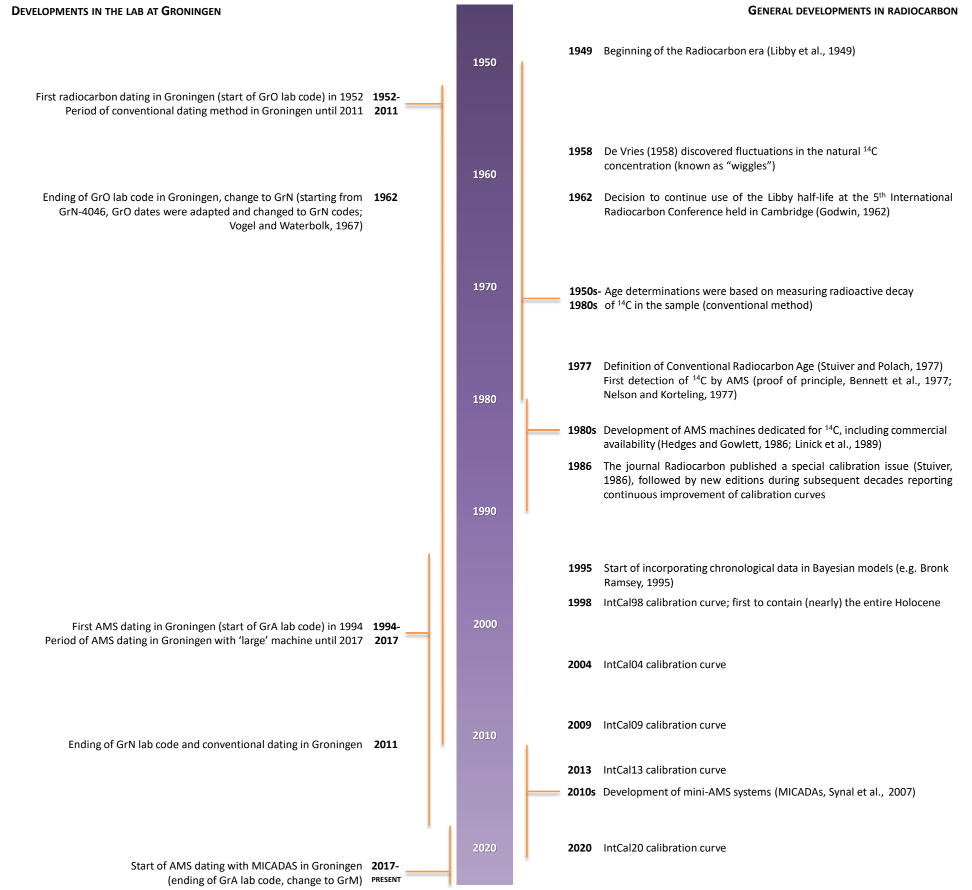

Figure 2.1: *Timeline of developments in radiocarbon dating (right). Changes at the radiocarbon laboratory in Groningen (left) are relevant for the case study.*

this is problematic because of the complications mentioned above. These are solved by the Radiocarbon Convention, which defines the ^{14}C timescale (Stuiver and Polach, 1977; Van der Plicht and Hogg, 2006):

i) The ^{14}C radioactivity is measured relative to that of a modern reference material, i.e. Oxalic Acid with a radioactivity of 0.226 Bq/g C;

ii) From this measured radioactivity the "radiocarbon date" is calculated using a half-life of 5,568 years;

iii) Radiocarbon dates are corrected for fractionation using the stable isotope ^{13}C (to a reference value δ^{13}C = -25‰, see below);

iv) Radiocarbon dates are expressed in the unit BP.

The original half-life value was chosen to keep the meaning of earlier reported dates unchanged. The chosen value for the δ^{13}C reference value is that of charcoal, wood and plants (including peat). The convention means that BP should not be taken literally: ^{14}C years differ from calendar years, and present is not today (or 1950). Calibration transfers ^{14}C dates into calendar dates. These are expressed in cal BP, which is defined as calendar years before 1950 CE. The calibration curves are regularly updated (fig. 2.1).

In radiocarbon practice, the δ^{13}C and %C values are indicators for sample integrity (Mook and Streurman, 1983). When these values are not within the accepted range, the organic sample material is usually degraded, or there is contamination. They are therefore an integral part of ^{14}C dating, also for legacy data. ^{13}C is a stable isotope and thus its concentration is time-independent. It can therefore be used as a measure of fractionation of the photosynthesis process. Since δ^{14}C = 2 δ^{13}C, we then also know the fractionation effect for ^{14}C, and thus the age deviation caused by this process. In addition, fractionation effects during laboratory procedures are taken into account automatically. The δ^{13}C is defined as δ^{13}C = $[^{13}R_{sample} - {}^{13}R_{reference}]/[^{13}R_{reference}]$ (x1000‰), where $^{13}R=[^{13}CO_2]/[^{12}CO_2]$. The reference is a belemnite known as PDB, with a well-known ^{13}C/^{12}C isotope ratio (Mook, 2006, and references therein).

In the early days of radiocarbon (the 1950's, i.e. before the Convention), δ^{13}C was not measured, and fractionation correction was not applied. Significance of δ^{13}C is dependent on the type of photosynthesis used by plants, known as the C_3 and C_4 pathways. For C_3 plants, the δ^{13}C value is around -25‰, not very different from the reference value so that fractionation corrections are small, within the measurement uncertainty and negligible. Therefore our peat dates that were not corrected for isotopic fractionation (i.e. measured before the Convention) are still useful. For completeness we note that for C_4 plants, the δ^{13}C value is around -10‰ which leads to large fractionation corrections; here the difference with the reference value (δ^{13}C=-25‰) is around 15‰, which corresponds to an effect of 240 BP for ^{14}C and cannot be neglected. Thus, for regions containing C_4 plants it will be necessary to correct previously uncorrected dates for the fractionation effect.

The %C refers to the organic C content of the sample after the pre-treatment (ideally ABA, the Acid-Base-Acid method) designed to isolate the pure datable fraction. This is different from the organic content of the original peat, such as measured with loss-on-ignition, where the weight loss is measured of dried untreated material before and after combustion at high temperature (e.g. Chambers *et al.*, 2011; Kennedy and Woods, 2013). The lower the carbon content of the ^{14}C sample, the larger the effect of contamination (i.e. all carbon that was not related to the sample when it was alive) will be (Lanting and Van der Plicht, 1994).

Initially, radiocarbon concentrations were measured by radiometry. This method requires large quantities (typically 1 gram) of carbon (Cook and Van der Plicht, 2013), meaning that only bulk samples could be dated. In the 1970s, Accelerator Mass Spectrometry (AMS) was developed for direct measurement of ^{14}C concentrations in a sample. This method is much more efficient, enabling dating samples of typically 1 milligram (Tuniz *et al.*, 1998). The most recent development is that of mini-AMS systems (MICADAS), based on the same technology but much smaller machines. Radiometry is still applied at some laboratories. Radiocarbon laboratory codes (available at www.radiocarbon.org) provide unique identifiers for dates and immediately provide information where the date was measured, often also on the measurement method (conventional or AMS).

For more information on radiocarbon see e.g. Bayliss *et al.* (2004); Walker (2005); Ramsey (2008b) and refer to e.g. Taylor (2000); Olsson (2009), and Wood (2015) for its development.

2.2.5 Case study selection and aims

Palaeogeographic maps are often built though integration of (legacy) data from various sources (Pierik and Cohen, 2020). Current palaeogeographic reconstructions of the Netherlands (Zagwijn, 1986; Westerhoff *et al.*, 2003; Vos, 2015a) were created with strong focus on the development of river deltas (e.g. Berendsen and Stouthamer, 2000, 2001) and coastal area (e.g. Hijma, 2009; Cohen *et al.*, 2014; Pierik *et al.*, 2017). In contrast, reconstructions of inland peatlands remain uncertain due to limited data on these areas (Spek, 2004; Van Beek, 2009; Vos, 2015a). Increased understanding of their spatiotemporal dynamics is needed to refine representation of these landscapes on the palaeogeographic map series, for development and validation of peat growth models (e.g. Kleinen *et al.*, 2012), and related quantification of their role in past, present and future carbon cycles (e.g. Yu *et al.*, 2011; Erkens *et al.*, 2016). Furthermore, insight in peatland palaeogeography is key to understand (pre)historic human habitation (Van Beek, 2015; Van Beek *et al.*, 2015) and to contextualise exceptional archaeological finds from wetlands (e.g. Chapman *et al.*, 2019; Van Beek *et al.*, 2019). Given the limited understanding on the development of Dutch inland peatlands, we selected a part of the coversand landscape in the Netherlands (fig. 2.2) as case study region, focusing on the northern area (approximately 4,700 km^2). Our research questions within the case study are:

i) Where and when was peat present at the surface in the study area?

ii) In what way does the period of peat initiation differ between landforms and related elevation?

iii) What can be inferred about processes responsible for (inland) peat initiation (and lateral expansion) based on exploratory data analyses?

2.2.6 Case study area

The (northern) coversand landscape (fig. 2.2) is characterised by diverse landforms, enabling peat growth in various geomorphological settings, and is representative for larger parts of the Northwest European Plain considering its surface and shallow subsurface deposits (more information below). The study area contains the coversand landscape stretching from its northern limits down to the rivers Reest and Schoonebeekerdiep as southern borders (fig. 2.2b and 2.2c). Parts of the region belong to a national park, a UNESCO Global Geopark and several Natura 2000 reserves.

During part of the Saalian (MIS 6), the northern Netherlands was covered by a continental ice sheet, leading to deposition of glacial till (Rappol, 1987; Van den Berg and Beets, 1987; Rappol *et al.*, 1989; TNO – Geological Survey of the Netherlands, 2021b).The central part of the study area is known as the Drenthe Plateau or till plateau (Ter Wee, 1972; Bosch, 1990). Meltwater scoured deep valleys east and south of the Drenthe Plateau, the Hunze valley (Bosch, 1990) and palaeo-Vecht valley (Ter Wee, 1966; Bosch, 1990; Kuijer and Rosing, 1994) respectively. The area east of the Hunze valley is also known as the Hunze Plain (Groenendijk, 1997). Here, fluvio(peri)glacial sands were deposited during the Saalian (in this part of the study area glacial till is only sporadically found; Bosch, 1990). In the Weichselian, the Drenthe Plateau became dissected by incising rivers, consequently glacial till is largely absent in river valleys (Klijnstra, 1979). During the coldest phase of the Weichselian coversand was deposited with thicknesses varying from 0.5 – 2 m (Ter Wee, 1979; TNO – Geological Survey of the Netherlands, 2021c). This deposit is present at the surface in the north-eastern, eastern and south-eastern parts of the Netherlands (fig. 2.2c) and the larger European Sand Belt (Koster, 1988, 2005).

Peat deposits in the study area formed both on the low- and high-lying plains (e.g. Casparie, 1972, 1993), in river valleys (e.g. Candel *et al.*, 2017) and in fossil pingos (e.g. De Gans and Sohl, 1981). Based on historical data peat thickness on the plains appears to have reached at least 7 m at some sites (Fochteloërveen, Douwes and Straathof, 2019), maximally 7 m in the largest pingos (Stokersdobbe, Paris *et al.*, 1979), and locally at least 7 m in river valleys that were deeply incised prior to the Holocene (Drentsche Aa river, Candel *et al.*, 2017).

In the northern Netherlands large-scale peatland reclamations took place from the eleventh and twelfth century onwards. These were initiated by monasteries

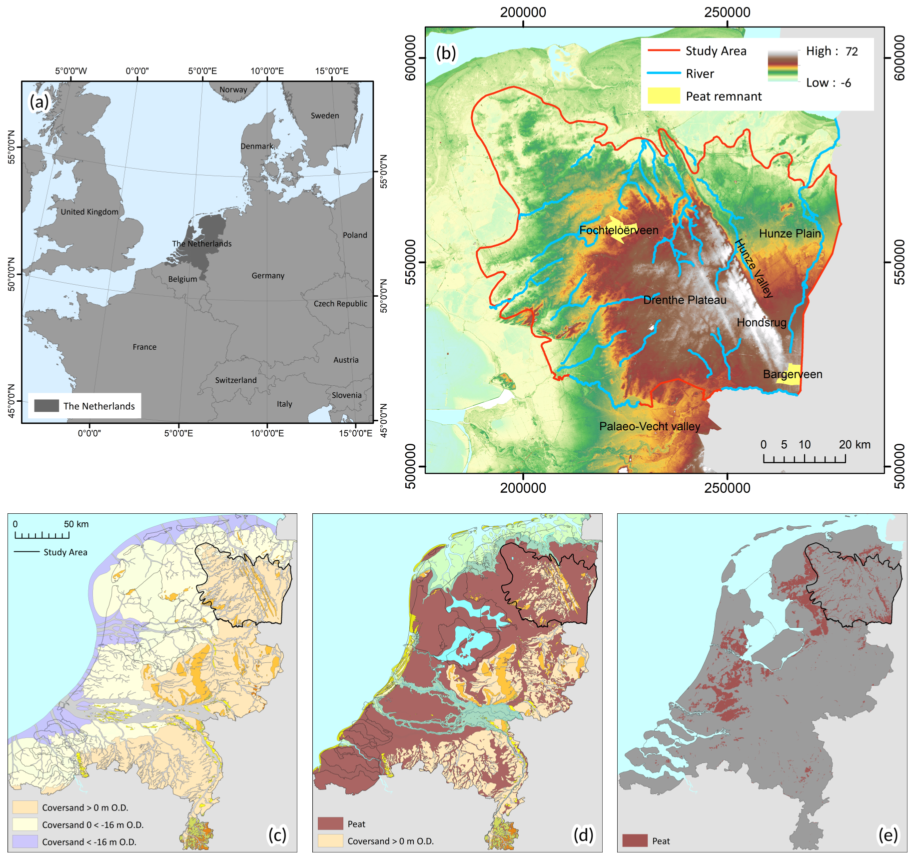

Figure 2.2: *Location and (palaeo)environmental characteristics of the case study region. (a) Location of the Netherlands in Europe. (b) Digital Elevation Model (DEM) of the northern coversand landscape. Elevation is in metres relative to Dutch Ordinance Datum (O.D., roughly mean sea level). Within the study area the present day positions of some of the largest rivers are shown to indicate main drainage directions. The two biggest peat remnants (nature reserves, Fochteloërveen and Bargerveen) are highlighted in yellow. Dataframe coordinates are in metres (Dutch RD-new [*Rijksdriehoeksstelsel*] projection). Position of the study area in the Netherlands is indicated in (c-e). (c) Extent of coversand in the Netherlands. (d) Reconstructed palaeogeography for 2,500 cal y BP, indicating assumed former extent of Dutch peatlands. For peatlands in the coversand region, this view is less certain (see text). Legend was simplified in (c) and (d), full details can be found in Vos and Vries (2013) and Vos* et al. *(2020). In (e) current distribution of peat soils (i.e. containing >20% organic matter) is shown. Sources: DEM of the Netherlands (AHN2; horizontal resolution 5 m, vertical resolution 0.2 m) from Van Heerd* et al. *(2000), AHN (2018); coversand extent and Dutch palaeogeography from Vos and Vries (2013) and Vos* et al. *(2020); rivers in the study area from Ministerie van Verkeer en Waterstaat (2007) Ministerie van Verkeer en Waterstaat (2007); Dutch soil map from Alterra (2014); two largest peat remnants (Natura 2000 areas) from Ministerie van Economische Zaken - Directie Natuur & Biodiversiteit (2018).*

and local landlords, originally for agricultural purposes (Van Beek *et al.*, 2015). From the late sixteenth century onwards commercial-scale peat-cutting for fuel became dominant (Gerding, 1995). As a result only small remnants of the former peat landscapes remain (fig. 2.2d and fig. 2.2e).

2.3 Approach and methods

We propose a workflow for data rescue in geochronological peatland research (fig. 2.3, section 2.3.1), which involves a rigorous quality assessment of legacy data. The rationale of this procedure is threefold:

i) To assist in systematically recording properties of legacy dates, using quantitative information and uniform qualitative categories where possible;

ii) To enable evaluation of data on various quality aspects, either determined by technical aspects of the date, properties of the date related to its landscape position, or both (section 2.3.1.2);

iii) To assign a penalty score to each date based on case-specific weights for quality aspects (section 2.3.1.3). This enables taking data quality into account in subsequent meta-analyses, to test for sensitivity using subgroups of data with different quality levels, and to safeguard robustness of conclusions.

To evaluate the power of the proposed methods, we apply the workflow to a case study, for which we have formulated three research questions on spatiotemporal peatland dynamics (section 2.2.5). For answering these questions, we tailor the proposed workflow as explained in section 2.3.2. Based on the process of data rescue and meta-analysis in the case study we identify research deficits to address during future studies and evaluate the value of data rescue in geochronological peatland research.

2.3.1 Workflow, database set-up and quality assessment

2.3.1.1 Overview of the workflow

The workflow for data rescue and reuse (fig. 2.3) consists of:

i) A database set-up that can be tailored as required by the study scope (table 2.1);

ii) A complementary set of quality criteria with flexible weights to suit specific research questions (table 2.2, see section 2.3.1.3 for more explanation on the use of weights);

iii) A script for automated quality assessment of the recorded legacy data using the weights defined in point (ii), to make the approach suitable for evaluating large legacy datasets.

Based on the literature discussed in section 2.2.4, we propose quality criteria that consider technical aspects of radiocarbon dating and sample selection, while other criteria are concerned with landscape position and taphonomy of the dated material (section 2.3.1.2). A penalty is assigned for traits that are considered negative (table 2.2). To allow automation of the quality screening process, quantitative information is used in the database where possible. Additionally, discrete and Boolean categories were defined that can be used to standardize qualitative descriptions. The quality assessment was scripted in Python, to automatically assign a penalty score to each date.

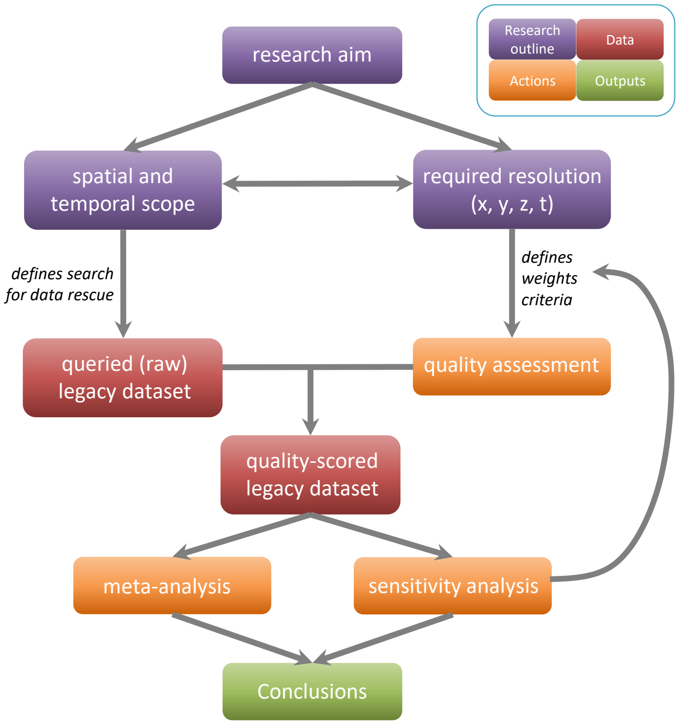

Figure 2.3: *Proposed workflow for data rescue, quality assessment and meta-analysis in geochronological (peatland) research. See legend in upper right for explanation of colours.*

Table 2.1: *Proposed database structure. For all categories 'NR' indicates not retrieved/reported.*

GENERAL	LabCode	Laboratory code as assigned by the lab that conducted the analysis.
	Add LabCode	Any additional lab codes that were assigned to the date.
	DatingTechnique	Either 'beta-counting' (i.e. radiometry) or 'AMS'. As the first AMS measurements were performed in 1977 (see fig. 2.1) all samples analysed before 1977 will automatically be categorised under 'Beta-counting'.
	YearOfDating	Year when the sample was dated by the laboratory. In case a period is given, the earliest year is recorded.
	CopyrightLicense	License under which the data was published (if applicable).
	ConsultedLab [1]	Either 'yes' or 'no' to indicate whether the lab was consulted for additional details on the sample.
	Reference	Original publication(s) that mentioned the date.
	ReliabATOrigPub	Any comments about whether the date was reliable according to its original publication.
	Notes	Any other comments (e.g. whether a lithological or lithogenetic cross-section is available, short description of the definition for basal peat as used by the original publication that mentioned the date).
AGE	14CMean	Reported mean age in conventional ^{14}C years (BP).
	14CSD	Reported standard deviation of the mean age in ^{14}C years.
	ReservoirCorrected14CMean	If applicable and reported, the mean age in ^{14}C years (BP) after applying a reservoir correction.
	CalMean	Reported mean calibrated age in years BCE (Before Common Era) / CE (Common Era).
	CalSD	Reported standard deviation of the mean age in calendar years.
	UnknownMean	Reported mean age, unknown whether the data represent uncalibrated or calibrated ages.
	UnknownSD	Reported standard deviation of the mean age, unknown whether the data represent uncalibrated or calibrated ages.
	Delta13	$^{13}\delta$ value used to correct the dating result for isotopic fractionation.

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Table 2.1 – continued from previous page

	Delta13source	Either 'measured', 'estimated' to indicate whether the reported $^{13}\delta$ value was quantified in the laboratory or that a standard estimate was applied.
	CarbonContent	Measured carbon content (%C) of the dated sample material.
LOCATION	LocationDescription	Description of the location where the sample was taken.
	X [2]	Column listing all X-coordinates in the Dutch RD-new projection, either reported or transformed from reported longitude.
	Y [2]	Column listing all Y-coordinates in the Dutch RD-new projection, either reported or transformed from reported latitude.
	XYuncertainty	Reported uncertainty of measured X and Y coordinates.
	Lat	Column listing latitude, in case location is only reported as geographical coordinates.
	Lon	Column listing longitude, in case location is only reported as geographical coordinates.
	LLuncertainty	Reported uncertainty of measured latitude and longitude, in case location is only reported as geographical coordinates.
	XYcategory [3]	Type of coordinate data; either 'recorded', 'field' or 'placename'.
ELEVATION	DepthBelowSurface	Reported depth of the sample (in case only one number is given) below the surface at the time of sampling, given in cm.
	DepthBelowSurfaceFrom	Reported depth of the upper boundary of the sample below the surface at the time of sampling, given in cm.
	DepthBelowSurfaceTo	Reported depth of the lower boundary of the sample below the surface at the time of sampling, given in cm.
	DepthNAP	Reported depth of the sample (in case only one number is given) in m NAP (Dutch Ordnance Datum, approximately mean sea level).
	DepthFromNAP	Reported depth of the upper boundary of the sample in m NAP (Dutch Ordnance Datum, approximately mean sea level).
	DepthToNAP	Reported depth of the lower boundary of the sample in m NAP (Dutch Ordnance Datum, approximately mean sea level).

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Table 2.1 – continued from previous page

LANDFORM AND STRATIGRAPHY	Landform	Either 'Valley', 'Pingo' 'Depression', 'Peatland (unspecified)', 'Ridge', 'Mound', 'Channel fill', 'Bog (hollow)', or 'Bog (hummock)'.
	Stratigraphy	Either 'Upperlimit', 'Lowerlimit', or 'Within' to indicate whether the sample was taken at the top of the peat layer, the base of the peat layer, or somewhere within the peat layer, respectively.
SAMPLE INFORMATION	SampleThickness [4]	Sample thickness in cm.
	SampleDetails	Any information on the sample material, species, etc.
	SampleContext	Either 'Environmental', 'Artefact' or 'Anthropogenic' (the latter in case of sediment sampled from anthropogenically disturbed contexts).
	SampleMaterial	Peat / Organic / Gyttja / Wood / Charred / Carbonate / *Gliede* (Dutch term used for amorphous organics in peatlands) / Dopplerite.
	MeasuredFraction	Details on measured fraction as provided by the referenced paper for the date.
	SampleType	Either 'bulk' or 'macro' to distinguish between bulk samples and samples consisting of plant macrofossils.
	SpeciesType [5]	In case of a 'bulk' SampleType this automatically becomes 'undefined'. In case of a 'macro' SampleType this column lists either 'terrestrial', 'aquatic', 'both', or 'NR'. Terrestrial and aquatic distinguish between plant species that might be affected by a reservoir effect.
	Aboveground	In case of a 'bulk' SampleType this automatically becomes 'undefined'. In case of a 'macro' SampleType either 'yes', 'no' or 'NR' must be selected to distinguish between seeds/leaves/stems or roots respectively.
	Pretreatment	Either 'ABA' or 'onlyA' to indicate whether the ABA protocol was used or only the first A, respectively.

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Table 2.1 – continued from previous page

1	In case lab data differed from data provided by publications, the lab was followed. For one entry in the case study this led to a major change in the age (GrN-5460, the datelist in which this date is mentioned contains an error).
2	In case no coordinates were provided by the original publications but the field of sampling was indicated, coordinates were retrieved based on georeferenced historical maps where the old field boundaries were indicated. If only a nearby village was mentioned, its central coordinates were registered.
3	These categories may after the quality assessment be replaced by a case-study dependent value, to be used as uncertainty range in further analyses (e.g. 'field' might be replaced by an uncertainty value of 100 m).
4	In case no sample thickness was retrieved, a default sample thickness can be defined after the quality assessment to use in further analyses.
5	To determine whether terrestrial or aquatic plants were used for dating the species was looked up in the Dutch online encyclopaedia of species (Soortenbank.nl, 2020). Samples that consisted of *Sphagnum* mosses that lacked further information on terrestrial or aquatic growth habit were listed as 'Undefined'.

Table 2.2: *Criteria used in the quality assessment, based on the categories listed in table 2.1. Numbers written below the header 'Criteria' indicate penalty size or disqualification for further analyses. Empty cells indicate that for this property a specific criterion level is not applicable. Subscores are calculated by multiplying weight times penalty.*

Category	Property	(Case-specific) weight	Criteria				Subscore dating penalty (Q_d)	Subscore taphonomic penalty (Q_T)	Total penalty score (Q)
			0	+1	+2	Disqualified			
AGE	Mean and SD	10	Mean and standard deviation are reported in radiocarbon years.	Only calibrated data are reported, or SD in radiocarbon years is missing.	Unknown whether data are reported in radiocarbon or calendar years.	A sample was dated but the age was not retrieved.	Q_{d1}		
	Delta13	5	$^{13}\delta$ value is reported based on measurements.	$^{13}\delta$ value is reported but was estimated.	No information on $^{13}\delta$ was retrieved.		Q_{d2}		
	Carbon content	2	Carbon content was reported.		Not retrieved.		Q_{d3}		
LOCATION	X, Y	9	Reported at site level (6-number RD-coordinates; degrees, minutes and seconds for geographic coordinates).	Reported at field level (3-number RD-coordinates; degrees and minutes for geographic coordinates).	Reported at village level.	Location was not retrieved.		Q_{T1}	
ELEVATION	Elevation	8	Reported in m. O.D.	Reported in m. relative to (former) surface.	Not retrieved.			Q_{T2}	
LANDFORM AND STRATIGRAPHY	Landform	6	Landform was described or clear from context.		Landform where sample was collected was not retrieved.			Q_{T3}	
	Stratigraphy	7	Stratigraphical position of sample was clear from text and/or geological cross sections and allows to distinguish between top/middle/bottom of peat layer.		Stratigraphical position of sample was not retrieved.			Q_{T4}	
SAMPLE DETAILS	SampleThickness	2	Sample thickness was reported.		Sample thickness was not retrieved.			Q_{T5}	
	SampleType	5	Macrofossil (AMS dating).	Bulk sample (AMS or conventional dating).	Not retrieved.		Q_{d4}		
	SpeciesType	5	Sample consisted of material from terrestrial species.	Sample consisted of material from aquatic species, or both terrestrial and aquatic.	Undefined (i.e. in case of a bulk sample) or not retrieved.		Q_{d5}		
	Aboveground	5	Yes, aboveground sample material (no roots).	No, (also) belowground sample material (i.e. including roots).	Undefined (i.e. in case of a bulk sample) or not retrieved.		Q_{d6}		
	Pre-treatment	5	Robust (ABA).	Gentle (A only).	No pre-treatment applied or not retrieved.		Q_{d7}		
SUM							$Q_d = \sum_{i=1}^{7} Q_{\text{di}}$	$Q_T = \sum_{i=1}^{5} Q_{\text{Ti}}$	$Q = Q_d + Q_T$

2.3.1.2 Quality criteria

2.3.1.2.1 Definition of quality

For constructing the quality assessment one has to decide what quality means, and for which properties it must apply. According to the Cambridge Dictionary (2020), quality means 'how good or bad something is' or 'a characteristic or feature of [...] something'. Both definitions are used in our quality assessment (see below).

When considering radiocarbon dates of peat layers, each date's quality may be assessed for its *dating quality* (Q_d) and *taphonomic quality* (Q_T). *Dating quality* refers to technical aspects of the radiocarbon date, i.e. sample characteristics and the way it was processed in the lab. *Taphonomy*, a term originating from palaeontology, is the science on how materials (or fossils) become embedded in their surroundings (e.g. Martin, 1999). The *taphonomic quality* therefore refers to characteristics of where the sample came from, e.g. its location and stratigraphical position. The degree to which a radiocarbon date represents the event of interest is determined by its dating and taphonomic quality. Both Q_d and Q_T are determined by the approach and methods that were followed by the researchers from the original study the date was obtained from. Fig. 2.4 provides a visualisation of the effects of methodology on the resulting Q_d and Q_T. As dating approaches were tailored to answer a particular research question (with a certain required level of certainty), Q_d and Q_T may diverge for radiocarbon dates originating from different studies.

In textbook examples where a bullseye is used to illustrate accuracy and precision, these concepts usually apply to a set of replicate measurements. Note that in fig. 2.4 and the explanation above, Q_d and Q_T apply to the accuracy of a single measurement (i.e. the degree to which a date represents the true age of the event of interest), and that precision (i.e. degree to which replicate measurements lead to the same result) is not indicated in fig. 2.4. The possibility to replicate a date is however fully dependent on the information contained in Q_d and Q_T, therefore a high penalty score for Q_d and Q_T will most likely result in low precision (e.g. if location is poorly known, attempting a replicate measurement cannot be performed with a high precision).

To ensure accuracy and robustness of conclusions derived from meta-analyses, quality assessment may provide insight in sources of error and allows to expand data analyses based on subsets of data with increasing uncertainty. To make the quality assessment flexible to answer a variety of research questions, we have created an adaptable, twofold approach. First, each date is evaluated for aspects that are considered negative (i.e. in line with the abovementioned definition 'how good or bad something is') for which penalties are assigned (for comparable approaches see e.g. Small *et al.*, 2017). For instance, a bulk sample is considered less reliable

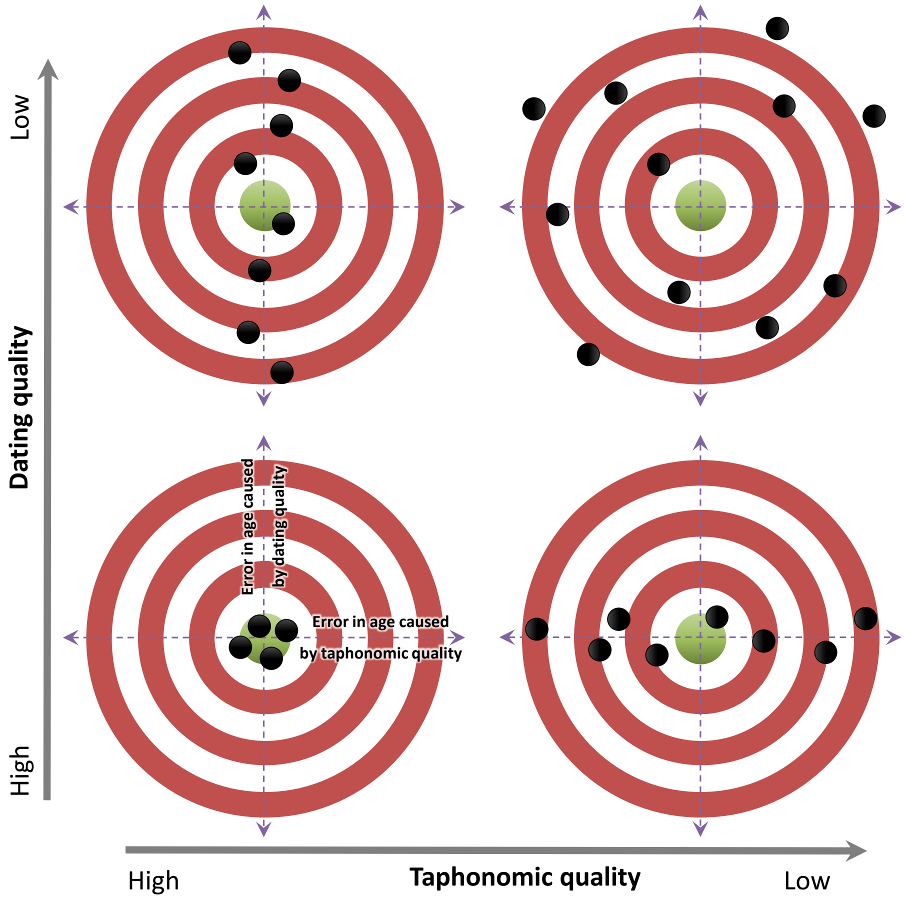

Figure 2.4: *Effect of methodology (dating and taphonomic quality) on representation of the true age of the event of interest (bull). The distance to the bull indicates how robust a date is, i.e. the degree to which the date corresponds with the true age of the event of interest. Note that multiple black dots (i.e. potential dating results) were drawn for the purpose of illustrating the effect of dating quality and taphonomic quality, whereas in reality they apply to a single measurement. In case of the lower left for example, the approach ensures a sample is collected from the right position (e.g. location, elevation, stratigraphical level), and strict methods are applied with regard to sample selection and laboratory procedures. With low dating and/or taphonomic quality, dates will deviate more from the true age of the event of interest. Our approach aims at attributing penalties to those dates in the quality assessment, as a way to characterise their trustworthiness and usefulness to answer a specific research question.*

than a plant macrofossil sample (Törnqvist *et al.*, 1992, 1998). Second, each date is assessed on the availability of information that allows to make informed choices with regard to data-analysis (i.e. 'a characteristic or feature of something'). In case of missing information or a low level of detail, a penalty is assigned. In this case the focus is not on the implication of the property (for instance, the location itself is not judged), but on knowledge *about* the property (do we know location well or not). Depending on the information that is available (and the resulting penalty score), data may be filtered prior to data-analysis (for example first including only sites with well-known location, then analysing the sites with uncertain location as well). This allows a purposeful assignment of dates to various analyses.

2.3.1.2.2 Design of the quality criteria

Age

This category contains criteria for three properties: *Mean and SD*, *Delta13*, and *Carbon content* (table 2.2). The property *Mean and SD* distinguishes the way in which the age is retrieved. Radiocarbon measurements are reported in BP, which require calibration to calendar years. For (re)calibration the original date in BP with its standard deviation is required. The property *Delta13* measures deviations caused by isotopic fractionation and differentiates whether $\delta^{13}C$ was measured, estimated in the original work or unknown (i.e. not reported). Carbon content refers to the %C of the ^{14}C sample after laboratory pre-treatments and is either measured or unknown.

The quality assessment does not distinguish between samples that were dated with radiometry or AMS. Both measure the $^{14}C/^{12}C$ ratios using the same reference sample and background materials; it is the sample size that makes the difference (Lanting and Van der Plicht, 1994). The sample size is included in the quality assessment as a property under *Sample Details* through *SampleType*.

Location

This category contains the combined property *X, Y*. The criteria are concerned with the level of detail regarding the location of the dated material and distinguish between recorded coordinates, field level or place names. If relevant for the research questions to be answered, these categories may be replaced by a case-study dependent value, to be used as uncertainty range in further spatial analyses (e.g. 'field' could be replaced by an uncertainty value of 100 m).

Elevation

This category contains one property of the same name, and relates to the level of detail regarding the elevation of the dated material. This can either be known relative to O.D., relative to the (former) land surface, or not retrieved.

Landform and Stratigraphy

This category contains *Landform* and *Stratigraphy* as two properties, each distinguish whether these properties were clear from the context of the date as provided by its source. If clear, filtering after the quality assessment allows for the selection of samples e.g. from specific stratigraphic positions, such as basal peat layers. Note that only if information on landform and stratigraphy was retrieved with the date, the information was registered and available for further analyses. We did not deduce landform from sample location (for some studies attempting legacy data analyses this might be an interesting option, depending on the level of detail of retrieved coordinates).

Sample Details

For this category five properties were included: *SampleThickness*, *SampleType*, *SpeciesType*, *Aboveground* and *Pre-treatment*. *SampleThickness* distinguishes whether thickness was reported or not. If thickness has consequences for the research questions to be answered, filtering after the quality assessment allows selection of samples of certain thickness ranges.

Based on the recommendation to date short-lived, aboveground plant macrofossils of terrestrial species (e.g. Törnqvist *et al.*, 1992; Piotrowska *et al.*, 2011) we have formulated the criteria for *SampleType*, *SpeciesType*, and *Aboveground*. *SampleType* differentiates macrofossil samples (dated with AMS) and bulk samples (mostly conventional dating) and implicitly contains information about sample size (mentioned above under Age). *SpeciesType* is concerned with the habitat of the organism(s) that were sampled, either terrestrial species, aquatic species, both, or undefined (i.e. in case of a bulk sample). The property *Aboveground* refers to whether only aboveground plant remains were present in the sample material (no roots) or that belowground tissues were also included (presence of roots leads to incorporation of younger carbon, e.g. Törnqvist *et al.* (1992). For bulk samples this automatically becomes undefined.

Pre-treatment distinguishes the preparatory protocols applied in the radiocarbon laboratory prior to measurement. This can either be robust pre-treatment (ABA, Acid-Base-Acid), a gentle one (A only), or none. The question to opt for A or ABA is closely connected to the %C parameter. Contaminations (such as mobile humic acids) are most adequately removed by a robust pre-treatment. However, when the amount of sample material is limited a gentle (or no) pre-treatment may be applied to ensure preservation of sufficient material for dating.

2.3.1.3 Weights in the quality assessment and interpretation of penalties

For each data entry, the taphonomic quality Q_T and dating quality Q_d are calculated using the quality criteria and (case-specific) weights listed in table 2.2. In case a specific criterion is irrelevant for the research questions to be answered, it can be assigned a weight of zero and will then no longer be considered. Depending on the case study and research aims weights may be adapted to tailor the quality assessment.

The total penalty score Q results from the sum of Q_T and Q_d. Q is normalized to 1, i.e. the minimum value is 0 (no penalties, reflecting highest quality) and the maximum possible value is 1 (poorest quality). Due to this normalization the maximum values of Q_T and Q_d are always below 1 and do not need to be equal, as they depend on the chosen weights. For instance, in our case study (section 2.3.2) the weights listed in table 2.2 are used which results in maximum values of Q_T and Q_d of 0.464 and 0.536 respectively. The normalized Q_T, Q_d and Q values may be used as such, or may be converted to four confidence levels based on user-determined cut-off values for Q_T and Q_d, defined by $Q_{T,lim}$ and $Q_{d,lim}$ (table 2.3).

Table 2.3: *Definition of the four confidence levels*

Confidence level	**Definition**		
Low Q_T, low Q_d (best)	$0 \leq Q_T < Q_{T,lim}$	AND	$0 \leq Q_d < Q_{d,lim}$
High Q_T, low Q_d	$Q_{T,lim} \leq Q_T \leq Q_{T,max}$	AND	$0 \leq Q_d < Q_{d,lim}$
Low Q_T, high Q_d	$0 \leq Q_T < Q_{T,lim}$	AND	$Q_{d,lim} \leq Q_d \leq Q_{d,max}$
High Q_T, high Q_d (worst)	$Q_{T,lim} \leq Q_T \leq Q_{T,max}$	AND	$Q_{d,lim} \leq Q_d \leq Q_{d,max}$

2.3.2 Application of the workflow to a case study

2.3.2.1 Case study: Data rescue and quality assessment

The data search scope was determined by the spatial definition of the study area presented above (fig. 2.2). All acquired dates were recorded irrespective of their measured radiocarbon age (no restrictions in time period were applied during the search phase). Data originate from 1955 to 2019 and stem from a wide variety of environmental and archaeological studies, including scientific literature, books and reports from contract-based archaeology. We used the database set-up of table 2.1 and recorded dates from peat layers (i.e. excluding dated archaeological artefacts originating from peat layers).

The majority of retrieved dates were performed by the radiocarbon facility of Groningen University (Centre for Isotope Research and its predecessors). The history of this laboratory is shown in fig. 2.1. Developments are also reflected in labcodes, moving from GRO and GrN (conventional measurement) to GrA (AMS) and GrM (AMS-MICADAS). Data registration changed along with these transitions, resulting in three large archives that evolved from hardcopy to semi-digital and now fully digital (Van der Plicht, 1992; Van der Plicht and Streurman, 2018). Consequently, data retrieval required both digital querying and hardcopy searching.

2.3.2.2 Case study: Meta-analysis

To answer the case study research questions (section 2.2.5), the quality assessment was adapted by choosing appropriate weights for the criteria. Subsequent meta-analysis of the resulting assessed dataset included three main elements: large-scale trends in peat initiation, trends for different landforms (and elevations), and a comparison between peat initiation trends with sea level and climate. More details are provided below.

We chose the criteria weights listed in table 2.2. In this way, the penalty contribution of each criterion is ordered based on the qualities we consider most important to answer the case study research questions. For these questions age and location are crucial, followed by elevation, stratigraphy and landform. To prevent qualities from becoming irrelevant, we kept the difference in weight between criteria relatively small. Based on the penalty scores each date was assigned to one out of four confidence levels based on the definitions listed in table 2.3, where $Q_{T,lim}$ and $Q_{d,lim}$ were set at 50% of their respective maximum values.

After completing the quality assessment filtering was applied based on (1) confidence level, (2) *Stratigraphy* (to select only basal peat dates), (3) *SampleMaterial* (to distinguish peat initiation processes, explained below), and (4) *Landform* (to derive landform-specific age trends). For analyses on the relationship between age and elevation, we calculated elevation relative to m O.D. for samples that were only retrieved with depth to the (former) surface. To this end, we derived the surface elevation from the DEM and subtracted the sample depth. For basal dates, elevation is not affected by compaction effects. Dates from within the peat or the top might be affected by compaction effects. However, as we only used these data for a general overview of the elevation range from which samples were retrieved, they were not corrected for compaction.

All ages were (re-)calibrated in OxCal (version 4.4, Ramsey, 1995, 2009) using IntCal20 (Reimer *et al.*, 2020). To analyse trends of peat initiation dates of basal peat layers (i.e. entries registered with stratigraphy 'lowerlimit') were selected and summarised using kernel density estimation (KDE) with the KDE_Model function in OxCal (Ramsey, 2017). To test model outcome for sensitivity to previously assessed data quality, the data subsets from the four confidence levels (fig. 2.5)

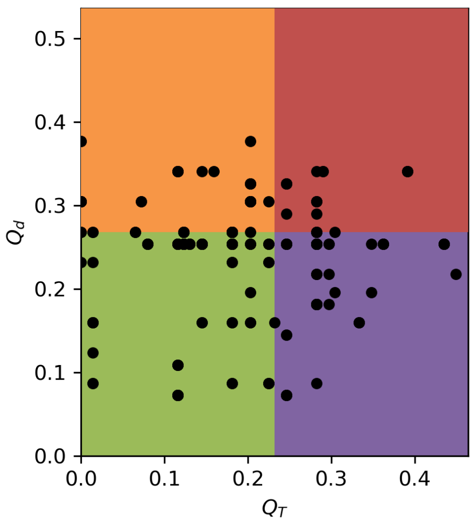

Figure 2.5: *Overview of the quality assessment of the case study dataset (n = 313), showing resulting Q_d and Q_T values for each data point (note that some points overlap). Limits of the confidence levels are defined in table 2.3, with $Q_{d,lim}$ and $Q_{T,\text{lim}}$ set at 50% of their respective maximum normalized values. The coloured quadrants indicate the four confidence levels that were used in subsequent data analyses.*

Table 2.4: *Chronostratigraphy as used in this paper. The Pleniglacial started before 55,000 cal years BP, i.e. the upper limit of IntCal20 (which matches the measurement limit of ^{14}C, ca. 50,000 BP).*

Period	From (cal years BP)	To (cal years BP)
Subatlantic	0	2,400
Subboreal	2,400	5,660
Atlantic	5,660	9,220
Boreal	9,220	10,640
Preboreal	10,640	11,560
Late Glacial	11,560	14,650
Pleniglacial	14,650	>55,000

were added to the model in separate runs and outcomes compared.

To derive spatiotemporal insights on peat initiation, data were plotted in GIS (ESRI's ArcMap, version 10.6) using the chronostratigraphy shown in table 2.4. To assign dates to the listed periods the μ value of the calibration was used for simplicity (i.e. instead of the 2σ age range). Similarly, μ was used to construct age-elevation plots.

To determine which peat initiation process (terrestrialisation, primary mire formation or paludification) was responsible for peat formation at a specific site, the

Table 2.5: *Classification of SampleMaterial to derive peat initiation process.*

Peat initiation process	**SampleMaterial filter**	**Green confidence level, n:**	**All confidence levels, n:**
Terrestrialisation	Gyttja	5	6
Either primary mire formation or paludification (indistinguishable)	*Gliede* (Dutch term used for amorphous organics in peatlands) Peat Wood	43	64
Paludification	Charred	2	4

sediment underlying basal peat often provides indications (Ruppel *et al.*, 2013). Typically, peat from terrestrialisation is underlain by lake sediments such as gyttja. Primary mire formation starts on inorganic sediment where fresh parent material is exposed, whereas paludification occurs on inorganic sediment where soils have formed through time, sometimes with litter layers of past vegetations. Unfortunately, information on soil horizons underlying peat deposits is limited for our case study data. To determine the prevalence of these three processes in the study area, we therefore assigned basal peat dates to each initiation process based on registered *SampleMaterial* (table 2.5).

2.4 Results

2.4.1 Data rescue for case study region

We compiled a dataset consisting of 313 legacy radiocarbon dates. The majority of retrieved dates indicates peat layers of Holocene age (85%), but also Late Glacial and Pleniglacial ages are represented (fig. 2.6a/c). Ages of the Subboreal (37%) and Atlantic (29%) periods are by far most frequent (fig. 2.6b), followed by the Late Glacial (14%) and Subatlantic (10%). Comparison of the reconstructed extent of peatlands (on the current palaeogeographical map series) and the spatial distribution of legacy data points shows that several large areas are underrepresented in the dataset (fig. 2.6a). Precision regarding the locations where the dated samples were collected appeared to be mixed (fig. 2.6e), with most sites only known at field level (52%; error range in order of 100 m). For only 21% the location was retrieved based on registered coordinates (the most detailed location description), while for 27% only the place name of the nearest village was retrieved (error range in order of 1 km).

2.4.2 Quality assessment

Based on the values for Q_d and Q_T, every date was subsequently assigned to one of four confidence levels (table 2.3, fig. 2.5). For green dates both Q_d and Q_T were fairly low, meaning that sufficient information is available regarding dating aspects and taphonomic characteristics. On the opposite side, red dates have high penalty scores for Q_d and Q_T indicating that information for these dates is very limited. Orange dates have sufficient information regarding taphonomy but lack detail regarding dating aspects, and vice versa for purple dates.

fig. 2.6b and fig. 2.7 provide an overview of the years when dates were performed, geographic focus through time, and relationship with assessed quality. In the initial stages of radiocarbon dating several studies applied the method for dating peat layers in the study area (fig. 2.7a). During the 1960s and 1970s numbers dropped, followed by a revival during the 1980s when several detailed peat studies were conducted. It appears that in the 1990s less peat dates were performed, however some large studies were published that were (partly) initiated in the 1980s (e.g. Groenendijk, 1997; Van Geel *et al.*, 1998). This relates to certain geographic foci (fig. 2.6b), e.g. the eastern part of the province of Groningen (Groenendijk, 1997), and the Bargerveen (Dupont, 1986) and Fochteloërveen (Van Geel *et al.*, 1998) peat remnants. The majority of retrieved dates were performed in the 2000s, with a main focus on the northern and north-western parts of the study area. Data quality does not show a strong trend over time (fig. 2.7b), indicating that year of dating is not necessarily indicative for quality. However, samples from the 2010s received on average the lowest penalty for taphonomic quality (Q_T).

2.4.3 Meta-analysis

2.4.3.1 Large-scale trends of peat initiation

To deduce spatiotemporal trends in peat initiation, we focused analyses on dates from basal peat layers only (n = 74, see 'lower limit' in fig. 2.6d). The estimated

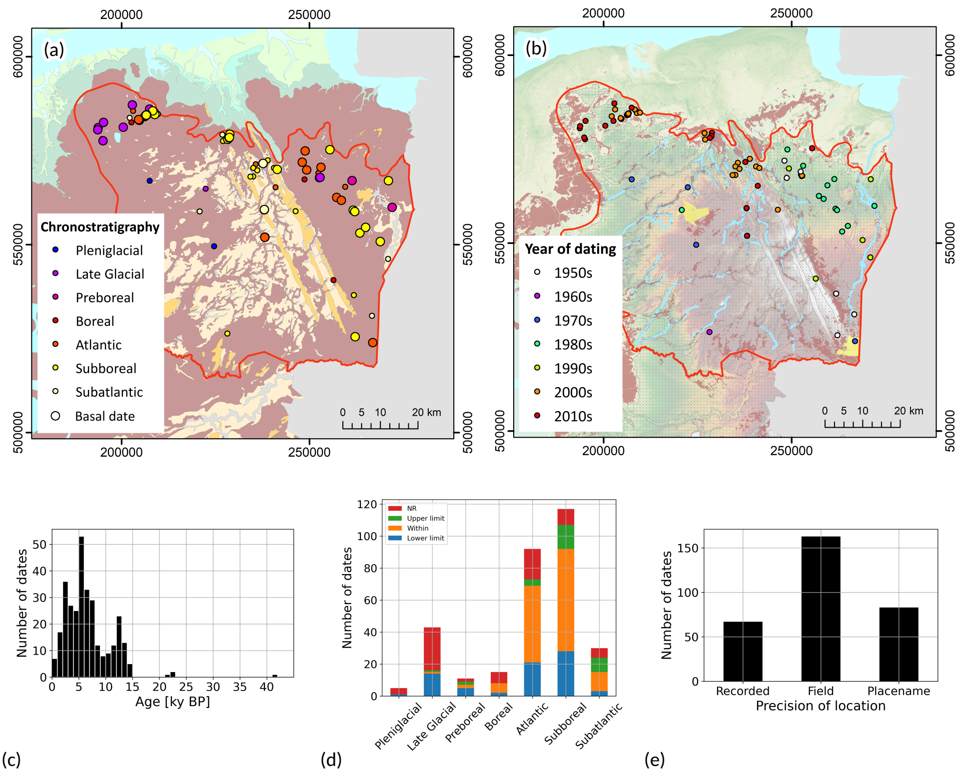

Figure 2.6: *Overview of age and location of case study legacy data points (n = 313). (a) Locations of data points binned based on chronostratigraphy, using definitions listed in table 2.4. Uncertainty of locations (see text) not shown for legibility. Do note that several data points overlap (i.e. multiple samples collected at (nearly) the same location). Basal peat date means stratigraphical position is 'lower limit'. Background map shows the reconstructed palaeogeography of the Netherlands for 2,500 cal y BP (also see fig. 2.2c). (b) Location of data points binned per decade when the date was performed. See legend in fig. 2.2b for other map elements. (c) Histogram of calibrated radiocarbon dates. (d) Histogram of chronostratigraphy. (e) Histogram showing precision classes for retrieved locations.*

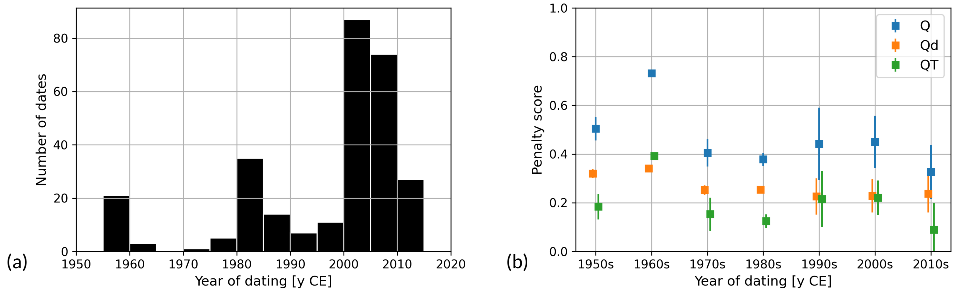

Figure 2.7: *Overview of years when dates were performed (i.e. between 1950s and 2020). (a) Histogram of data points per 5-year period. (b) Assessed quality (Q, Q_d, Q_T) averaged per decade.*

distribution of these ages is shown in fig. 2.8a to fig. 2.8c, based on green dates with applied filter for aboveground remains of terrestrial macrofossils (n = 12), green dates without filtering applied (n = 50), and dates from all confidence levels combined (n = 74) respectively. The distribution in fig. 2.8a shows a clear bimodal distribution, with peaks at about 14,000 cal y BP (Late Glacial) and 4,500 cal y BP (Subboreal). This trend is still visible in fig. 2.8b, while the largest dataset of fig. 2.8c reveals additional peaks around 11,500 cal y BP (Preboreal) and 6,500 cal y BP (Atlantic). All models show a clear low at 9,500 cal y BP (Boreal). Models of green plus orange confidence level data and green plus purple were also modelled and gave intermediate outcomes (not shown).

Based on the available information, most peat initiation sites appear to result either from primary mire formation or paludification (table 2.5). However, one would expect the number of terrestrialisation sites to be larger, as 19 dates were collected in topographic depressions such as pingos (table 2.6, apparently gyttja was only found/sampled at some of the pingo sites). As the study area has been deglaciated since the penultimate glacial, all land in this region has been exposed for the past 130,000 years. Paludification was therefore probably the dominant peat formation process in the study area.

2.4.3.2 Peat initiation trends for different landforms and elevations

We grouped landforms into four categories (table 2.6). Both for green confidence level dates and dates from all confidence levels combined KDE models were constructed (fig. 2.9, showing only models from all confidence levels combined). Too little data were available to model only green confidence level dates that were filtered for aboveground terrestrial macrofossils. The distribution for 'Peatlands (unspecified)' in fig. 2.9c shows two peaks similar to model outcomes in fig. 2.8.

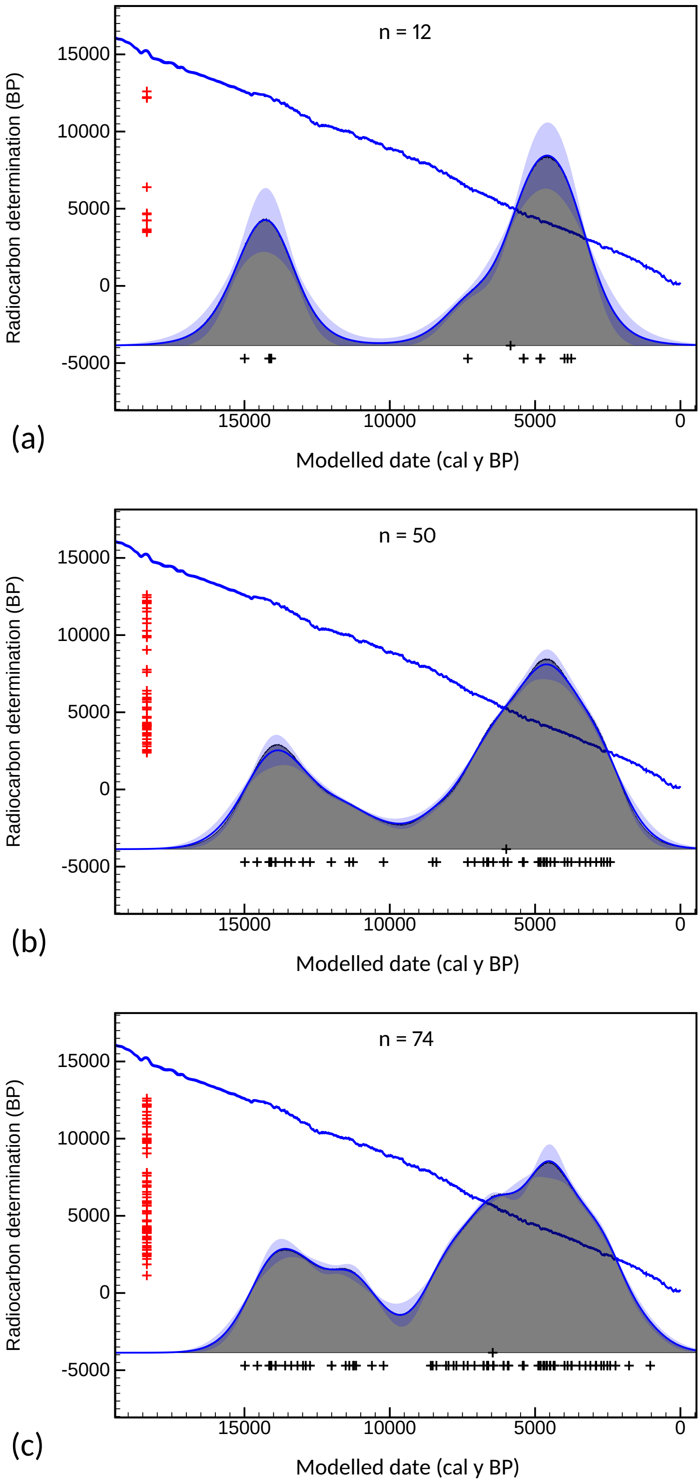
n = 12
Radiocarbon determination (BP)
15000
10000
5000
0
-5000
15000
10000
5000
0
Modelled date (cal y BP)
(a)
n = 50
Radiocarbon determination (BP)
15000
10000
5000
0
-5000
15000
10000
5000
0
Modelled date (cal y BP)
(b)
n = 74
Radiocarbon determination (BP)
15000
10000
5000
0
-5000
15000
10000
5000
0
Modelled date (cal y BP)
(c)

Figure 2.8: *(Figure on previous page). Outputs of KDE models for basal peat ages in the case study dataset. Results are based on model runs of basal ages with (a) green confidence level that were based on aboveground remains of terrestrial macrofossils (n = 12), (b) dates with green confidence level with no further filtering applied (n = 50), (c) all confidence levels combined (n = 74). The dark grey area indicates the sampled KDE estimated distribution. The blue line shows the mean of the KDE distribution, the lighter blue band shows the $\pm 1\sigma$ range. The red crosses show the central values for the entered dates, the black crosses show the medians of the marginal posterior distributions for every dated event. The calibration curve is indicated for reference (Reimer* et al., *2020).*

For these samples the palaeo-landform underlying the organic deposits was unclear (i.e. could not be retrieved from the date's reference). Samples from 'Plains and ridges' (fig. 2.9d) appear to be of younger age, overlapping only with the second peak in the bimodal distributions of fig. 2.8. The model for 'Topographic depressions' (fig. 2.9e) results in a multi-peak distribution that does not show a clear age trend. Samples from 'Valleys' (fig. 2.9f) result in a wide distribution with two small peaks, covering the Late Glacial and entire Holocene. The model for 'Plains and ridges' was also run with samples of all stratigraphical positions, as a way to validate that the basal ages are always oldest, and that retrieved dates that were indicated to originate from higher stratigraphical positions are indeed younger (fig. 2.9g).

Age-elevation plots were constructed for basal peat samples (fig. 2.10c, n = 73) and for samples from all stratigraphical positions (fig. 2.10d, n = 302). Basal peat samples from topographic depressions mostly date from before 6,000 cal y BP. Valleys are located both at lower and higher positions and have ages crossing the Late Glacial and entire Holocene (fig. 2.9f), with high-lying locations being youngest (fig. 2.10c). Basal dates from plains all date from after 6,000 cal y BP. Basal dates from low-lying plains ($\leq$0 m O.D.) fit the Relative Sea Level (RSL) curve for the Wadden Sea (fig. 2.10c, Meijles *et al.*, 2018). Basal peats from the high-lying plains (between 5 and 10 m O.D.) are all younger than 5,000 cal y BP. When plotting data from all stratigraphical positions (not only basal dates, fig. 2.10d), several lines are visible in the data, which represent vertical series of dates from certain peat cores (i.e. in stratigraphical order). The linear slope of these lines indicates the vertical accumulation speed, which lies between 0.35 - 0.57 mm/y. As elevations from non-basal dates were not corrected for potential compaction issues, these lines indicate only the minimum accumulation speed.

Table 2.6: *Landform groupings, specifying applied landform filter and number of dates with green confidence level and all confidence levels combined (only basal dates).*

Landform grouping	Landform filter	Green confidence level, n:	All confidence levels, n:
Peatlands (unspecified)	Peatland (unspecified)[1] Bog (hummock)[1] Bog (hollow)[1]	17	17
Topographic depressions	Pingo Depression[2]	15	19
Plains and ridges	Plain Mound Ridge	9	9
Valleys	Valley Channel fill	8	24

[1] Dates from studies that did not contain information on underlying landform.
[2] Topographic lows such as deflations in coversand.

2.5 Discussion

Here we first discuss the main findings of the case study, followed by experiences regarding data retrieval, representativity of the resulting dataset, and effect of the quality assessment. Based on this we evaluate the proposed workflow.

2.5.1 Case study

2.5.1.1 Main findings on peatland development

The legacy dataset indicates peat initiation in the study area from at least the Late Glacial onwards (fig. 2.6). KDE model results show a bimodal distribution of basal peat dates, with a first peak during the Late Glacial, a low in the Boreal period, followed by a rise starting in the Atlantic and finally a peak during the Subboreal (fig. 2.8). The majority of data points is located in the northern half of the study area. Here, several spatial clusters indicate areas with simultaneous peat initiation, e.g. during the Atlantic and Subboreal in the east of the province of Groningen (Groenendijk, 1997).

When considering peat initiation for landform groups, several trends can be distinguished (fig. 2.9). Onset of peat growth took place during the Late Glacial

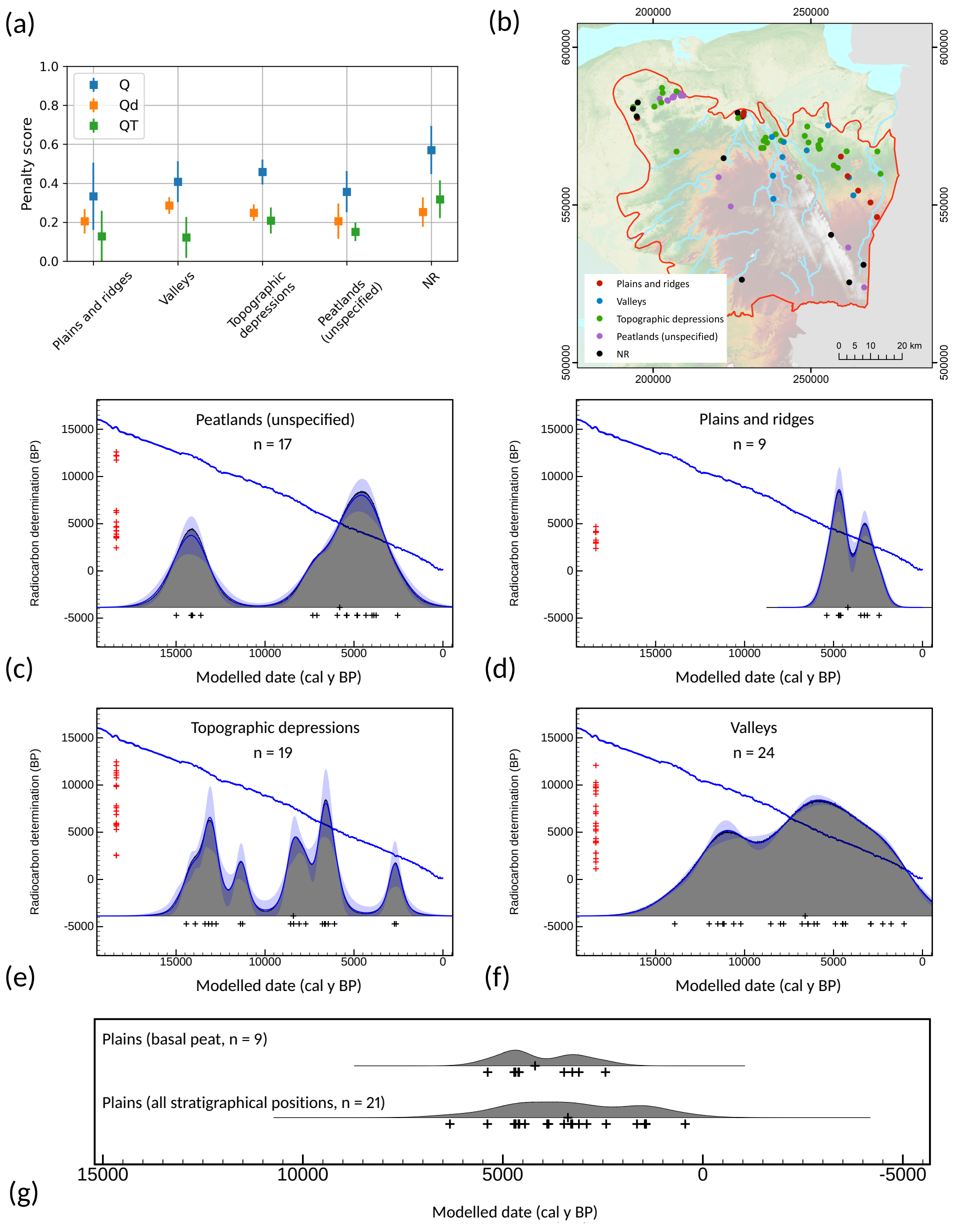

Figure 2.9: *Overview of landform data. (a) Assessed quality (Q, Q_d, Q_T) averaged per landform. (b) Locations of data points binned based on landform grouping (table 2.6). Do note that several data points overlap (i.e. multiple samples collected at (nearly) the same location). (c-f) KDE models of peat initiation per landform grouping (detailed in table 2.6, for interpretation of KDE plots see caption fig. 2.8). Results are from model runs where dates from all confidence levels were included. (g) Comparison of model outcomes for landform type 'Plains and ridges' when only basal dates are included versus dates from all stratigraphical positions.*

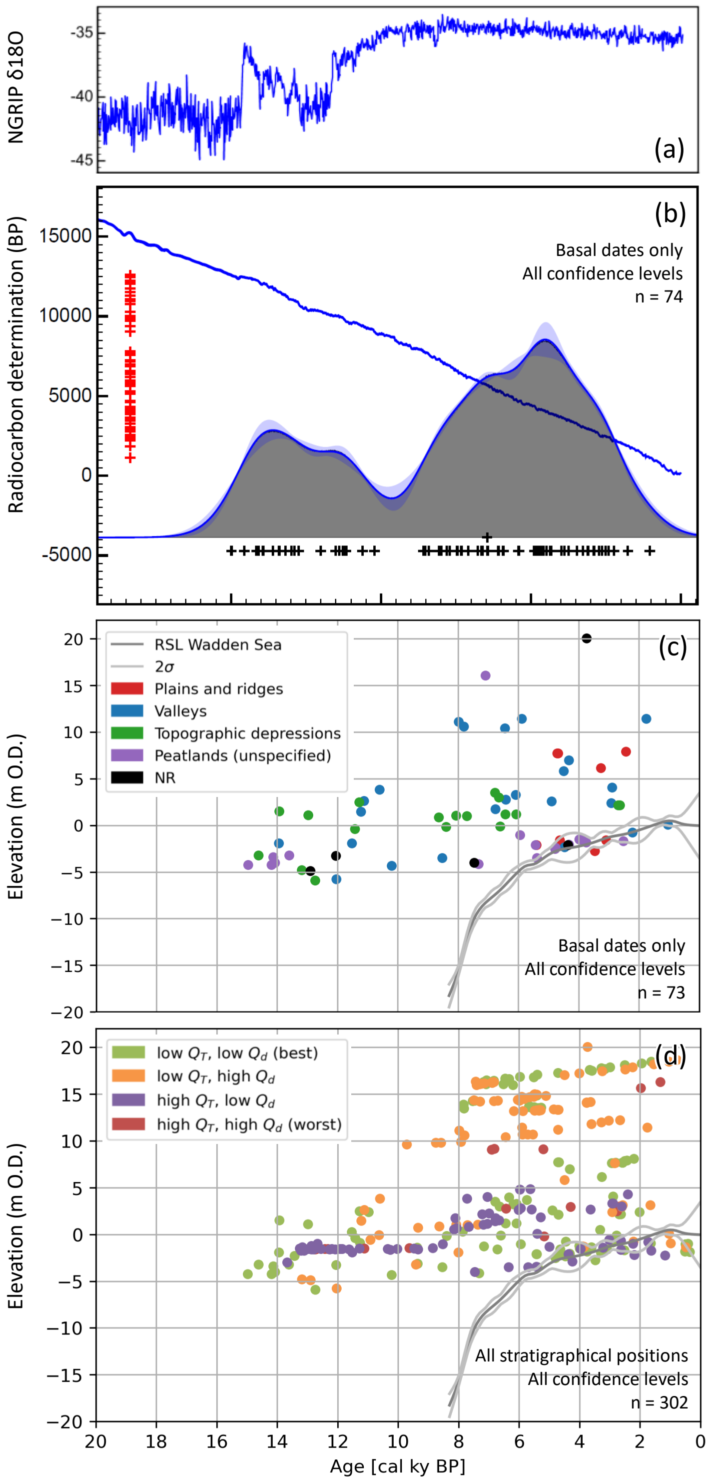
NGRIP δ18O
-35
-40
-45
(a)
Radiocarbon determination (BP)
15000
10000
5000
0
-5000
(b)
Basal dates only
All confidence levels
n = 74
Elevation (m O.D.)
20
15
10
5
0
−5
−10
−15
−20
RSL Wadden Sea
2σ
Plains and ridges
Valleys
Topographic depressions
Peatlands (unspecified)
NR
(c)
Basal dates only
All confidence levels
n = 73
low Q_T, low Q_d (best)
low Q_T, high Q_d
high Q_T, low Q_d
high Q_T, high Q_d (worst)
(d)
All stratigraphical positions
All confidence levels
n = 302
20
18
16
14
12
10
8
6
4
2
0
Age [cal ky BP]

Figure 2.10: *(Figure on previous page). Comparison of peat initiation data with $\delta^{18}O$ and sea level rise curves. In (a) the $\delta^{18}O$ curve is shown (GICC05 NGRIP $\delta^{18}O$ data accessed through OxCal). The bimodal distribution of peat initiation dates (including all confidence levels), is shown in (b), see fig. 2.8c for details. In the age-elevation plot in (c) only basal peat dates are included (n = 73, note in (b) n = 74, i.e. for one date no elevation data is available). Data points are coloured by landform. In (d) peat dates from all stratigraphical positions are shown (n = 302), data points are coloured by confidence level. Note that sample elevation in (d) for non-basal dates is only indicative as it was not corrected for potential compaction effects. The RSL curve (data from Meijles* et al. *(2018) was added to (c) and (d). The data points that were used by Meijles* et al. *(2018) to generate the RSL curve are not part of our case study dataset.*

and entire Holocene in river valleys, whereas it started on plains and ridges only during the Subboreal. In topographic depressions peat initiation was rather erratic through time. For sites with unclear palaeo-landform underlying the organic deposits ('Peatlands (unspecified)'), peat initiation follows the bimodal distribution mentioned earlier. Age-elevation plots show a general trend that peat growth started earliest at the lowest locations, and reaches higher positions later in time (fig. 2.10).

Our analyses point to changes in several boundary conditions that, either alone or in combination, may have led to peat initiation (and lateral expansion). The first peak of the bimodal distribution coincides with the Bølling-Allerød interstadial, and ends with the onset of the Younger Dryas (figs. 2.10a and 2.10b). Comparison of fig. 2.8 with fig. 2.9 suggests that this peak primarily consisted of peat initiation in topographic depressions (fig. 2.9e) and onset of peat growth in river valleys (fig. 2.9f). The rise and maximum of the second peak in the bimodal distribution coincide with strong sea level rise (fig. 2.10b and fig. 2.10c, Meijles *et al.*, 2018) and the hypsithermal (Holocene Thermal Maximum; 9,000 to about 5,000-6,000 years ago; Wanner *et al.*, 2008; Renssen *et al.*, 2009). Given favourable climatic conditions for peat growth, combined with sea level rise and related groundwater level rise, peat deposits increasingly filled (higher located) river valleys (fig. 2.9f and fig. 2.10c) and eventually formed on high-lying plains (fig. 2.9d and fig. 2.10c). The drop of the second peak coincides with neoglacial cooling (5,000-6,000 years ago to pre-industrial time; Wanner *et al.*, 2008), perhaps indicating less favourable climatic conditions. However, as peat covered an increasingly large area, further initiation and expansion may also have become limited due to lack of sites suitable for peat growth.

Casparie and Streefkerk (1992) state that for the Netherlands two main phases of climate-induced mire initiation occurred, from 7,000-6,500 BCE (9,000-8,500 cal y BP, start of Atlantic) and around 5,000 BCE (7,000 cal y BP, middle Atlantic). Both periods fall between the start of the second peak and the 'bump' prior to its maximum in fig. 2.8c, but the legacy dataset shows no indication for a drop of peat initiation between 8,500 and 7,000 cal y BP. Van Geel *et al.* (1998) advocate that the 2,800 cal y BP event is a cause for peat initiation. Locally peat may have initiated at this timing, however, their sampling location may also have been a site overgrown through lateral expansion of a pre-existing, older peatland. Presence of a main initiation period around 2,800 cal y BP is not supported by the bimodal distribution of the legacy data. Based on detailed palynological investigations in the Bargerveen peat remnant, (indicated in fig. 2.2b), Dupont (1986) concludes that human influences can be traced in arboreal pollen data only from 5,500 cal y BP onwards, which suggests that human impact on peat initiation was probably limited in the study area.

On the Dutch national palaeogeographical map series (table 2.7), peat initiation in the study area starts at the earliest around 7,500 cal y BP, slightly later than the rise of the second peak in the bimodal distribution in fig. 2.8. No peat deposits are present on the maps prior to 7,500 cal y BP, whereas our results indicate that a peat initiation peak during the Late Glacial must have resulted in peat cover prior to this date (mainly in topographic depressions and river valleys, fig. 2.9e and fig. 2.9f). According to the map series, maximum extent of peatlands was reached between 3,250 and 2,500 cal y BP (table 2.7). The basal dates in the legacy dataset are mostly older than this, indicating that the majority of peatlands in the study area indeed formed before 2,500 cal y BP. However, some basal dates show younger ages (fig. 2.8), especially in valleys (fig. 2.9f), indicating that peat initiation (or lateral expansion) continued at least at some sites after 2,500 cal y BP. Non-basal dates show that vertical peat growth continued as well (fig. 2.10d), suggesting that maximum extent and maximum thickness of peat deposits were probably not reached at the same time.

Table 2.7: *Comparison of peatland initiation and expansion in the study area as indicated by three Dutch national palaeogeographical map series.*

	Zagwijn (1986)	**Westerhoff *et al.* (2003)**	**Vos *et al.* (2020); Vos (2015a)**
Nr. of maps/timeframes	10	6	13
Peat initiation [1]	~ 7,500 cal y BP	~ 6,500 cal y BP	~ 7,500 cal y BP
Maximum extent [1]	~ 3,250 cal y BP	~ 2,600 cal y BP	~ 2,500 cal y BP

[1] For our study area

Based on what could be derived from the legacy data, and considering the surface exposure of the study area for 130,000 years (Ter Wee, 1962), paludification seems to have been the most prominent process causing peat formation in the study area. Paludification may result from environmental factors but also from autogenic processes leading to lateral expansion of peatlands (see section 2.2.2). For our case study, it is often unclear whether dates stem from the same former peatland, as this would already require a clear view of their palaeogeography. Consequently the dataset is not suitable to draw inferences on local peat initiation versus lateral expansion of existing peatlands.

The legacy dataset leads us to tentatively conclude that the study area witnessed two major phases of peat initiation, where the earliest peak was probably mostly driven by climate whereas the second was the result of climate in combination with Holocene sea level rise. We did not consider presence of impermeable deposits in the study area, these may have further enhanced the potential for peat growth, but the degree to which this contributed and on which spatial scale remains so far unclear.

2.5.1.2 Experiences regarding data retrieval

Most scientific publications from which data was collected were fairly easy to find using basic literature searches and keyword queries. Reports from contract-based archaeology were easily accessed, however due to the vast amount of reports available it was generally difficult to find relevant information.

Irrespective of data source, we were able to retrieve the labcode for all samples, thus providing insights in the uncalibrated dating results. In case of ambiguities, dates could be retrieved from the Groningen databases. The bulk SampleType was mainly deduced from labcodes. Details for macrofossil samples were retrieved from publications and lab archives. Overall, we found many more dates than anticipated.

Unfortunately, quite often location and sample elevation were not documented in great detail (fig. 2.6e). For our GIS analyses, the spatial error was considered irrelevant due to the fairly large scale of the study area. However, location was needed to calculate former sample elevation relative to m O.D., as for a large number of samples elevation was only reported relative to the (former) surface. With imprecise location and surface levels changing over time e.g. due to peat compaction and oxidation, these calculations only yield estimations for sample position relative to m O.D..

The stratigraphical position of samples was sometimes reported elaborately, e.g. including cross-sectional profiles. However, for a fairly large number of dates ($n = 75$ out of 313) we were unable to interpret stratigraphy. These dates indicate that organic deposits were present at this location at the dated age, but further implications are much more difficult to deduce.

2.5.1.3 Representativity of the legacy dataset

The meta-analysis of Ruppel *et al.* (2013) indicated a lack of data for the northwest European Plain. The legacy dataset of our case study demonstrates that this image is not entirely valid: our search revealed 74 basal peat dates in the studied region. Additionally, sea level research such as the reconstructed RSL curve for the Wadden Sea (Meijles *et al.*, 2018) is based on elaborate datasets of (legacy) basal peat dates.

However, despite our efforts a limited amount of dates was found in the southern half of the study area. This is probably due to two major factors. As can be deduced from fig. 2.6b and fig. 2.7, research traditions and related concentrations of studied sites create a bias in the dataset as a whole. In addition, large scale peat reclamations of the past have largely determined the distribution of surviving peat remnants and consequently potential sites for field study. While interpreting the data these factors should be kept closely in mind.

To address these biases in the dataset future studies may include (legacy) dates that were not performed on peat deposits directly, but on archaeological artefacts that were retrieved from peat layers or from underneath them. It has for example been demonstrated that the coversand landscape underlying the northern part of the former Bourtangermoor (Dutch-German border area, the surviving remnant on Dutch territory is the Bargerveen, fig. 2.2b) is very rich in Mesolithic sites (Groenendijk, 2003). Such finds provide a terminus post-quem for peat initiation, even though potential hiatuses have to be taken into account. Well-preserved overgrown cultural landscapes are also known from northern Germany (e.g. Pantzer, 1986). Well-dated archaeological finds from peat layers may both provide a terminus ante-quem (for underlying peat layers) and/or terminus post-quem (for overlying layers), depending on the local stratigraphy. As archaeological finds from peatlands were often recovered in the distant past during peat-cutting (Van Beek *et al.*, 2015), they do require a quality assessment of their own, tailored for archaeological aspects in addition to taphonomic (Q_T) and dating (Q_d) quality.

2.5.1.4 Effect of the quality assessment

The quality assessment shows that the data points are dispersed through the four confidence levels, indicating that for some samples taphonomic quality is relatively low whereas for others problems lie in the dating quality (fig. 2.5). A significant part of the data points received a green confidence level (n = 121 out of 313), which allows most detailed filtering options as for many aspects sufficient information is available.

The KDE modelling runs with different confidence level groups (fig. 2.8) lead to distributions that are comparable in overall shape, but vary at a more detailed level.

Green confidence level models (with and without filtering, fig. 2.8a and fig. 2.8b) result in a clear bimodal distribution. When including all data (fig. 2.8c) this trend remains visible but becomes less clearly defined. The use of confidence levels provides insight in this confounding effect caused by dates with low taphonomic or dating quality. This approach can however only be applied if the (sub)dataset is large enough, e.g. for the analysis of landform groups this subdivision was not fully possible.

2.5.2 Evaluation of approach

The proposed workflow and quality assessment demonstrate the balancing act to reach robustness without being too strict and consequently discarding the majority of data. All data points contain information, the question is how to extract it adequately. The quality assessment has a flexible set-up and depending on the research questions to be answered, assessment criteria can be in- or excluded or made more impactful using the weights. Subsequent filtering allows tailor-made and informed decisions for data analysis. For instance, if for a certain research question (e.g. reconstructing a sea level curve) it is unnecessary to know a detailed location of the date but crucial to know its elevation and stratigraphical position, weights may be adjusted accordingly which will result in a higher penalty for dates that do not match these criteria.

The case study shows that varying criteria have been used to define peat initiation and to subsequently select samples, resulting in divergent approaches to date the onset of peat accumulation. Consequently this led to a range in taphonomic (Q_T) and dating (Q_d) quality in our quality assessment. The methods of the studies from which dates were retrieved partly depend on the research objectives, but also reflect methodological possibilities at the time of dating, for instance use of bulk sampling prior to the development of AMS.

Discussions on methodological aspects of dating and 'best practices' are reflected in the quality criteria. For instance, a bulk sample receives a penalty for *SampleType*, as bulk samples are generally large and consist of an uncharacterised mixture of organic compounds (e.g. Törnqvist *et al.*, 1992, 1998). Inherently, this means a penalty is also assigned for *SpeciesType* and *Aboveground*, as it is unknown which species and which plant tissues are contained within the sample. If for a given peatland a reservoir effect is expected (Kilian *et al.*, 1995; Blaauw *et al.*, 2004), then either weights for these properties can be increased, filtering can be applied (to exclude all samples with unknown and aquatic species), or both.

It is important to note that the penalty score is cumulative, not exclusive. For instance, if it is known whether a sample consisted of macrofossils it will receive no penalty for the property *SampleType*. However, for a sample that consisted of bulk, the overall penalty score may still be low (and resulting confidence level green) if other properties (with an assigned weight above zero) were well-known and few further penalties were assigned. In case *SampleType* is crucial to answer the research question, either its weight should be increased substantially, or a filter should be applied after the quality assessment to generate a list of dates for instance with green confidence level and only macrofossils as *SampleType*.

It is also important to realise that the stricter the boundaries of the confidence levels are defined, and the more subsequent filtering is applied, the smaller the resulting subset of datapoints will be. This may also result in overrepresentation of samples from a few studies from a specific area (as these have comparable taphonomic and dating quality), which may affect how representative outcomes are for the study area as a whole.

Finally, the quality assessment only makes a difference if the dates actually differ for the selected criteria, otherwise the majority will receive the same penalty. This means that the combination of criteria used (i.e. turned on and off by reducing the weight to zero) is crucial to really distinguish dates based on their quality.

2.5.3 Implications and recommendations

Data rescue and reuse lead to improved continuity of data (Gil *et al.*, 2016) and development of new, overarching insights (e.g. Tolonen and Turunen, 1996; Ruppel *et al.*, 2013, this study). Based on the process of data rescue and meta-analysis of the case study it appears that the two largest peat remnants in this area, Fochteloërveen and Bargerveen, have so far only been considered by two studies dating one and two vertical cores respectively (Van Geel *et al.*, 1998; Dupont, 1986). These remnants are the main storage sites of the remaining peat archives and have scientific potential yet to be discovered.

The properties that are recorded and their level of detail always depend on the research question to be answered. Additionally, awareness of what is relevant to report may differ between disciplines. However, based on experiences with data reuse in our case study, we emphasize the importance of recording detailed information on basic properties such as geographical location, elevation, stratigraphical position, and sample details. With peat soils further diminishing in spatial extent but also in thickness, we underline the importance of registering coordinates, and where possible elevation in m O.D.. Without this information options for future peat studies that require field data are further reduced. Additionally, sharing data based on the FAIR principles is key (Gil *et al.*, 2016; Wilkinson *et al.*, 2016), otherwise options for reuse decrease rapidly (Savage and Vickers, 2009).

2.6 Conclusion

We developed a workflow for reuse of legacy geochronological data in peatland studies, including rigorous quality assessment. The latter can easily be tailored to specific research questions by adjusting the relative weights assigned to penalized aspects.

The proposed approach was tested on a case study of (former) peatlands in the Netherlands. Peat growth started in the Late Glacial (~14,000 cal y BP), dropped during the Boreal (~9,500 cal y BP) and showed a second peak in the Subboreal (~4,500 cal y BP). Peat initiation occurred in the Late Glacial and throughout the Holocene in river valleys, whereas only during the Subboreal on plains and ridges. We tentatively conclude that the earliest peak was mostly driven by climate (Bølling-Allerød interstadial), whereas the second was probably the result of Holocene sea level rise and related groundwater level rise in combination with climatic conditions (hypsithermal).

Studies that reuse legacy data may yield new insights that require a birds-eye view to be discovered. However, their success depends on data retrieval. We therefore emphasize the importance of FAIR sharing detailed information on basic properties such as geographical location, elevation, stratigraphical position, and sample details. These should be recorded irrespective of research aim, to prevent further data loss from peat archives that are at risk of disappearing.

Author contributions

Funding was secured by RvB. CQ drafted the outline for the research, and improved it based on input from RvB, YvdV and JW. CQ designed the workflow for reusing legacy data, created the database set-up and draft version of the quality assessment. Data collection was initiated by CQ and to a large extent completed by TH, who also elaborately recorded all data. HvdP provided expertise on radiocarbon dating aspects and insight knowledge on the radiocarbon dates performed in Groningen to check and complement the dataset. All authors provided further input for the quality assessment, for which background mathematics were discussed by CQ and JQ. Approach for the data analysis was chosen by CQ and YvdV. JQ programmed the Python scripts for the automation of the quality assessment and to generate data visualisations. CQ performed the data analyses in OxCal and GIS. CQ wrote the main body of text, and finalised it based on feedback from all authors.

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Chapter 3

Dating basal peat: The geochronology of peat initiation revisited

Cindy Quik, Sanne Palstra, Roy van Beek, Ype van der Velde,
Jasper Candel, Marjolein van der Linden, Lucy Kubiak-Martens,
Graeme Swindles, Bart Makaske, Jakob Wallinga
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Abstract

Attributing the start of peat growth to an absolute timescale requires dating the bottom of peat deposits overlying mineral sediment, often called the *basal peat*. Peat initiation is reflected in the stratigraphy as a gradual transition from mineral sediment to increasingly organic material, up to where it is called peat. So far, varying criteria have been used to define basal peat, resulting in divergent approaches to date peat initiation. The lack of a universally applicable and quantitative definition, combined with multiple concerns that have been raised previously regarding the radiocarbon dating of peat, may result in apparent ages that are either too old or too young for the timing of peat initiation. Here, we aim to formulate updated recommendations for dating peat initiation. We provide a conceptual framework that supports the use of the organic matter (OM) gradient for a quantitative and reproducible definition of the mineral-to-peat transition (i.e., the stratigraphical range reflecting the timespan of the peat initiation process) and the layer defined as *basal peat* (i.e., the stratigraphical layer that is defined as the bottom of a peat deposit). Selection of dating samples is often challenging due to poor preservation of plant macrofossils in basal peat, and the representativity of humic and humin dates for the age of basal peat is uncertain. We therefore analyse the mineral-to-peat transition based on three highly detailed sequences of radiocarbon dates, including dates of plant macrofossils and the humic and humin fractions obtained from bulk samples. Our case study peatland in the Netherlands currently harbours a bog vegetation, but biostratigraphical analyses show that during peat initiation the vegetation was mesotrophic. Results show that plant macrofossils provide the most accurate age in the mineral-to-peat transition and are therefore recommendable to use for ^{14}C dating basal peat. If these are unattainable, the humic fraction provides the best alternative and is interpreted as a terminus-ante-quem for peat initiation. The potential large age difference between dates of plant macrofossils and humic or humin dates (up to ~1700 years between macrofossil and humic ages, and with even larger differences for humins) suggests that studies reusing existing bulk dates of basal peat should take great care in data interpretation. The potentially long timespan of the peat initiation process (with medians of ~1000, ~1300 and ~1500 years within our case study peatland) demonstrates that choices regarding sampling size and resolution need to be well substantiated. We summarise our findings as a set of recommendations for dating basal peats, and advocate the widespread use of OM determination to obtain a low-cost, quantitative and reproducible definition of *basal peat* that eases intercomparison of studies.

3.1 Introduction

The start of peat growth represents a major landscape change. Attributing this transition to an absolute timescale requires dating the bottom of peat deposits overlying mineral sediment, often called the *basal peat*. Robust age control of basal peat layers is of paramount importance, not only for studies aimed directly at peatlands, for instance concerning their palaeogeography, development and carbon sequestration (e.g. Gorham *et al.*, 2007; Yu *et al.*, 2011), but also for interdisciplinary research fields that harness the peat archive for climate and sea level reconstructions (e.g. Törnqvist and Hijma, 2012; Morris *et al.*, 2018) or to contextualize wetland archaeology (e.g. Chapman *et al.*, 2013).

Peat growth results from a positive production-decay balance, i.e. where the decay rate of organic material is slower than the rate of production. The decay rate primarily depends on moisture level, which in turn is influenced by various factors such as climate (e.g. Weckström *et al.*, 2010), changes in hydrological base level (sea level rise, e.g. Berendsen *et al.*, 2007) or regional groundwater changes (e.g. Van Asselen *et al.*, 2017), landforms and surface topography (e.g. Almquist-Jacobson and Foster, 1995; Mäkilä, 1997; Loisel *et al.*, 2013), impermeable deposits or resistant layers in the soil profile (e.g. Breuning-Madsen *et al.*, 2018; Van der Meij *et al.*, 2018), and anthropogenic influence (e.g. Moore, 1975, 1993).

A wetland is an area where the substrate is water-saturated or inundated for a substantial period (Charman, 2002c; Joosten and Clarke, 2002). A minimum depth of 30 cm of peat is required to classify a wetland area as a peatland (Charman, 2002c; Joosten and Clarke, 2002; Rydin and Jeglum, 2013c). This implies that during build-up of the first organic deposits, the area is not yet a peatland according to definition, but rather a wetland where peat formation occurs. As a result of these definitions, one could make a distinction between peat initiation (i.e., build-up of the first organic deposits) and peatland initiation (i.e., referring to the moment when 30 cm of organic deposits has formed in a certain area). In the current paper, we focus on peat initiation (prior to the formation of a peat layer with a thickness of 30 cm or more).

Peat initiation may occur through (a combination of) three processes, briefly outlined below based on Charman (2002c) and Rydin and Jeglum (2013d). Terrestrialisation (also called infilling) refers to the process where peat develops in or at the edge of water bodies. Terrestrialisation is characterized by gyttja deposits at the base, which require a water depth of at least 0.5 m to form (Bos, 2010). Paludification refers to peat formation on previously unsaturated mineral substrate, and thus reflects moistening of the landscape. Primary mire formation involves peat growth on newly exposed waterlogged substrate (e.g. after land uplift from sea). Here, peat growth starts directly on the fresh parent material. When a peat surface rises above the regional groundwater level, consequent strong dependence on rainwater leads to ombrotrophication, which may result in a fen-bog transition (Charman, 2002a; Rydin and Jeglum, 2013d; Loisel and Bunsen, 2020). Peatlands not only grow vertically, but also expand laterally, which results in a larger peat-covered area. Paludification of surrounding soils due to poor drainage at the edge of the peatland, and resulting peatland expansion, is known as an autogenic process (Charman, 2002a). However, allogenic factors such as climate and topography influence the rate and extent of lateral spread (e.g. Korhola, 1994; Ruppel *et al.*, 2013).

Peat initiation can be studied at various scales (fig. 3.1a). At the landscape scale, peat initiation refers to the onset of peat growth at a certain locus, that expands over time to cover a larger area. In this case, the term peat initiation refers to the location and time where the nucleus of the resultant peatland developed. In contrast, at the very local scale, peat initiation may be used to indicate the moment of accumulation of the first peat deposits at a specific location, where the location may reflect a development locus but could also be a site that became covered by peat through lateral expansion of a nearby locus. To distinguish lateral expansion from a development locus, one or multiple transects of basal peat dates are usually required (e.g. Mäkilä, 1997; Mäkilä and Moisanen, 2007; Chapman *et al.*, 2013). The approach for dating peat initiation at both scales is similar, while the research aim determines which scale level is of interest.

Peat initiation is a process that takes place during a certain timespan, which is reflected in the stratigraphy as a gradual transition from mineral sediment to increasingly organic material (fig. 3.1b), up to where it is called peat (depending on definitions used). We propose it would be most accurate to speak of a period of peat initiation, which requires a series of vertical dates that encloses the gradual stratigraphical boundary. However, a single date of *basal peat* is often used to reflect peat initiation, potentially for reasons of practicality or feasibility when there is need to date many sites. This requires however an unambiguous and explicit definition of *basal peat*.

So far, varying criteria have been used to define *basal peat*, resulting in divergent approaches to date the onset of peat accumulation (Quik *et al.*, 2021). Current approaches, which are partly dependent on the research objectives, vary from visual determinations and basic laboratory analyses such as loss-on-ignition (e.g. Edvardsson *et al.*, 2014) to detailed micromorphological analyses (e.g. Cubizolle *et al.*, 2007) and studies of plant macrofossils (e.g. Loisel *et al.*, 2013). Depending on the approach taken, the accuracy of resulting dates to represent peat initiation may be called into question, as the (possibly site-specific) definition of the *basal peat* often remains implicit.

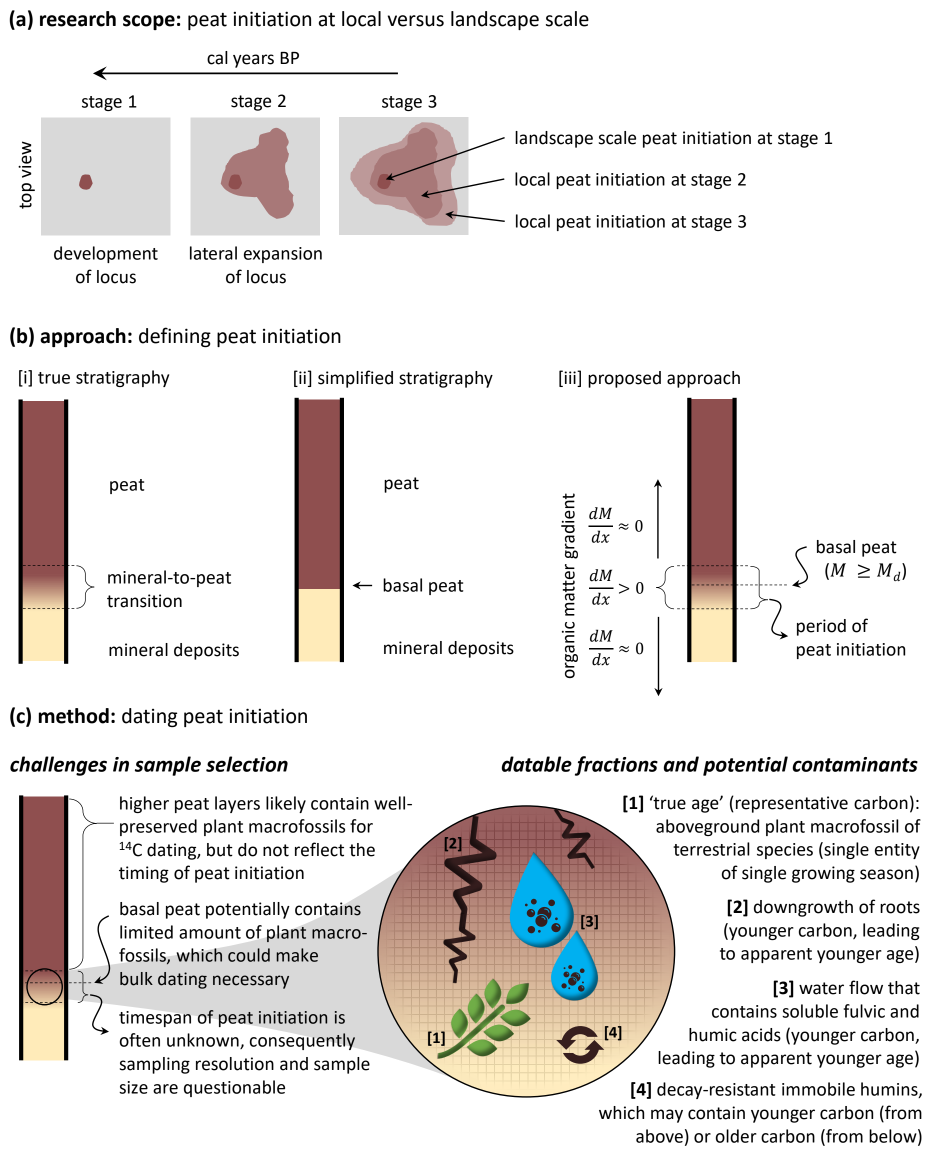


Figure 3.1: *Conceptual framework for dating peat initiation. (a) Schematic top-view of a landscape (peat is indicated in brown), showing the meaning of* peat initiation *at both the landscape and local scales. (b) Schematic cores showing [i] stratigraphy that results from peat initiation, [ii] simplified interpretation of this stratigraphy, and [iii] the approach we propose in this study. Here, we propose using the organic matter gradient to characterise the mineral-to-peat transition and to define* basal peat*. To qualify the material as peat, the OM content should be above a certain value denoted with M_d, where the first cm of material that has an OM content equal to or above M_d is defined as the* basal peat*. (c) Schematic core showing challenges with sample selection, and datable fractions and potential contaminants for ^{14}C dating* basal peat*.*

The international soil classification of the World Reference Base for Soil Resources states that 'organic material' has $\geq$ 20% soil organic carbon in the fine earth fraction (by mass) (IUSS Working Group WRB, 2015). A practical challenge of this definition is that determination of soil organic carbon requires expensive analyses (e.g. elemental analysis), whereas soil organic matter (which includes both organic carbon and, if present, inorganic carbon such as carbonates) can be measured with an inexpensive, simple protocol (loss-on-ignition).

To the best of our knowledge, both the mineral-to-peat transition and the layer called *basal peat* (the stratigraphical level used to reflect peat initiation), are not universally defined based on organic matter (OM) content. A universal definition eases inter-site comparisons, but a site-specific definition may be preferable to cover regional differences. Both require that the properties to define *basal peat* are explicit and reproducible. For example, Cubizolle *et al.* (2007) use 30% OM as lower limit for peat in the French Massif Central, whereas for instance Loisel *et al.* (2013) use 50% OM for an Alaskan peatland. To stimulate the use of quantitative and reproducible definitions, a property such as OM content is recommendable, as it can be measured relatively easily and at low cost. As there is a clear gradient in organic matter (indicated by the variable M) at the transition from mineral sediment to peat (i.e., as a function of distance x upwards in the profile), both the mineral-to-peat transition (i.e., the period of peat initiation) and the *basal peat* (i.e., the stratigraphical layer that is defined as the bottom of a peat deposit) can be defined by the organic matter content [$M(x)$] and the organic matter gradient [the derivative given by $\frac{dM}{dx}$] (fig. 3.1b).

After defining *basal peat*, adequate sampling and sample pre-treatment for radiocarbon dating are required to accurately derive the age of the basal peat layer. The discussion on which samples most accurately indicate the age of peat layers started several decades ago (e.g. Törnqvist *et al.*, 1992, 1998; Shore *et al.*, 1995; Nilsson *et al.*, 2001; Brock *et al.*, 2011; Van der Plicht *et al.*, 2019). Various studies have highlighted multiple concerns with the radiocarbon dating of peat. If carbon from other carbon sources is incorporated or mixed with the original sample material and cannot be removed (by manual selection and/or chemically), this may result in apparent ages that are either too old or too young for the peat layer of interest (table 3.1).

Table 3.1: *Concerns with ^{14}C dating of peat samples. 'Organism' refers to a plant of peat-forming vegetation.*

Processes when the organism was alive *Apparent older age*	***Processes after the organism died*** *Apparent younger age*
Circumstances where organisms incorporate carbon from a reservoir that is not in equilibrium with the atmosphere (so-called reservoir effect), causing apparent ages that are too old: ▪ This typically applies to aquatic samples from marine or freshwater circumstances (the latter is also known as hardwater effect, e.g. Törnqvist *et al.*, 1992; Philippsen, 2013). Relevance of a reservoir effect for peat samples has been postulated (Kilian *et al.*, 1995; Blaauw *et al.*, 2004). Incorporation of older carbon or ^{14}C-depleted carbon may also occur through: ▪ Decomposition of underlying peat layers and subsequent assimilation of CO_2 (Smolders *et al.*, 2001). ▪ Assimilation of CH_4 originating from bacterial methanogenesis (Van der Plicht *et al.*, 2019).	Mixing with younger carbon through: ▪ Downgrowth of roots (Törnqvist *et al.*, 1992). ▪ Translocation of mobile humic acids downwards in a profile, followed by chemical break-down to humins (Palstra *et al.*, 2021). ▪ Contamination during sample storage by microbial growth (Wohlfarth *et al.*, 1998) or laboratory pretreatments. Small samples or samples with low carbon content are particularly sensitive to contamination (Van der Plicht *et al.*, 2019), especially if samples are older than 20 ka.

Bulk dating is often complicated by difficulties with interpreting the resulting age, which represents a mixture of ages of various organic fractions. The development of AMS in radiocarbon has enabled new possibilities for dating peat deposits due to much lower requirements regarding sample sizes (e.g. Tuniz *et al.*, 1998; Jull and Burr, 2015). The concerns outlined in table 3.1 have led to the recommendation to date short-lived, aboveground plant macrofossils of terrestrial species with AMS (e.g. Piotrowska *et al.*, 2011).

Unfortunately, AMS dating of terrestrial macrofossils is not always possible for mineral-to-peat transitions (fig. 3.1c). Depending on the type of mire and local circumstances, the basal peat layer may have an amorphous peat facies largely devoid of (identifiable) plant macrofossils. Limited presence of plant macrofossils may require resorting to bulk sampling for radiocarbon dating the basal peat layer, which could hamper interpretation of dating results. The magnitude of this problem appears to vary. For instance, Törnqvist *et al.* (1992) found age differences of up to 600 ^{14}C year between bulk and macrofossil samples from mid-latitude minerotrophic peats, whereas Berendsen *et al.* (2007), who studied comparable deposits, and Holmquist *et al.* (2016), who looked at basal peat from circum-arctic peatlands, reported no significant age differences. Depending on the duration of the period in which the basal peat forms, sampling plant macrofossils from higher positions in the peat profile to circumvent bulk sampling at the base may no longer reflect peat initiation, as a potentially large age difference between these layers might exist.

Pre-treatment of bulk samples using acids and base solutions results in multiple organic fractions which are defined based on their solubilities (Brock *et al.*, 2011; Van der Plicht *et al.*, 2019): fulvic acids are soluble in both alkaline and acids, humic acids are soluble in alkaline but insoluble in acids, and humins are insoluble in alkaline and acids. Fulvic acids are usually removed during pre-treatment and not used for dating. Because of their high mobility, which allows them to translocate easily through a soil profile, significantly younger dates might be obtained for fulvics than for the humic and humin fraction from the same layer (Shore *et al.*, 1995). As the solubility of humics is determined by pH and lower under acidic conditions (Wüst *et al.*, 2008), their mobility depends on environmental circumstances and may change through time. There is no clear consensus in literature on whether humic or humin dates are most representative for dating peat layers. Examples range from studies where no significant age differences are reported (e.g. Cook *et al.*, 1998; Waller *et al.*, 2006), studies that consider humins to be most appropriate for peat (e.g. Hammond *et al.*, 1991; Van der Plicht *et al.*, 2019) and humics for deposits with low carbon amounts (Van der Plicht *et al.*, 2019), or where a conclusion that one or the other fraction is more reliable could not be drawn unquestionably (Brock *et al.*, 2011). Moreover, hardly any studies focus on *basal peat* layers while investigating the ages of these organic fractions (with the exception of Brock *et al.*, 2011). It is therefore unknown which carbon fractions of these basal peat layers, which might be slightly different in organic carbon composition (especially in carbon content) compared to peat samples from higher positions in peat profiles, are most representative for the time period of peat initiation.

In the current study we aim to formulate recommendations for dating *basal peat*. Issues that we specifically address are (1) peat initiation is a process of a certain timespan rather than an event, (2) *basal peat* needs to be clearly defined, (3) selection of dating samples is typically challenging due to potential poor preservation of plant macrofossils in *basal peat* and (4) the representativity of humic and humin dates for the age of *basal peat* is questionable. We analyse lithological, biostratigraphical and geochronological characteristics of the mineral-to-peat transition in a bog remnant, focusing on understanding the course of the process of peat initiation and related implications for dating.

3.2 Methods

3.2.1 Selection of study area and overview of methods

The Fochteloërveen peat remnant (the Netherlands, fig. 3.2) was selected as case study region. This peatland, with its surface area of approximately 2,500 hectares, is one of the largest raised bog remnants of Northwest Europe. The area is considered representative for many (non-coastal) peatlands of the Northwest European Plain with regard to the widespread distribution of its mineral substrate and characteristic climatic conditions (see section 3.2.2). As many European peatlands are subject to ongoing excavation or affected by reclamation relics from historical peat-cutting, basal peat layers may be damaged. In the Fochteloërveen, several former peat cutting pits (some of which are currently artificial lakes) are present and superficial patterns of historical buckwheat fire culture can be recognized. However, the latter disturbed only the surface of the peatland and therefore basal peat layers are undamaged in the majority of the area. A recent study on peat initiation trends in the northern Dutch coversand landscape (Quik *et al.*, 2021) provides background information on peat growth in the wider study region, and demonstrated that the Fochteloërveen (as one of the few surviving bog remnants) has so far received limited scientific attention regarding its initiation and age.

Three sites (named S17, S18 and S20, fig. 3.2a and 3.2b) in the Fochteloërveen peat remnant were selected for dating (for further details on choices for site selection see section 3.2.3). At each of these sites a core containing the mineral-to-peat transition was obtained. Note that the meaning of *basal peat* in this study is much broader than the 'Basisveen Bed' as known in Dutch stratigraphy (TNO – Geological Survey of the Netherlands, 2021a). For each of the three sites, selected levels in the peat core were analysed for percentage organic matter (OM) through loss-on-ignition (LOI), plant macrofossils (PM) and testate amoebae (TA). The palaeo-environmental setting was reconstructed based on analyses of PM and TA. Based on LOI data, samples for radiocarbon (^{14}C) dating were selected from multiple levels within each core. When attainable, (charred) plant macrofossils were selected for dating. Additionally the original bulk material was sampled and chemically processed to derive humic and humin fractions for dating. All steps are explained below.

3.2.2 Study Area

The northern Netherlands was covered by a continental ice sheet during the Saalian (MIS 6), which led to deposition of glacial till (Rappol, 1987; Van den Berg and Beets, 1987; Rappol *et al.*, 1989; TNO – Geological Survey of the Netherlands, 2021b) on the Drenthe Plateau or till plateau (Ter Wee, 1972; Bosch, 1990). During the Weichselian (OIS 4-2), aeolian cover sands were deposited over an extensive area of Northwest Europe, forming the European Sand Belt (Koster, 1988, 2005). On the Drenthe Plateau these cover sands occur with a thickness varying from 0.5 to 2 m (Ter Wee, 1979; TNO – Geological Survey of the Netherlands, 2021c). The Fochteloërveen peat remnant is located near the western edge of the Drenthe Plateau and is part of three catchments, draining into the rivers Drentsche Aa, Peizerdiep and Tjonger (fig. 3.2c). Historical data of the 18th century indicate that peat thickness at the Fochteloërveen has diminished over the past centuries with as much as 7 m at some locations (Douwes and Straathof, 2019). Our corings (see section 3.2.3) demonstrated that peat thickness currently varies from 20 cm to 225 cm at approximately 100 visited locations distributed over the peatland. Current climate is characterised by average temperatures of 2.8° C in January and 17.5° C in July, average annual rainfall of 805 mm, and a potential evapotranspiration of 566 mm (KNMI, 2021).

As a result of large-scale historical peatland reclamations (e.g. Gerding, 1995; Van Beek *et al.*, 2015) currently only small remnants of the former extensive North-west European peat landscapes remain (fig. 3.2d). The Fochteloërveen remnant is protected as Natura 2000 area and harbours a wide range of plant and animal species (Provincie Drenthe, 2016). Main threats to the quality and continuity of the area include atmospheric nitrogen deposition and desiccation due to intense drainage for surrounding agriculture. Since the 1980s nature conservation is aimed at peatland restoration (Altenburg *et al.*, 2017).

3.2.3 Site selection and stratigraphy

We performed an elaborate field exploration of the peat remnant consisting of around 100 corings (some grouped in transects of 185 to 575 m long). For each core the stratigraphy was described (see table 3.2 for details).

As the basal peat is not oligotrophic (see 3.3 Results for further information), field determination of the degree of humification using the scale for ombrotrophic peat by Von Post (Aaby, 1986) does not fully apply. Additionally, the use of Munsell colour charts for fresh organic deposits is often difficult as the material changes in colour following exposure to oxygen. Instead, we applied asimplified version of the organic-facies determination key by Bos *et al.* (2012), which is originally intended for organic sediments in deltaic settings. Our basic field classi-

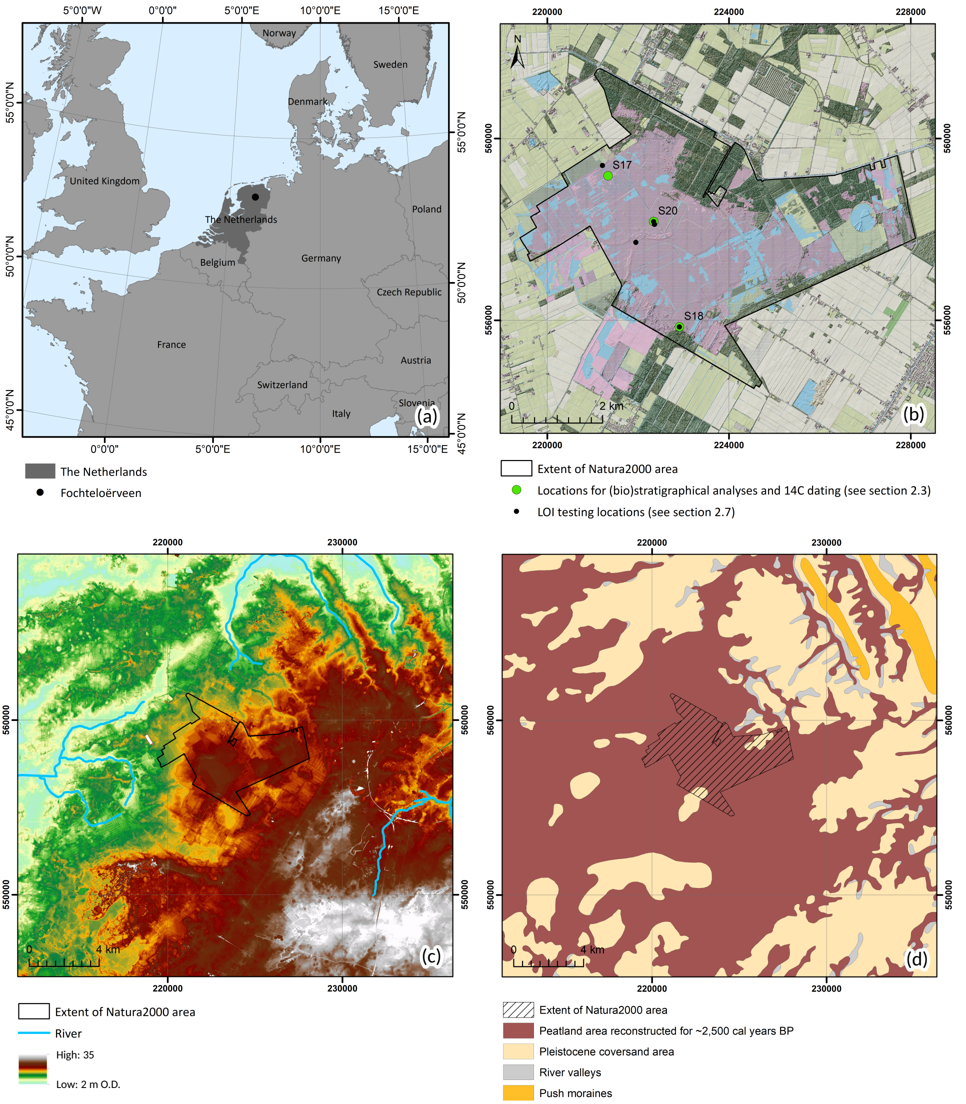


Figure 3.2: *(a) Location of the Netherlands and the Fochteloërveen peat remnant in Europe. (b) Topographical map of Fochteloërveen, indicating sampling locations. Dataframe coordinates are in metres (Dutch RD-new [*Rijksdriehoeksstelsel*] projection). (c) Digital Elevation Model (DEM) of Fochteloërveen and surroundings, showing the main drainage pattern. Elevation is in metres relative to Dutch Ordnance Datum (O.D., roughly mean sea level). (d) Reconstructed palaeogeography for ~2,500 cal years BP, indicating assumed former extent of the peatland area around Fochteloërveen. Sources: topography (OpenSimpleTopo, 3200 pixels/km) by Van Aalst (2021); DEM of the Netherlands (AHN3; horizontal resolution 5 m, vertical resolution 0.1 m) from AHN (2021a,b); rivers from Ministerie van Verkeer en Waterstaat (2007); Natura 2000 area from Ministerie van Economische Zaken - Directie Natuur & Biodiversiteit (2018), palaeogeographical map (500 BC) from Vos and Vries (2013); Vos* et al. *(2020)*

fication differentiates amorphous organic material (similar to *amorphous organics* in Bos *et al.*, 2012), and non-decomposed peat (similar to *oligotrophic peat* in Bos *et al.*, 2012) where further botanical specification is obtained later through microscopic analyses of plant macrofossils.

Following the field exploration, 21 cores originating from sites distributed over the peatland were collected for future analyses. To address the current research aim, three cores were selected based on a set of criteria considering lithological representativity, spatial distribution and elevation (see table 3.3 for a comparison of these properties and further details on selection criteria). Each core was collected from a transect along a cover sand ridge that underlies the peat deposits. Site S17 (transect in fig. 3.3) is located in what is probably a valley or topographic low in the sand landscape underlying the peat deposits, cores S20 and S18 (transects not shown) are located at peat-covered flanks of sand ridges.

Table 3.2: *Lithology and lithogenetic interpretation of the stratigraphical layers occurring from the surface downwards (modified from Bos et al., 2012).*

Lithology	***Symbol***	***Lithogenetic interpretation***
Peat with brown colouring and clearly recognisable plant remains.	V3	Non-decomposed peat
Peat with blackish-brown colouring, greasy consistency and very few recognisable plant remains.	V3*	Amorphous peat (highly humified; *sapric* cf. IUSS Working Group WRB, 2015)
Mixture of peat with very fine to moderately fine sand, dark brown colouring.	ZV/VZ	Peaty sand/sandy peat (gradual transition zone from Pleistocene mineral deposits to overlying organic deposits)
Very fine to moderately fine sand with colour varying from dark brown to light grey, locally loamy, sporadically containing pebbles (ø 1-5 mm).	P	Pleistocene mineral deposits

Table 3.3: *(a) Criteria for the selection of sites for a vertical dating series, with their respective rationale. (b) Properties of the three sampled sites compared with the minimum (Min), maximum (Max) and average (Avg) of the in total 21 sampled sites of the peat remnant (i.e., where a core for analyses was collected). The surface elevation was measured with a vertical precision of ~10 mm. The total thickness of organic deposits is the sum of V3, V3* and ZV/VZ. The top of the Pleistocene mineral deposits was derived from the surface elevation minus the total thickness of organic deposits as determined visually in the field (i.e., might deviate slightly from the* basal peat *layer that was defined later based on OM%). NA = not applicable. For other stratigraphical abbreviations see explanation in table 3.2.*

(a)	Selection criteria	Rationale
	The site is part of a coring transect (distance between 185 and 575 m long).	The coring transect provides relevant background information regarding the landscape position of the site.
	The obtained core contains the (visual) mineral-to-peat transition.	Cores containing the mineral-to-peat transition will be most straightforward to analyse and are not compromised by suboptimal sampling conditions.
	For the three selected sites, the cores have V3* layers of varying thickness, and at least one site contains a ZV layer.	Analyses of three sites with a representative thickness range of V3* and presence of a ZV layer will cover the stratigraphical diversity that is present in the study area (see table 3.3b) and potentially in other regions. This ensures that any methodological recommendations will have a wide applicability.
	The three selected sample sites are well-distributed spatially and of varying elevation.	Our approach should be applicable to different landscape positions.

(b)	Property	S17	S18	S20	Min	Max	Avg
	Surface elevation (m. O.D.)	9.308	11.999	10.781	9.31	12.00	10.70
	Total thickness organic deposits (cm)	216	30	35	30	216	94
	Thickness V3 (cm)	182	16	24	16	182	74
	Thickness V3* (cm)	34	6	11	6	34	17
	Thickness ZV/VZ (cm)	0	8	0	0	8	3
	Top of Pleistocene mineral deposits (m. O.D.)	7.15	11.70	10.26[1]	7.15	11.70	9.70
	Location	East	West	Central	NA	NA	NA

[1] Corrected for standing water at the surface.

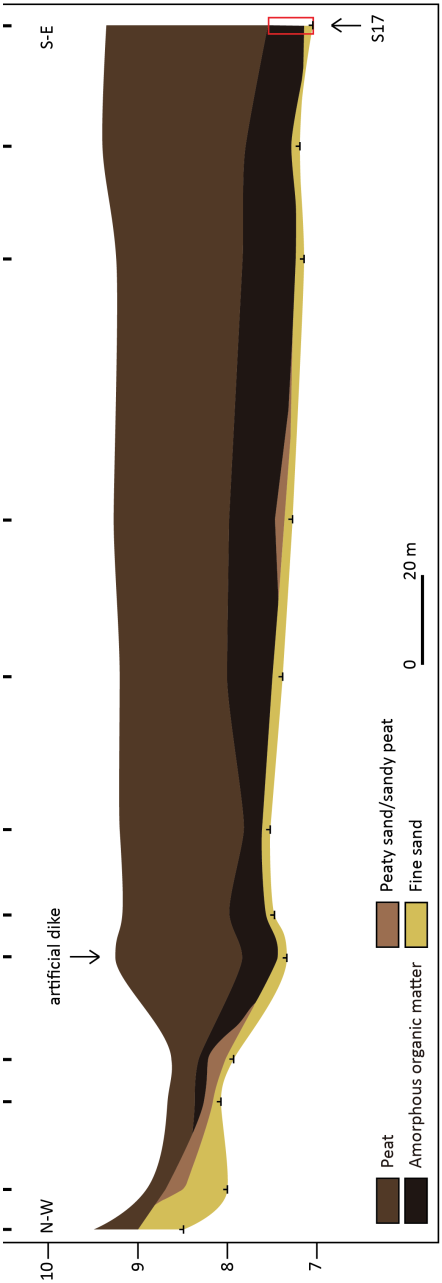


Figure 3.3: *Example cross section, showing stratigraphical context of core S17 (on the right). The red box indicates the sampled reach of the profile. About 1 m further in S-E direction, a wide ditch hampered additional corings to extend the transect.*

3.2.4 Collection of cores

The three cores were collected in 2019 with a hand-operated stainless-steel peat corer (Russian type) of 50 cm long and 60 mm outer diameter, with an equivalent core volume of 0.5 dm^3 (Eijkelkamp Soil & Water, 2018). This type of corer was found to be most useful for sampling both peat and water saturated mineral sediments underneath in one core, with minimal disturbance and low risk of contamination. Other types of corers were considered unsuitable for this purpose. For instance, augers or gouge corers often disturb the sample and do not protect it from contamination as there is no closed coring chamber. A Van der Staay suction corer (Wallinga and Van der Staay, 1999), which is used to sample water saturated mineral deposits, cannot sample peat layers as these block the suction mechanism. The Russian corer is generally used for sampling deeper (i.e. mostly catotelm) peat layers (Vleeschouwer *et al.*, 2010). Field testing demonstrated that this corer was able to simultaneously sample both peat and the top of water saturated mineral deposits adequately (fig. 3.4). In areas where the mineral deposits are compacted so firmly that hand-operated corers cannot be pressed down to a sufficient depth, the use of percussion drilling equipment might be useful (e.g. Eijkelkamp Agrisearch Equipment, 2022).

Each time prior to sampling a new core, the coring chamber and pivoting blade (fin or lid) were cleaned with a fresh microfiber cloth, followed by a thorough rinse with deionised water. Directly after this cleansing routine the corer was pressed down with the pivoting blade closed. After reaching the desired sampling depth the corer was turned 180° clockwise to collect the sample, upon which the pivoting blade closed the coring chamber and the corer was retrieved. Subsequently the corer was kept horizontally with the pivoting blade facing upwards. The blade was carefully turned to retrieve the (undisturbed) core. At this point the core was photographed. Retrieval and packaging of the core followed the procedures proposed by Vleeschouwer *et al.* (2010) and Givelet *et al.* (2004), and proceeded as follows. The core was covered with plastic cling film. Then a PVC half-circular pipe was placed over the core, upon which the corer was rotated to transfer the plastic-covered core to the PVC pipe. The exposed side was covered with the remaining plastic film and the core was secured with plastic tape. Through these steps, which took about 5 minutes from retrieval to packaging, handling of the core in the field was minimized. The name, top and bottom of the core were marked with water-resistant labels. The PVC pipes were transported in horizontal orientation to prevent damage to the cores and stored in a refrigerator of 3° C within 12 hours. Location and elevation of all sampling sites were recorded with a Topcon 250 Global Navigation Satellite System (GNSS) receiver, with a horizontal precision of ~5 mm and vertical precision of ~10 mm (RTK; TOPCON, 2017).

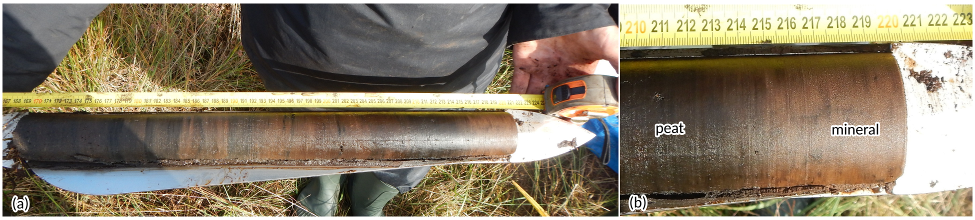


Figure 3.4: *Photograph of core S17 taken directly after collecting the core in the field, (a) overview photo (bottom at the right), (b) detail of the mineral-to-peat transition.*

3.2.5 Core processing and subsampling

The cores were opened in the laboratory of BIAX Consult (Zaandam, the Netherlands). Each core was photographed again, the stratigraphy was described and based on visual inspection the approximate mineral-to-peat transition was determined. Around this transition, a range of contiguous 1-cm-thick slices was cut from the core. Outer edges of each slice were carefully cleaned to prevent contamination. Total sample volume for each cleaned level amounted to ~7 cm^3. The samples were subsampled for multi-proxy analysis based on a priority flowchart (fig. 3.5), which is further explained below.

A bulk subsample (2 cm^3) was collected for dating. The remaining material (around 5 cm^3) was used for PM to analyse plant species and to select suitable plant macrofossils for radiocarbon dating. The PM subsamples were obtained from the filtrate after gently rinsing with warm water over a 0.25 mm sieve. A pollen sample (0.5 ml) was collected from the sieving water for future study and stored at 3° C. Sieving water (0.5 ml) and any remaining non-sieved material (ranging between 1 up to 3 cm^3 depending on how much material remained) was collected for TA analysis. Considering its destructive protocol, LOI was performed only on non-sieved material that remained after TA analysis (typically between 1 and 2 cm^3). To gain more insight in the organic matter gradient in the cores, additional levels were sampled where only LOI was performed (without biostratigraphical analyses and ^{14}C dating). For these levels 2 cm^3 of unsieved material was used for LOI, the remainder was stored at 3° C for future reference. Table 3.4 provides an overview of all collected subsamples for the three cores.

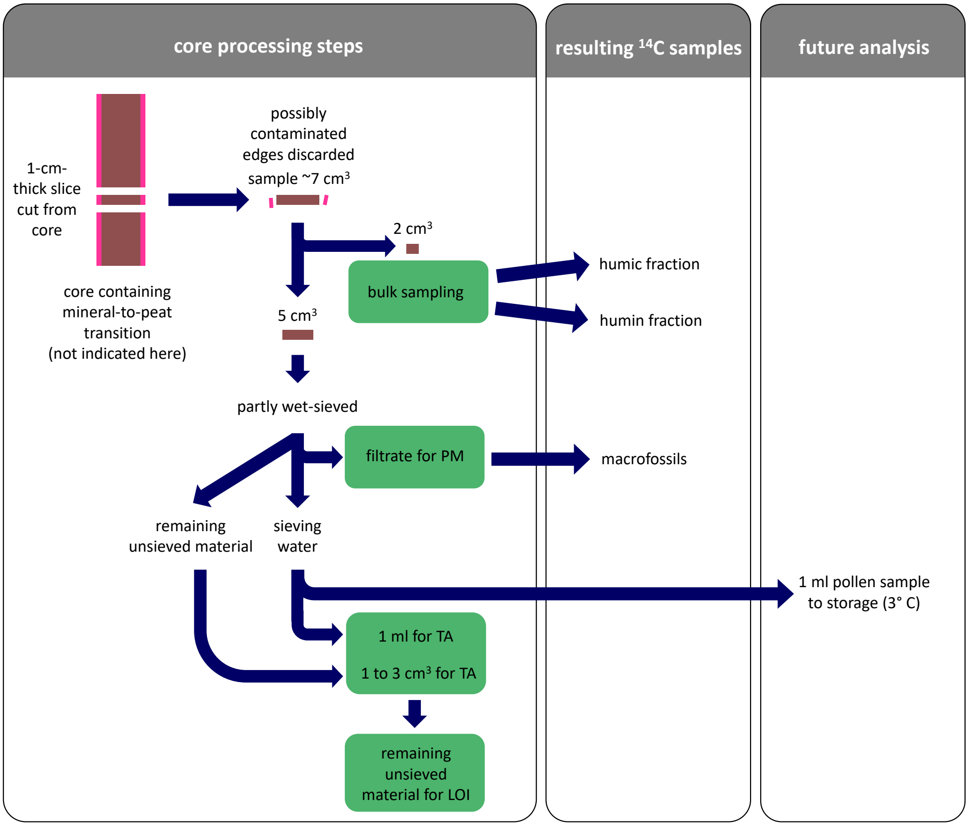


Figure 3.5: *Flowchart showing allocation of sample material from each 1-cm-thick core slice, subsequent processing steps and resulting fractions for ^{14}C dating. PM = plant macrofossil analysis, TA = testate amoebae analysis, LOI = loss-on-ignition.*

Table 3.4: *Overview of analyses and resulting fractions for ^{14}C dating for each investigated level of the cores S17, S18 and S20. PM = plant macrofossil analysis, TA = testate amoebae analysis, LOI = loss-on-ignition.*

Core	From (m O.D.)	To (m O.D.)	PM	TA	LOI	^{14}C bulk humic	^{14}C bulk humin	^{14}C macrofossils
S17	7.495	7.505	X	X		X	X	X
	7.485	7.495	X	X	X	X	X	X
	7.475	7.485	X	X		X	X	X
	7.430	7.440	X		X			
	7.390	7.400	X		X			
	7.350	7.360			X			
	7.300	7.310	X	X	X	X	X	X
	7.290	7.300	X	X	X	X	X	X
	7.280	7.290	X	X		X	X	X
	7.230	7.240			X			
	7.220	7.230			X			
	7.210	7.220	X	X	X	X	X	X
	7.200	7.210	X	X	X	X	X	X
	7.190	7.200	X	X		X	X	X
	7.180	7.190	X	X	X		X	
	7.170	7.180	X	X	X	X	X	
S18	11.80	11.81	X	X	X	X	X	
	11.79	11.80	X	X	X	X	X	X
	11.78	11.79	X	X	X	X	X	X
	11.77	11.78	X	X		X	X	X
	11.76	11.77			X			
	11.75	11.76			X			
	11.74	11.75			X			
	11.73	11.74	X	X		X	X	X
	11.72	11.73	X	X	X	X	X	X
	11.71	11.72	X	X	X	X	X	
	11.70	11.71	X	X		X	X	
	11.69	11.70			X			
	11.68	11.69	X	X		X	X	
	11.67	11.68	X	X	X	X	X	
	11.66	11.67	X	X	X	X	X	
	11.65	11.66	X	X		X	X	
S20	10.40	10.41			X			
	10.39	10.40			X			
	10.38	10.39	X	X	X	X	X	
	10.37	10.38	X	X	X	X	X	X
	10.36	10.37	X	X	X	X	X	X
	10.35	10.36	X	X	X		X	
	10.34	10.35			X			
	10.33	10.34	X	X	X	X	X	X
	10.32	10.33	X	X	X	X	X	X
	10.31	10.32	X	X		X	X	X
	10.30	10.31	X	X	X	X	X	
	10.29	10.30	X	X		X	X	
	10.28	10.29			X			
	10.27	10.28			X			
	10.26	10.27	X	X		X	X	X
	10.25	10.26	X	X	X	X	X	X
	10.24	10.25	X	X	X	X	X	X

3.2.6 (Bio)stratigraphical analyses

The percentage organic matter was determined using LOI (see e.g. Chambers *et al.*, 2011; Kennedy and Woods, 2013). The used subsamples for LOI had a volume of 1 to 2 cm^3. Sample dry weight was determined after drying for 24 hours at 105° C, followed by combustion at 550° C. Subsample dry weight was ~0.65 g on average, of which the remaining mineral component (dry ash) after combustion amounted to ~0.29 g. A microbalance (0.0001 g) was used to maximise measurement precision for these small subsample sizes.

PM analyses were conducted at BIAX Consult in Zaandam, the Netherlands. Mosses and seed remains of vascular plants in the filtrate were identified with a Leica binocular incident light microscope at magnifications of x6 to x50. Identifications followed Körber-Grohne (1964); Körber-Grohne (1991), Berggren (1969, 1981), Anderberg (1994), Smith (2004), and Cappers *et al.* (2006).

TA subsamples were analysed at Queen's University Belfast, United Kingdom. These subsamples were wet-sieved at 300 μm and back-sieved at 15 μm following standard procedures described by Booth *et al.* (2010). Two slides per sample (2 x 21 x 21 mm cover glasses) were studied using a high power binocular microscope under x20 to x40 magnification.

3.2.7 Defining basal peat (determining $\mathrm{M_d}$ value)

To gain a thorough understanding of the OM gradient around the mineral-to-peat transition in our study area prior to selecting a defining OM value (i.e., M_d, fig. 3.1b) above which the material is called *peat*, a vertical series of LOI measurements was performed for five duplicate cores (i.e., additional cores that were collected approximately 10 cm next to the locations of the 21 sampling sites). In this way, the OM gradient could be determined for a continuous sequence (of 22 to 26 cm long) with a resolution of 1 cm (note that this was not fully possible for the cores of sites S17, S18 and S20 that were collected for dating, as for some investigated levels no unsieved material remained after completion of the biostratigraphical analyses to perform LOI). The resulting OM gradients were analysed to derive a substantiated value for M_d.

3.2.8 Radiocarbon dating

The material reserved for bulk sampling was used without removal of roots and provided sufficient humics and humins to date for nearly each level (table 3.4). For plant macrofossil samples, only charred aboveground plant material was selected for radiocarbon dating; waterlogged (uncharred) belowground plant remains like rootlets, radicelles and rhizomes were present abundantly, but aboveground waterlogged plant remains were scarce. From 22 levels of the three cores, charred aboveground plant remains from terrestrial plants could be retrieved (tables 3.4 and 3.5).

Radiocarbon measurements were performed at the Centre for Isotope Research of the University of Groningen (the Netherlands), using a MICADAS Accelerator Mass Spectrometer (Ionplus AG; Synal *et al.*, 2007). For background information on the principles of radiocarbon dating we refer to e.g. Bayliss *et al.* (2004); Ramsey (2008b); and Törnqvist and Hijma (2012). For a full description of the (pre-treatment) methods in Groningen we refer to Dee *et al.* (2020). Here we only concisely describe details of chemical pre-treatment and other relevant characteristics of our dating samples.

The acid-base-acid (ABA) method was applied to all the charred plant remains, with respective temperatures of 80°, 80° and 20° C. For the humin and humic fractions the bulk sample material was first pre-treated with acid and base, both at 80° C. Then the base solution was kept separate and the humic fraction was obtained by addition of acid (at 20° C). The solid humic fraction was rinsed with decarbonized water to almost neutral pH and dried in an oven at 80° C. The solid material (humin fraction) that remained after the base step was rinsed to neutral pH and then treated with acid (at 20° C), rinsed with decarbonized water to neutral pH and dried in an oven at 80° C. The sample material was not sieved during the entire procedure, to secure that the very small organic particles in the bulk material were retained. Instead, a centrifuge was used to separate the solid and liquid fractions. Some of the humin fraction samples contained a lot of sand and little organic remains, which resulted in a very low carbon yield of the combusted subsample (tables 3.7-3.9). Also the obtained humic fraction yields were very low for several samples.

After chemical pre-treatment (sub)samples were weighed in tin capsules and combusted to CO_2 in an elemental analyser (IsotubeCube NCS). This analyser is coupled to an Isotope Ratio Mass Spectrometer (Isoprime 100) for measurement of $\delta^{13}C$ in the sample material. Resultant CO_2 was graphitized to carbon using hydrogen and an iron catalyst. The graphite was pressed into aluminium cathodes and measured on ^{12}C, ^{13}C and ^{14}C atoms with the MICADAS. The samples measured as graphite in the AMS, can be divided in two groups. Part of the humic and humin fractions were relatively small (up to 1 mg carbon) and these samples were measured in an AMS batch for small-sized samples. The measurement error for these samples is around ± 40 yrBP. The other part of the samples was measured as graphite in a regular AMS batch (for masses >1 mg and <2.5 mg C) and the measurement uncertainty for these samples is in general below ± 30 yrBP.

Three charred plant remains samples of S17 (M6, M12 and M3) and one humic fraction of S18 (M12) had very small sizes (< 0.5 mg) and were treated in a different way. These samples were combusted with an elemental analyser (Isotube Cube) to CO_2. The CO_2 was led into the AMS and measured directly on carbon isotopes. Since much lower carbon masses are measured in the AMS (in a much shorter time period) when introduced as CO_2 gas compared to graphite samples, the measurement uncertainty for these samples is larger ($\pm$ 60-80 yrBP) compared to the samples measured as graphite.

The ^{14}C measurement results ($F^{14}C$ and ^{14}C age in tables 3.7 to 3.9) are calculated according to the conventions (Stuiver and Polach, 1977), OX-II (SRM 4990C) was used as calibration standard, and the results are corrected for background signals using background reference materials and for isotopic fractionation using the $\delta^{13}C$ value measured with AMS.

3.2.9 Calibration and age-depth modelling

The radiocarbon dates were calibrated using IntCal20 (Reimer *et al.*, 2020) in the OxCal program (version 4.4; Ramsey, 1995). The calibrated ages are presented as likelihoods in age-depth plots in OxCal (i.e., initially no further assumptions were applied in a Bayesian modelling framework). Subsequent modelling was based on the following assumptions:

- Plant macrofossil ages provide the best estimate of the age of a peat layer (based on correct chronology as shown in fig. 3.7a/e/i and in line with the consensus in literature to date short-lived, aboveground plant macrofossils of terrestrial species with AMS, see e.g. Piotrowska *et al.*, 2011.
- For reasons outlined in fig. 3.1, humic and humin samples may potentially yield different ages than plant macrofossil samples.
- Agreement of humic/humin ages with plant macrofossil ages indicates that the humic/humin samples are contemporaneous with the peat layer from which they were obtained. As such, they provide a representative indication of the age of the peat layer.
- In contrast, disagreement of humic/humin ages with plant macrofossil ages indicates that the humic/humin samples are not contemporaneous with the peat layer from which they were obtained, and do not accurately represent the age of the peat layer.

For each core, the dates of plant macrofossils were modelled using the P_Sequence function (Ramsey, 2008a) as follows. Start and end of the P_Sequence were defined with a Tau_Boundary and regular Boundary respectively. The levels of the start of the peat initiation process, basal peat layer and end of the peat initiation process (i.e., as based on %OM data, see fig. 3.7) were specified in the P_Sequence. If no macrofossil date for these levels was available, the Date command was added as query to generate an age distribution. The Difference command was used to calculate a distribution for the amount of time that passed between the start and end of the peat initiation process. A t-type outlier model (Ramsey, 2009) using a T(5) distribution and U(0,4) scale was combined with the P_Sequence. The t-type outlier model is intended for cases where the measured sample might not relate to the event being dated (Ramsey, 2009). The prior probability for a macrofossil date to be an outlier was set to 5% (i.e., one out of twenty might be an outlier). The resulting age-depth models were calculated based on a model averaging approach, where macrofossil dates that are more probable to be outliers are down-weighted (Ramsey, 2009). See the link to the dataset on page 57 for the OxCal scripts.

The likelihoods of humic and humin ages were plotted together with the macrofossil-based P_Sequences. The degree of overlap of the humic/humin likelihoods with the 95% confidence interval of the P_Sequences indicates the accuracy of the humic/humin dates in representing the age of the peat layer from which they were obtained.

Table 3.5: *Overview of the charred aboveground plant remains that were selected for radiocarbon dating. When a number is given, this is the exact amount encountered, cf. = resembles, + = present, ++ = frequent. The sample weight is the mass of the sample before the start of the chemical pre-treatment.*

Core	From (m O.D.)	To (m O.D.)	Aboveground plant remains (all charred) for ^{14}C dating	Sample weight (mg)
S17	7.495	7.505	*Calluna vulgaris*, twig fragments + Herbaceous stem, fragments + *Sphagnum*, stem fragments +	8.63
	7.485	7.495	*Erica tetralix*, leaf fragments + *Calluna vulgaris*, twig fragments + *Calluna/Erica*, twig fragments + *Herbaceous stem*, fragments + *Bryales*, stem fragments +	20.78
	7.475	7.485	*Erica tetralix*, 3 leaves *Eriophorum vaginatum*, 1 spindle *Calluna/Erica*, twig fragments +	4.21
	7.300	7.310	Deciduous wood, undetermined	1.36
	7.290	7.300	Herbaceous stem fragments +	0.87
	7.280	7.290	Herbaceous stem ~18 fragments (incl. cf. *Juncus*)	11.75
	7.210	7.220	Herbaceous stem fragments (cf. *Eriophorum*) ++	9.70
	7.200	7.210	Herbaceous stem and stem base fragments (cf. *Eriophorum*) ++	12.99
	7.190	7.200	Herbaceous stem ~16 small fragments	3.07
S18	11.79	11.80	*Calluna vulgaris*, twig fragments + *Calluna/Erica*, twig fragments + Herbaceous stem, fragments + *Sphagnum*, stem fragments +	2.34
	11.78	11.79	*Calluna/Erica*, twig fragments + Herbaceous stem, fragments +	0.57
	11.77	11.78	Cyperaceae (cf. *Eriophorum)*, stem base 3 fragments Herbaceous stem, fragments +	3.30
	11.73	11.74	*Calluna/Erica*, twig fragments (lower parts) + Herbaceous stem, fragments + *Sphagnum*, stem 1 fragment	8.16
	11.72	11.73	*Calluna/Erica*, twig fragments + Herbaceous stem, fragments +	7.44
S20	10.37	10.38	*Erica tetralix*, 1 leaf *Calluna/Erica*, twig fragments +	4.98
	10.36	10.37	*Erica tetralix*, 2 leaves *Calluna/Erica*, twig fragments +	18.09
	10.33	10.34	*Erica tetralix*, 1 leaf *Calluna/Erica*, twig fragments + *Bryales*, stem fragments +	4.86
	10.32	10.33	*Calluna/Erica*, twig fragments	5.26
	10.31	10.32	*Calluna/Erica*, twig fragments + Herbaceous stem, fragments +	4.47
	10.26	10.27	Herbaceous stem, 2 small fragments	0.04
	10.25	10.26	Herbaceous stem, fragments + Charcoal, small fragments +	1.58
	10.24	10.25	Herbaceous stem, 1 fragment Charcoal, 1 small fragment	1.04

3.3 Results

3.3.1 The organic matter gradient of the mineral-to-peat transition: defining basal peat (M_d)

The five vertical series of LOI measurements to derive the OM gradient at the mineral-to-peat transition are shown in fig. 3.6. The data show a clear and abrupt rise of OM over a distance of a few cm. Based on this outcome *peat* was defined as material with an OM percentage of 40% or higher (i.e., the defining value M_d = 40%). The layer called *basal peat* is therefore the first cm of material with OM $\geq$ 40%.

3.3.2 Plant macrofossils (PM) and testate amoebae (TA)

Overall the samples that originated from the stratigraphical layer described as amorphous organic matter (table 3.2) contained few macrofossils. In the non-decomposed (waterlogged) peat (table 3.2) mostly belowground remains such as rootlets, radicelle and rhizomes were preserved. Few waterlogged aboveground plant tissues were present, however charred aboveground remains could often be identified (table 3.6).

In general, all investigated levels of the three cores contained small unidentifiable rootlets. Part of the rootlets was of Cyperaceous origin, of which some were identified as *Carex radicelle*. The bottom levels of S18 and S20 contained fine sand, and in some of these levels also sclerotia of the mycorrhizal fungus *Cenococcum geophilum* were present. In the core of lowest elevation, S17, the bottom levels (7.17 to 7.20 m O.D.) contained a few leaves of Sphagnum austinii (S. imbricatum) and six megaspores of *Selaginella selaginoides*. From 7.20 to 7.22 m O.D. many charred herbaceous stems were present, of which some likely derived from stem bases (corm) of *Eriophorum*. Slightly higher in the profile (7.28 to 7.31 m O.D.) fewer herbaceous stems were observed and many sclerotia of the fungus *Cenococcum geophilum* were found. The upper three levels, from 7.475 to 7.505 m O.D., contained vegetative remains of *Eriophorum vaginatum*, *Erica tetralix*, *Calluna vulgaris*, *Bryales* species, *Sphagnum austinii* and other *Sphagnum* species. In core S20, between 10.30 and 10.34 m O.D., leaf and/or stem remains of *Poaceae* (including *Phragmites* and other species) were present, which were not found in core S17 and S18. In the upper levels of cores S18 and S20, charred herbaceous stems and twigs of *Calluna vulgaris* and/or *Erica tetralix* were found. In addition, the upper levels of core S20 contained some stems of *Bryales* mosses, whereas in core S18 some charred *Sphagnum* stems were found. Both core S18 and S20 contained waterlogged seeds of *Juncus* (*Juncus conglomeratus/effusus*) in their upper levels.

Almost none of the investigated levels contained suitable material for testate amoebae analyses. In four subsamples only a few damaged or broken tests were present, which could be identified as *Difflugia pristis* or other *Difflugia* species.

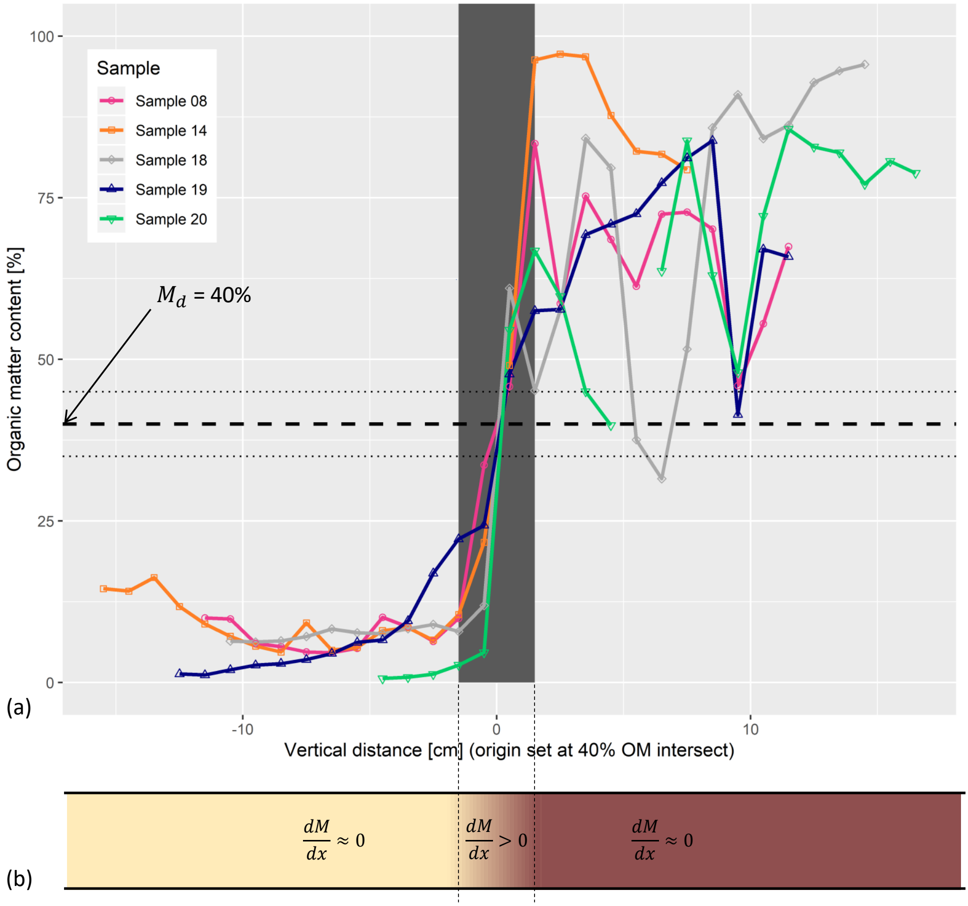


Figure 3.6: *(a) Organic matter data of five cores (for locations, see fig. 3.2). The dashed horizontal line shows the value of M_d, which was set at 40% OM. The dotted horizontal lines indicate an OM content of 35% and 45% for ease of comparison. For one 1-cm-thick layer of core 20 no data were available, this causes the discontinuity in the green line. (b) Schematic core rotated 90° clockwise, showing conceptual organic matter gradient (see also fig. 3.1b.*

Core	From (m O.D.)	To (m O.D.)	*Sphagnum*, stem fragments (c)	*Sphagnum austinii*, leaves	*Bryales*, stems (c)	*Calluna vulgaris*, twig fragments (c)	*Calluna vulgaris*, leaves (c)	*Calluna vulgaris*, leaves	*Calluna/Erica*, twig fragments (c)	*Erica tetralix*, leaves, fragments (c)	*Erica tetralix*, leaves, fragments	Poaceae (excl. *Phragmites*), leaf/stem epider	Poaceae (incl. *Phragmites*), leaf/stem epider	*Eriophorum vaginatum*, spindle (c)	Cyperaceae, cf. *Eriophorum*, stem base (c)	Herbaceous stem fragments (c)	*Juncus*, seeds	*Juncus conglomeratus/effusus*, seeds	*Carex*, radicelle	Cyperaceae, rootlets/radicelle	Undetermined rootlets/radicelle	Undetermined rhizome epidermis	Wood, decidous, fragments (c)	*Cenococcum geophilum*, sclerotia	*Selaginella selaginoides*, megaspores	*Difflugia*	*Difflugia pristis*	Charcoal, fragments	Fine sand	Stratigraphy
17	7.495	7.505	+	+		+										+					+++	+								peat
17	7.485	7.495		+	+	+		2	+	+						+					+	+								peat
17	7.475	7.485							+	3				1							+++									peat
	‖	‖																												
17	7.430	7.440				8	2			12	1															NA	NA			peat
	‖	‖																												
17	7.390	7.400			+											+	+							+		NA	NA			peat
	‖	‖																												
17	7.300	7.310																		+	+	++	+	++++						peat
17	7.290	7.300														+				+	+++	+++		+++						peat
17	7.280	7.290														18						+		++						peat
	‖	‖																												
17	7.210	7.220													+	++			+	+	+	+								MtP
17	7.200	7.210													+	++			+	+	+	+								BP
17	7.190	7.200		+												16			+	+	+	+								MtP
17	7.180	7.190																	+	+	+	+								MtP
17	7.170	7.180		+															+	+	+				6		2			MtP
18	11.79	11.80	+			+			+							+		++	+	+	+									peat
18	11.78	11.79							+							+		++	+	+	+									MtP
18	11.77	11.78													3	+		++	+	+	+									MtP
	‖	‖																												
18	11.73	11.74	+						+							+			+	+	+					1				BP
18	11.72	11.73							+							+			+	+	+								+	MtP
18	11.71	11.72																	+	+	+								+	mineral
18	11.70	11.71																	+	++	++			+					+	mineral
	‖	‖																												
18	11.68	11.69																	+	++	++			+						mineral
18	11.67	11.68																	+	+	+								+++	mineral
18	11.66	11.67																	+	+	+								+++	mineral
18	11.65	11.66																	+	++	++			+					+++	mineral
20	10.37	10.38							+	1								++		++	+									peat
20	10.36	10.37							+	2									+	+	++									peat
	‖	‖																												
20	10.33	10.34			+				+	1			+							+	++	+								MtP
20	10.32	10.33							+											+	++	+								MtP
20	10.31	10.32							+							+				+	++	+								MtP
20	10.30	10.31										+							+	+	++									BP
20	10.29	10.30																		+	++					1				MtP
	‖	‖																												
20	10.26	10.27														2			+	+	++								++	mineral
20	10.25	10.26														+				+	++			++				+	++	mineral
20	10.24	10.25														1			+	+	++							1	++	mineral

Table 3.6: *(Table on previous page). Results of the analyses of plant macrofossils and testate amoebae. When a number is given, this is the exact amount encountered, (c) = charred, cf. = resembles, + = present, ++ = frequent, +++ = abundant, ++++ = extremely abundant, NA = not available. Final column indicates stratigraphy (also see table 3.2), MtP (indicated with light grey shading) = mineral-to-peat transition (see fig. 3.7), BP = basal peat.*

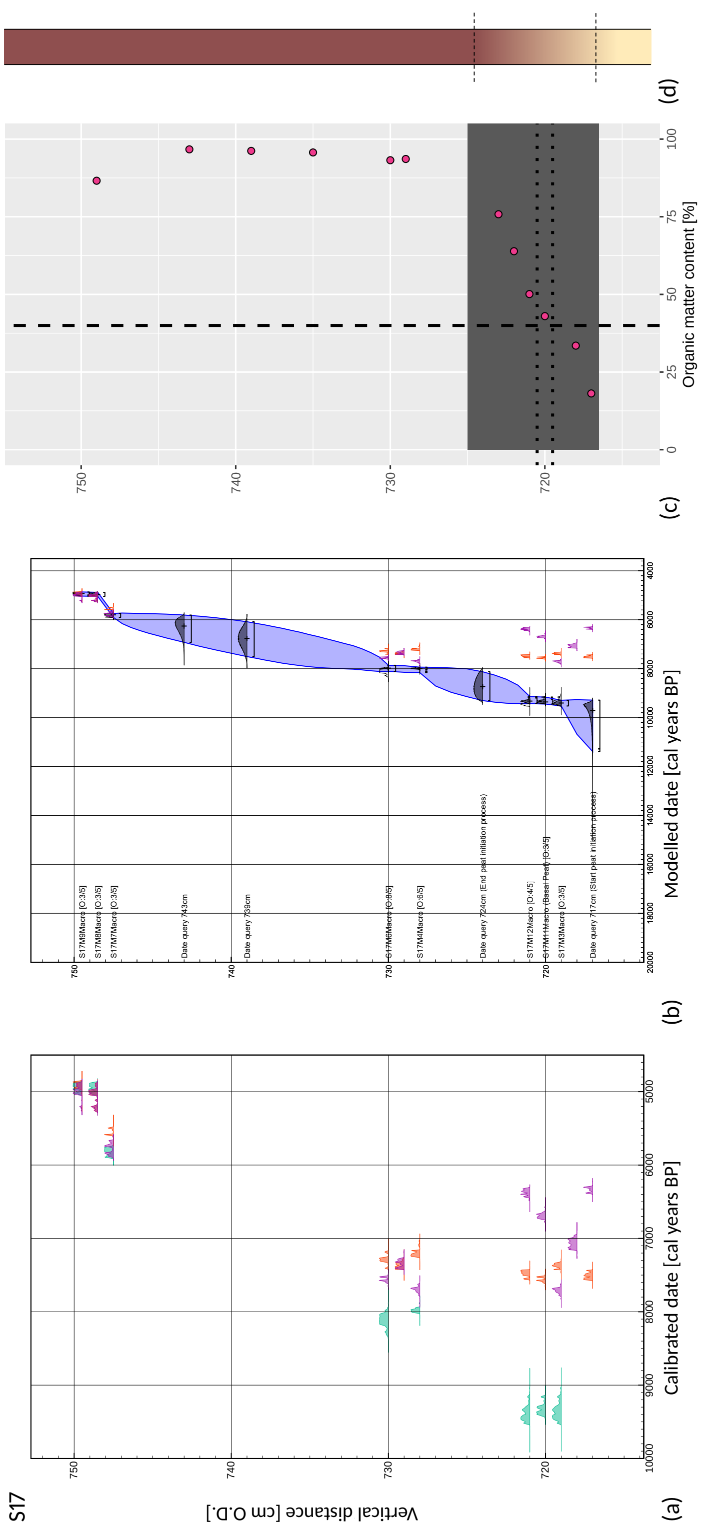
3.3.3 Dating results

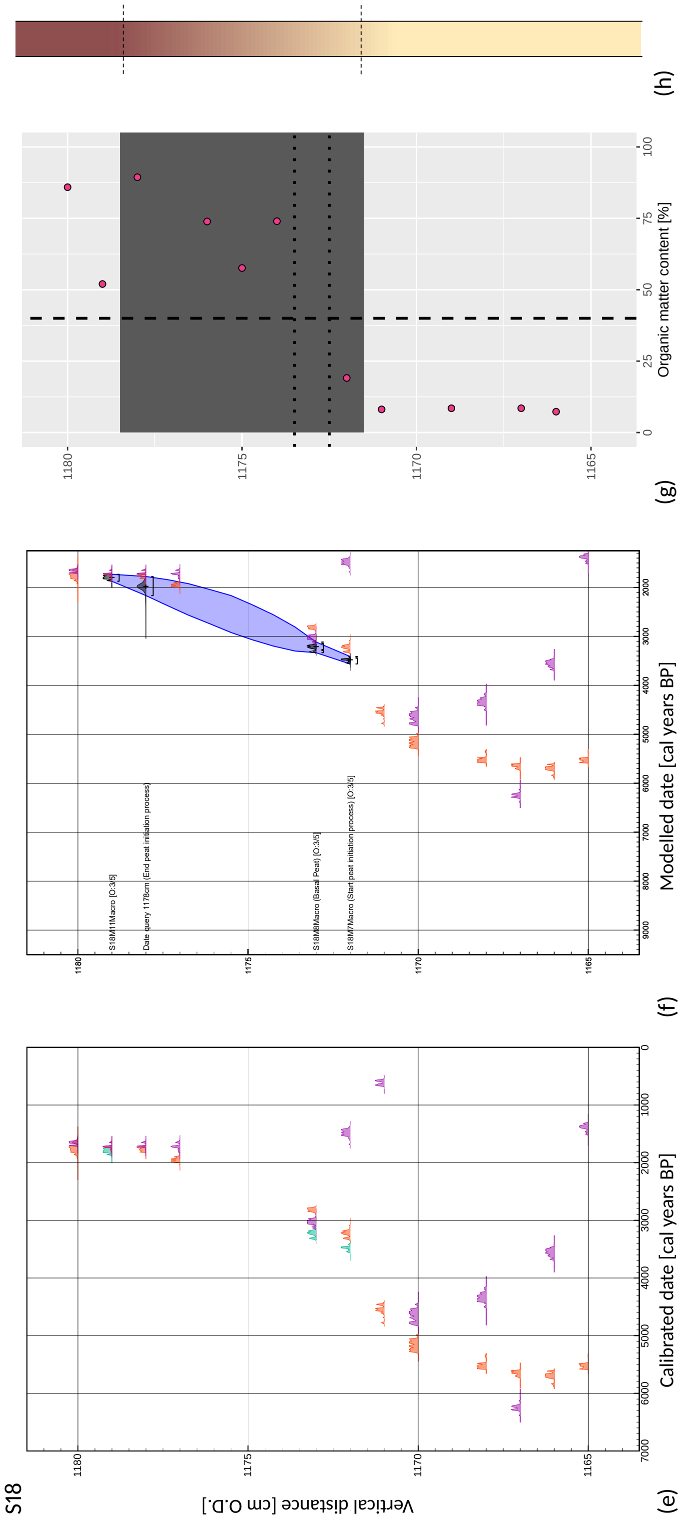
The radiocarbon dating results for the investigated levels for each core are shown in tables 3.7 to 3.9. The calibrated ages, modelled P_Sequences, and OM content are shown in fig. 3.7. Overall, the chronological order of the dates from macrofossils concurs with stratigraphical position (older at the bottom and younger towards the top). However, there is one reversal in core S20 at 10.31 to 10.32 m O.D.. The chronological order of the humic dates is also largely correct, with a few exceptions of minor reversals (S17: 7.19 and 7.28 m O.D.; S18: 11.65 m. O.D.; S20: 10.24 m. O.D.). For higher levels (above the mineral-to-peat transition), humin ages converge with those based on humics and plant macrofossils. For lower levels however, humin ages are scattered.

Dates of plant macrofossils, humics and humins diverge for samples from the mineral-to-peat transition (i.e., in fig. 3.7 between 'Start of peat initiation process' and 'End of peat initiation process'), especially for core S17. The higher in the profile and the further away from the mineral-to-peat transition, dates of plant macrofossils and both humic and humin fractions are increasingly in agreement. At the levels where the radiocarbon ages diverge, dates of plant macrofossils represent the oldest fraction in cores S17 and S18. For core S17 the difference between the macrofossils and humics is relatively constant for the samples below 7.22 m O.D., while also the dates of these fractions are relatively constant with increasing depth. In core S20, no plant macrofossils were available from the sandy layers at the bottom. Here, the humics are generally oldest, humin ages are very dispersed.

The part of the stratigraphy with the rising OM gradient ('period of peat initiation' as explained in fig. 3.1b, also see fig. 3.6) reflects the timespan (duration) of the peat initiation process. Based on the P_Sequences presented in fig. 3.7, this timespan was modelled (fig. 3.8). Results show that the peat initiation process took a median of 1073 years at the location of core S17 (91 – 2706 years at 95.4% probability). At the site of S20 the process took a bit longer with a median duration of 1343 years (472 – 2040 at 95.4%). The process took longest at site S18, here the median lies at 1510 years (1301 – 1714 years at 95.4%).

Figure 3.7: *(Figure on next pages). Overview of dating results and OM percentages for core S17 (a-d), S18 (e-h) and S20 (i-l). (a/e/i) Age-depth plot showing the likelihoods of all dated fractions; green = macrofossils, orange = humics, pink = humins. Note that some likelihoods overlap, see tables 3.7-3.9 for an overview of all dated fractions per layer. (b/f/j) Age-depth plot showing the result of a P_Sequence based on macrofossil dates, accompanied with an outlier model (see Methods for details). The probability for a date to be an outlier is indicated behind each date at the left side of the plot in the format [O:x/5], where x gives the posterior probability and 5 the prior probability that was entered in the outlier model (always set to 5%). Blue shading = 95.4% confidence interval, + = median of modelled posterior distribution, orange = likelihood of humics, pink = likelihood of humins. Degree of overlap of the humic/humin likelihoods with the confidence interval of the P_sequence indicates accuracy of the humic/humin dates in representing the age of the peat layer from which they were obtained. (c/g/k) Organic matter data, the combination of dashed and dotted lines indicates which sample is the first with OM $\geq$ 40%, dark grey shading = samples that encompass the peat initiation process (mineral-to-peat transition). (d/h/l) Schematic cores showing conceptual stratigraphy as in fig. 3.1b and 3.6b.*


S17
Vertical distance [cm O.D.]
Calibrated date [cal years BP]
Modelled date [cal years BP]
Organic matter content [%]
(a)
(b)
(c)
(d)


S18
Vertical distance [cm O.D.]
Calibrated date [cal years BP]
Modelled date [cal years BP]
S18M11Macro [O:3/5]
Date query 1178cm (End peat initiation process)
S18M8Macro (Basal Peat) [O:3/5]
S18M7Macro (Start peat initiation process) [O:3/5]
Organic matter content [%]
(e)
(f)
(g)
(h)

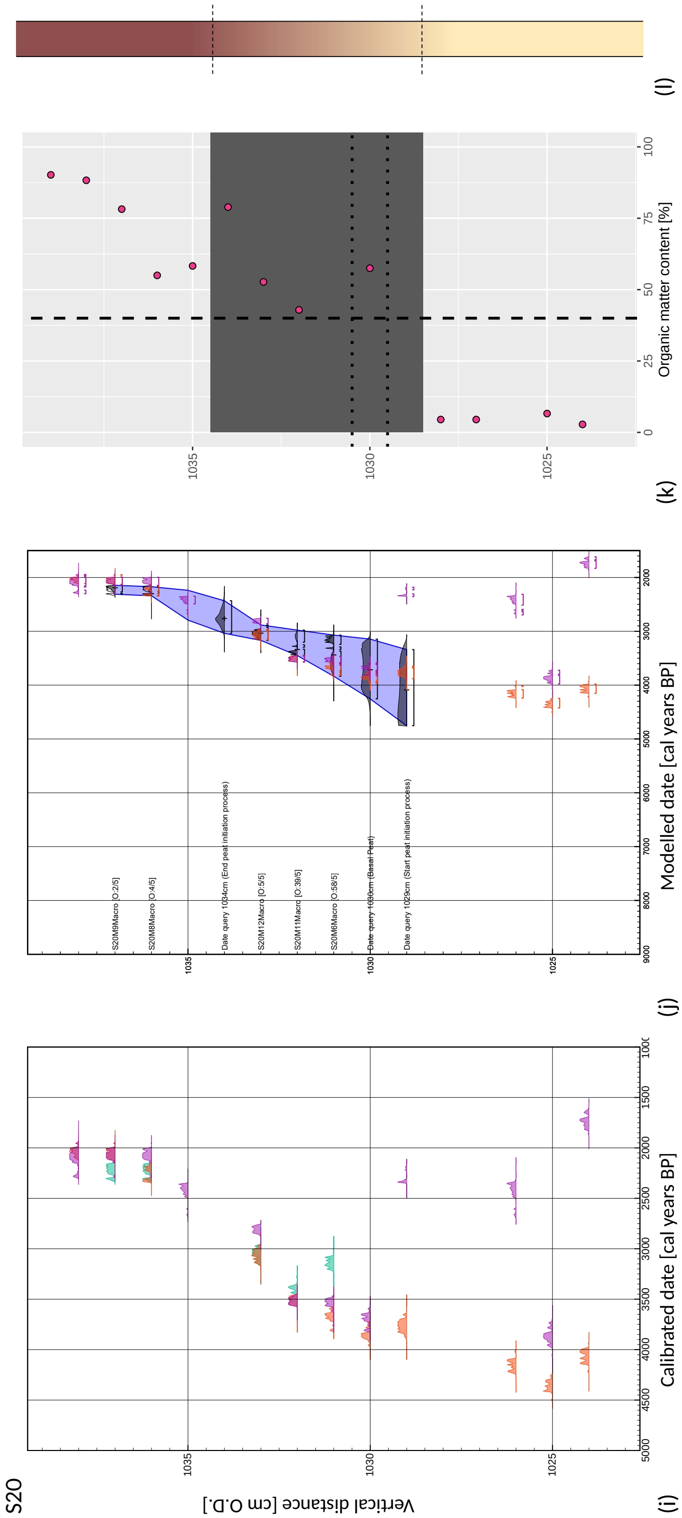

S20
Vertical distance [cm O.D.]
Calibrated date [cal years BP]
(i)
Modelled date [cal years BP]
S20M9Macro [O:2/5]
S20M8Macro [O:4/5]
Date query 1034cm (End peat initiation process)
S20M12Macro [O:5/5]
S20M11Macro [O:39/5]
S20M6Macro [O:58/5]
Date query 1030cm (Basal Peat)
Date query 1029cm (Start peat initiation process)
(j)
Organic matter content [%]
(k)
(l)

Table 3.7: *Dating results for core S17. CPR = charred plant remains, NA = not available.*

From (m O.D.)	*To (m O.D.)*	*Sample name*	*Dated fraction*	*Lab-ID*	*$F^{14}C$*	*± (1σ)*	*^{14}C age (yrBP)*	*± (1σ)*	*$\delta^{13}C$ (IRMS)*	*± (1σ)*	*%C*
7.495	7.505	S17-M9-B	humin	GrM-23376	0.5775	0.0019	4410	26	-27.09	0.15	62.1
7.485	7.495	S17-M8-B	humin	GrM-23797	0.5759	0.0018	4433	26	-27.17	0.15	55.0
7.475	7.485	S17-M7-B	humin	GrM-23515	0.5354	0.0017	5019	26	-27.62	0.15	64.5
7.300	7.310	S17-M6-B	humin	GrM-23516	0.4345	0.0015	6696	29	-27.56	0.15	63.7
7.290	7.300	S17-M5-B	humin	GrM-23517	0.4504	0.0016	6407	29	-28.57	0.15	55.5
7.280	7.290	S17-M4-B	humin	GrM-23520	0.4255	0.0016	6864	30	-27.79	0.15	56.3
7.210	7.220	S17-M12-B	humin	GrM-23731	0.4973	0.0017	5612	27	-28.28	0.15	13.9
7.200	7.210	S17-M11-B	humin	GrM-23732	0.4817	0.0017	5868	29	-28.08	0.15	5.9
7.190	7.200	S17-M3-B	humin	GrM-23733	0.4247	0.0016	6878	30	-28.25	0.15	9.5
7.180	7.190	S17-M2-B	humin	GrM-23734	0.4644	0.0017	6162	29	-28.05	0.15	10.7
7.170	7.180	S17-M1-B	humin	GrM-23736	0.5023	0.0017	5532	27	-28.16	0.15	7.2
7.495	7.505	S17-M9-B	humic	GrM-23285	0.5821	0.0019	4346	26	-28.13	0.15	57.2
7.485	7.495	S17-M8-B	humic	GrM-23829	0.5759	0.0019	4433	27	-27.09	0.15	50.5
7.475	7.485	S17-M7-B	humic	GrM-23830	0.5477	0.0018	4836	27	-28.45	0.15	49.1
7.300	7.310	S17-M6-B	humic	GrM-23831	0.4527	0.0016	6365	30	-28.23	0.15	50.3
7.290	7.300	S17-M5-B	humic	GrM-23832	0.4486	0.0016	6439	29	-28.45	0.15	56.8
7.280	7.290	S17-M4-B	humic	GrM-24024	0.4585	0.0016	6264	29	-27.49	0.15	9.3
7.210	7.220	S17-M12-B	humic	GrM-24025	0.4408	0.0016	6580	29	-26.79	0.15	15.7
7.200	7.210	S17-M11-B	humic	GrM-23865	0.4346	0.0016	6695	30	-26.99	0.15	20.9
7.190	7.200	S17-M3-B	humic	GrM-23866	0.4465	0.0016	6477	30	-27.30	0.15	15.0
7.170	7.180	S17-M1-B	humic	GrM-23867	0.4383	0.0016	6625	30	-27.57	0.15	22.1
7.495	7.505	S17-M9	CPR	GrM-23521	0.5791	0.0017	4388	24	-26.32	0.15	66.1
7.485	7.495	S17-M8	CPR	GrM-23522	0.5786	0.0019	4395	26	-26.55	0.15	61.5
7.475	7.485	S17-M7	CPR	GrM-23523	0.5315	0.0018	5077	27	-27.85	0.15	67.1
7.300	7.310	S17-M6	CPR	GrM-23491	0.4032	0.0041	7300	80	NA	NA	NA
7.280	7.290	S17-M4	CPR	GrM-23524	0.4097	0.0016	7168	30	-26.30	0.15	64.0
7.210	7.220	S17-M12	CPR	GrM-23492	0.3513	0.0033	8400	80	NA	NA	NA
7.200	7.210	S17-M11	CPR	GrM-23525	0.3556	0.0013	8305	30	-25.42	0.15	63.1
7.190	7.200	S17-M3	CPR	GrM-23493	0.3528	0.0036	8370	80	NA	NA	NA

Table 3.8: *Dating results for core S18. CPR = charred plant remains, NA = not available.*

From (m O.D.)	*To (m O.D.)*	*Sample name*	*Dated fraction*	*Lab-ID*	*$F^{14}C$*	*± (1σ)*	*^{14}C age (yrBP)*	*± (1σ)*	*$\delta^{13}C$ (IRMS)*	*± (1σ)*	*%C*
11.80	11.81	S18-M12-B	humin	GrM-23819	0.8017	0.0022	1775	22	-27.79	0.15	49.9
11.79	11.80	S18-M11-B	humin	GrM-23820	0.7969	0.0021	1823	22	-28.20	0.15	24.4
11.78	11.79	S18-M10-B	humin	GrM-23822	0.7979	0.0022	1814	22	-28.13	0.15	42.9
11.77	11.78	S18-M9-B	humin	GrM-23825	0.7971	0.0028	1821	29	-27.74	0.15	38.0
11.73	11.74	S18-M8-B	humin	GrM-23826	0.6973	0.0022	2896	26	-27.30	0.15	20.1
11.72	11.73	S18-M7-B	humin	GrM-24009	0.8177	0.0044	1615	45	NA	NA	1.4
11.71	11.72	S18-M6-B	humin	GrM-24010	0.9203	0.0049	665	45	NA	NA	2.8
11.70	11.71	S18-M5-B	humin	GrM-24011	0.5993	0.0035	4115	45	NA	NA	2.8
11.68	11.69	S18-M4-B	humin	GrM-24012	0.6145	0.0033	3910	45	NA	NA	0.08
11.67	11.68	S18-M3-B	humin	GrM-24013	0.5070	0.0028	5455	45	NA	NA	2.4
11.66	11.67	S18-M2-B	humin	GrM-24014	0.6602	0.0036	3335	45	NA	NA	0.05
11.65	11.66	S18-M1-B	humin	GrM-24015	0.8293	0.0048	1505	45	NA	NA	0.05
11.80	11.81	S18-M12-B	humic	GrM-23499	0.7958	0.0064	1840	60	NA	NA	NA
11.79	11.80	S18-M11-B	humic	GrM-23868	0.7963	0.0021	1830	21	-27.91	0.15	49.0
11.78	11.79	S18-M10-B	humic	GrM-23870	0.7938	0.0020	1855	21	-28.22	0.15	53.4
11.77	11.78	S18-M9-B	humic	GrM-23871	0.7790	0.0021	2006	22	-28.66	0.15	53.2
11.73	11.74	S18-M8-B	humic	GrM-23872	0.7117	0.0019	2732	22	-28.35	0.15	49.1
11.72	11.73	S18-M7-B	humic	GrM-23873	0.6861	0.0021	3026	24	-28.31	0.15	38.2
11.71	11.72	S18-M6-B	humic	GrM-23875	0.6029	0.0019	4064	26	-28.04	0.15	36.6
11.70	11.71	S18-M5-B	humic	GrM-23878	0.5718	0.0019	4491	26	-28.31	0.15	36.3
11.68	11.69	S18-M4-B	humic	GrM-23879	0.5526	0.0018	4765	26	-28.93	0.15	39.8
11.67	11.68	S18-M3-B	humic	GrM-23880	0.5410	0.0018	4935	27	-28.91	0.15	37.9
11.66	11.67	S18-M2-B	humic	GrM-23881	0.5380	0.0018	4980	27	-29.06	0.15	32.0
11.65	11.66	S18-M1-B	humic	GrM-23882	0.5512	0.0018	4785	26	-29.16	0.15	28.5
11.79	11.80	S18-M11	CPR	GrM-23287	0.7902	0.0024	1892	24	-28.18	0.15	62.9
11.73	11.74	S18-M8	CPR	GrM-23827	0.6863	0.0020	3024	24	-27.69	0.15	64.0
11.72	11.73	S18-M7	CPR	GrM-23828	0.6659	0.0020	3267	24	-27.62	0.15	62.2

Table 3.9: *Dating results for core S20. CPR = charred plant remains, NA = not available.*

From (m O.D.)	*To (m O.D.)*	*Sample name*	*Dated fraction*	*Lab-ID*	*F14C*	*± (1σ)*	*^{14}C age (BP)*	*± (1σ)*	*δ^{13}C (IRMS)*	*± (1σ)*	*%C*
10.38	10.39	S20-M10-B	humin	GrM-23798	0.7686	0.0043	2115	45	-28.06	0.15	49.1
10.37	10.38	S20-M9-B	humin	GrM-23799	0.7692	0.0023	2108	24	-28.55	0.15	47.2
10.36	10.37	S20-M8-B	humin	GrM-23800	0.7693	0.0023	2107	24	-27.04	0.15	27.8
10.35	10.36	S20-M7-B	humin	GrM-23801	0.7423	0.0022	2394	24	-28.10	0.15	37.5
10.33	10.34	S20-M12-B	humin	GrM-23802	0.7131	0.0024	2716	27	-29.16	0.15	16.2
10.32	10.33	S20-M11-B	humin	GrM-23803	0.6628	0.0020	3304	24	-28.60	0.15	26.7
10.31	10.32	S20-M6-B	humin	GrM-23812	0.6608	0.0020	3328	24	-29.69	0.15	29.5
10.30	10.31	S20-M5-B	humin	GrM-23813	0.6518	0.0021	3438	26	-30.09	0.15	34.9
10.29	10.30	S20-M4-B	humin	GrM-24006	0.7512	0.0022	2298	24	NA	NA	7.7
10.26	10.27	S20-M3-B	humin	GrM-24007	0.7451	0.0043	2365	45	NA	NA	2.4
10.25	10.26	S20-M2-B	humin	GrM-23737	0.6413	0.0033	3570	40	NA	NA	13.2
10.24	10.25	S20-M1-B	humin	GrM-24008	0.7963	0.0040	1830	40	NA	NA	1.3
10.38	10.39	S20-M10-B	humic	GrM-23968	0.7723	0.0021	2076	22	-28.07	0.15	53.4
10.37	10.38	S20-M9-B	humic	GrM-24018	0.7707	0.0025	2093	26	-27.94	0.15	42.8
10.36	10.37	S20-M8-B	humic	GrM-24017	0.7543	0.0026	2265	27	-26.83	0.15	16.6
10.33	10.34	S20-M12-B	humic	GrM-23883	0.6954	0.0021	2918	24	-28.05	0.15	35.1
10.32	10.33	S20-M11-B	humic	GrM-24019	0.6635	0.0025	3295	30	-28.20	0.15	27.8
10.31	10.32	S20-M6-B	humic	GrM-23884	0.6530	0.0021	3424	26	-28.22	0.15	49.1
10.30	10.31	S20-M5-B	humic	GrM-24021	0.6419	0.0022	3561	27	-28.77	0.15	46.7
10.29	10.30	S20-M4-B	humic	GrM-23969	0.6473	0.0033	3495	40	-29.29	0.15	32.7
10.26	10.27	S20-M3-B	humic	GrM-23885	0.6247	0.0020	3779	26	-29.11	0.15	30.0
10.25	10.26	S20-M2-B	humic	GrM-24022	0.6135	0.0020	3924	27	-28.75	0.15	14.9
10.24	10.25	S20-M1-B	humic	GrM-23886	0.6290	0.0023	3725	29	-28.85	0.15	20.2
10.37	10.38	S20-M9	CPR	GrM-23814	0.7580	0.0020	2225	22	-24.54	0.15	66.4
10.36	10.37	S20-M8	CPR	GrM-23815	0.7577	0.0020	2229	22	-25.24	0.15	63.9
10.33	10.34	S20-M12	CPR	GrM-23208	0.6962	0.0027	2910	30	-26.94	0.15	60.6
10.32	10.33	S20-M11	CPR	GrM-23817	0.6746	0.0022	3163	26	-26.90	0.15	71.3
10.31	10.32	S20-M6	CPR	GrM-23818	0.6906	0.0021	2974	24	-26.53	0.15	63.1

3.4 Discussion

Here we discuss the process of peat initiation as reflected by the mineral-to-peat transition in the stratigraphical record, the resulting definition of *basal peat* (3.4.1), followed by the reconstructed palaeoenvironment (3.4.2), the course and timespan of peat initiation (3.4.3), and the age assemblage of the different carbon fractions (3.4.4). Based on this, recommendations for dating *basal peat* are formulated (3.4.5).

3.4.1 Mineral-to-peat transition and basal peat (defining M_d)

Our analyses demonstrate that the organic matter content shows a clear and steep rise over a distance of a few centimetres, starting at low values of about 10% and increasing to more than 90% (fig. 3.6). This gradient reflects the stratigraphical mineral-to-peat transition. The drastic rise in OM content occurs around an OM percentage of 40%. In the explanation of the Dutch soil classification system by De Bakker and Schelling (1966), a range of organic matter classes is defined based on OM and clay percentages (by mass). For soils containing 0 to 8% clay (as in our case study area), the material is called *peat* when containing $>$35% OM (in case of 8% clay) or $>$40% OM (when containing 0% clay). This is in strong agreement with the results of our LOI tests (fig. 3.6), based on which we have selected 40% OM as cut-off value (M_d) above which we define the material as *peat*. The first 1-cm-thick subsample that contained $\geq$ 40% OM is therefore defined as the basal peat layer.

3.4.2 Palaeoenvironment

The investigated cores contained a limited amount of well-preserved plant macrofossils. Part of these remains is charred (table 3.6). In several levels sclerotia of *Cenococcum geophilum*, a mycorrhizal fungus that usually lives in the sandy subsoil, were observed (table 3.6). In peat, the presence of *C. geophilum* may indicate relatively dry conditions (Van Geel, 1978). Presence of charred and uncharred plant remains in multiple levels of the cores suggests (local) wildfires (for more information on (palaeo)wildfires in peatlands see e.g. Zaccone *et al.*, 2014; Nelson *et al.*, 2021; Rein and Huang, 2021). Dry periods allow further breakdown of material, which could explain the rather poor preservation of uncharred (waterlogged) macrofossils.

It is important to note that even though a bog remnant is studied here, the basal peat is in fact fen peat (which is quite often the case; see e.g. Korhola, 1994; Cubizolle *et al.*, 2007). The mineral-to-peat transition is later followed by a fen-bog transition as a result of ombrotrophication (for more information on the latter transition see e.g. Almquist-Jacobson and Foster, 1995; Hughes, 2000; Hughes and Barber, 2004; Väliranta *et al.*, 2017; Loisel and Bunsen, 2020). Our findings indicate that at all three cored locations the peat-forming vegetation was initially mesotrophic. The local vegetation was dominated by sedges, with some presence of *Juncus* (table 3.6). After the peat initiation process, conditions became more oligotrophic, and the vegetation at S17 and S18 developed probably to an oligotrophic bog with *Calluna vulgaris*, *Erica tetralix* and *Sphagnum* (ombrotrophic conditions). At the location of S20 no *Sphagnum* remains were found, but the vegetation likely changed to a moss (*Bryales*) and heather vegetation.

The investigated cores appeared to be very low in testate amoebae content. However, the presence of *Difflugia* species in a few samples suggests very wet conditions. This taxon and the presence of abundant diatoms (which were observed during TA analysis but not subject of further study) suggest a fen environment (rather than an ombrotrophic bog), which is in agreement with the botanical data. Testate amoebae are often poorly preserved under fen-type conditions, possibly due to predation, physical disaggregation or chemical dissolution, or a combination of these (Roe *et al.*, 2002; Swindles and Roe, 2007; Swindles *et al.*, 2020).

In the investigated levels, *C. geophilum* does not occur simultaneously with *Difflugia* species. This mutual exclusion suggests respectively drier and wetter conditions that alternated during the timespan of the peat initiation process. Additionally, a detailed study by Sullivan and Booth (2011) has shown that several *Difflugia* species (including *D. pristis*) are able to cope with fairly high levels of short-term variability in environmental conditions at the peat surface. This variability appeared to be higher at locations with loose-growing *Sphagnum* (rather than dense *Sphagnum* cover) or where vegetation was dominated by vascular plants and non-*Sphagnum* bryophytes (Sullivan and Booth, 2011). We suggest that such conditions may be similar to those in our study area during peat initiation and the transition to an oligotrophic bog.

3.4.3 Time span of the peat initiation process

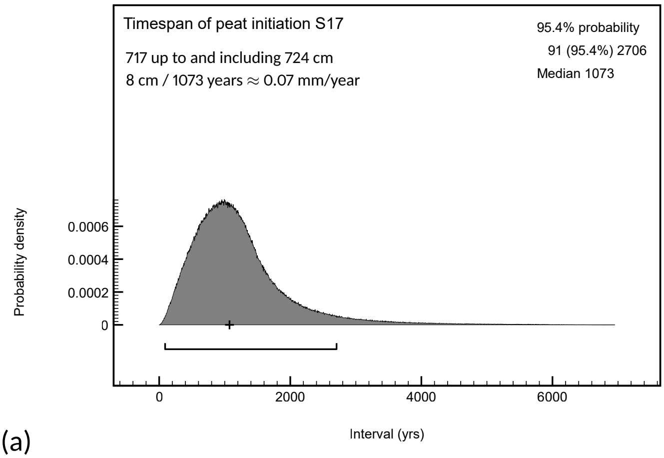
The stratigraphical reach with the rising OM gradient (fig. 3.1b and 3.6) reflects the timespan of the peat initiation process. Based on the P_Sequences in fig. 3.7, these timespans were modelled for each core (fig. 3.8). Results show that this process lasted for 1073, 1510 and 1343 years (medians) for core S17, S18, and S20 respectively. In the stratigraphy, this is reflected in a vertical distance of respectively 8, 7 and 6 cm. This means that apparent vertical accumulation during these first stages of peat development varied between the sites with values of 0.07, 0.05 and 0.04 mm/year for core S17, S18, and S20 respectively. A typical value given for the apparent peat accumulation rate in the catotelm is 1 mm/year, and may be lower further down in the catotelm due to compaction and anaerobic decomposition (Rydin and Jeglum, 2013e). A low apparent accumulation rate is indeed the case here, with rates far below 1 mm/year. This implies that 1 cm of peat, at the slowest rate of 0.04 mm/year, reflects about 250 years of peat growth.

Very few studies have investigated the timespan that is reflected in the first centimetres above the layer they define as basal peat. For two cores, Berendsen *et al.* (2007) dated a pair of vertically spaced samples (taken 11 cm apart in one core and 9 cm apart in the other), and found age differences of respectively 60 and 120 calendar years. Based on this, they conclude that within-core sampling resolution is less critical than previously assumed.

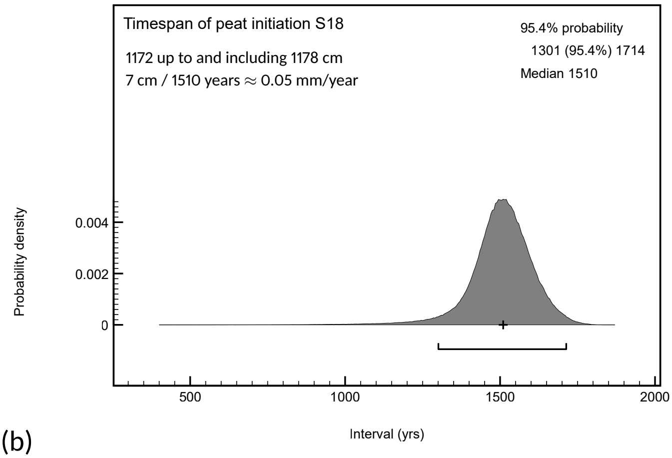
The difference between our results and those of Berendsen *et al.* (2007) highlights that the peat initiation process cannot be assumed to be rapid in all cases and is influenced by environmental setting. Depending on the timespan of the peat initiation process and the apparent accumulation rate, a high vertical sampling resolution and small sample thickness can be crucial to obtain accurate dates. The duration of peat initiation also determines to which degree a date of basal peat is representative to use as starting point for build-up of peat deposits.

It is important to note that the reconstructed timespans and apparent accumulation rates are based on age-depth relationships (instead of a mass-age relationship). These age-depth relationships do not consider gross accumulation and subsequent decay separately, but only the apparent vertical increase (potentially affected by decomposition and/or compaction). Due to water-saturated conditions for significant periods of time, bioturbation by soil fauna is presumably low during the peat initiation process. This assumption is corroborated by the intact chronostratigraphy of macrofossils shown in our cores (fig. 3.7a/e/i). As the timespan of the peat initiation process is potentially long, we emphasize that sampling resolution and sample thickness are key points to consider when dating the start of peat growth.

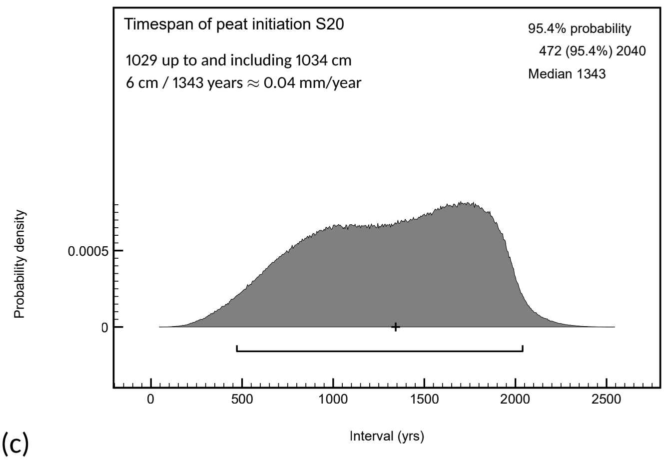
Figure 3.8: *(Figure on next page). Timespan (duration in years) of the peat initiation process in cores S17, S18 and S20, derived from the P_Sequence models shown in fig. 3.7(b/f/j) (see Methods for details). Apparent accumulation rate (expressed in mm/year) was calculated by dividing the stratigraphical distance of the peat initiation process (provided in cm, see also fig. 3.7(b/f/j)) by the modelled median of the timespan. Note that these accumulation rates are based on an age-depth relationship (instead of a mass-age relationship) and do not consider gross accumulation and subsequent decay separately, but only the apparent vertical increase (potentially affected by decomposition and/or compaction).*


Timespan of peat initiation S17
717 up to and including 724 cm
8 cm / 1073 years ≈ 0.07 mm/year
95.4% probability
91 (95.4%) 2706
Median 1073
Probability density
0.0006
0.0004
0.0002
0
0
2000
4000
6000
Interval (yrs)

(a)


Timespan of peat initiation S18
1172 up to and including 1178 cm
7 cm / 1510 years ≈ 0.05 mm/year
95.4% probability
1301 (95.4%) 1714
Median 1510
Probability density
0.004
0.002
0
500
1000
1500
2000
Interval (yrs)

(b)


Timespan of peat initiation S20
1029 up to and including 1034 cm
6 cm / 1343 years ≈ 0.04 mm/year
95.4% probability
472 (95.4%) 2040
Median 1343
Probability density
0.0005
0
0
500
1000
1500
2000
2500
Interval (yrs)

(c)

3.4.4 Age assemblage of carbon fractions

Our data demonstrate that macrofossils (i.e., in situ material) in the basal peat layer are oldest, and that both humics and humins generally show younger ages. In line with the general consensus in literature (e.g. Piotrowska *et al.*, 2011), we consider the macrofossils to reflect the 'true' age, i.e. representative for the timing when the vegetation accumulated at the specific location. Aboveground remains (no roots) of terrestrial plants are expected to have been in equilibrium with atmospheric ^{14}C values until they died and we therefore do not expect any reservoir effect (also see Blaauw *et al.*, 2004). In this study, samples were carefully selected, cleaned and pre-treated with the full ABA-protocol to minimise the presence of any contamination with carbon from sources other than the original plant materials (see sections 3.2.6 and 3.2.8). The macrofossils show a clear chronological order, with samples dating younger upwards in the profile, which suggests that macrofossil relocation through bioturbation is unlikely. There is only one reversal for the macrofossils in core S20 at 10.31 m O.D., while the humic and humin fractions of this same layer do not show a deviation in chronology. The cause for this deviation remains unclear. The outlier model shows that there is an increased chance that either S20M11macro or S20M6macro is an outlier; through the model averaging approach these dates are corrected in the P_Sequence (fig. 3.7j).

Despite the correct chronological order of the humic dates, the age difference between humics and plant macrofossils in core S17 from 7.19 to 7.30 m O.D. shows that the absolute humic ages are likely too young (fig. 3.7a and 3.7b). This difference in age ranges from about 1700 to 800 years. The same applies to core S18 at depths 11.72 and 11.73 m O.D. (fig. 3.7e and 3.7f), with age differences of about 250 to 400 years. This is different in core S20, where two humic samples dated older than macrofossils from the same layer. At 10.31 m O.D., the macrofossil sample deviates from the chronology (see above), which causes a fairly large difference with the humic age of approximately 530 years (fig. 3.7i and 3.7j). At 10.32 m O.D. however, where the macrofossil date concurs with chronological order, the humic date is only about 120 years older.

The humins, both in the *basal peat* but also below in the Pleistocene deposits, show younger ages than the humics and plant macrofossils, and remarkably little coherence. In the sandy Pleistocene layers the organic matter content was low and sand content high. Separating this small amount of carbon from the sand in the lab appeared to be challenging, resulting in several humin samples with fairly low %C (tables 3.7 to 3.9). If some younger material is incorporated here, the influence on the resulting age will be larger due this small sample size. This may account for part of the observed variation.

Overall, both the humic and humin fractions derived from the mineral-to-peat transition result in younger ages. Fluctuating water tables during the process of peat initiation (discussed above), might explain the origin of younger carbon in these first peat layers. Changes in hydraulic head may lead to both upward and downward (and also sideward) movement of soluble organic compounds (Waddington and Roulet, 1997). Low water levels specifically allow downward water movement through the profile, potentially transporting mobile humic acids that contain young carbon to lower levels. As the mobility of humics is pH-dependent (Wüst *et al.*, 2008), the initial mesotrophic conditions allow higher mobility than the more acid, ombrotrophic conditions that follow later in time (see above).

Brock *et al.* (2011) dated humic and humin fractions from three grain sizes obtained through wet-sieving (63-125 μm, 125-250 μm and >250 μm), originating from a 1-cm-thick layer positioned 1 cm below the level they regarded to reflect peat initiation. Their results show that for two of these grain sizes, the humic and humin dates are not significantly different from each other. However, both the dates of the humics and the humins become older with increasing grain size, suggesting that the fine particulate matter may be responsible for younger contaminations in both fractions. In our study, the bulk material was not sieved during the entire pre-treatment procedure, to secure that the very small organic particles in the bulk material were retained. Presence of this fine fraction may be responsible for the observed younger dates of the humics and humins, but does not explain the erratic pattern of the humin dates.

Downgrowth of roots may also cause age differences in bulk samples compared to aboveground plant macrofossils, a problem that appears to be of particular relevance in the case of slowly accumulating (fen) peat (Streif, 1972; Törnqvist *et al.*, 1992) such as encountered here during the peat initiation process. The effect may also depend on the botanical composition of the peat-forming vegetation, as certain species such as *Phragmites* or *Eriophorum vaginatum* (table 3.6) can produce fairly deep roots (Kohzu *et al.*, 2003; Iversen *et al.*, 2015). As humics and humins result from decomposition, their ages may result partly from in-situ carbon and partly from younger carbon that originated from mobile fulvic and humic acids and roots. Additional dating of separated rootlets at multiple levels slightly above the mineral-to-peat transition may shed more light on the sources of error in the ages of the humics and humins for dating peat initiation.

Holmquist *et al.* (2016), who compared radiocarbon dating results for plant macrofossil and bulk samples obtained from basal peat in circum-arctic peatlands, found no significant difference in ages. Based on this they conclude that evidence for a consistent systematic bias introduced by the incorporation of bulk peat dates in large basal ^{14}C databases from peatlands is lacking. In contrast, the large age difference between dates of plant macrofossils and humic or humin dates (up to ~1700 years between macrofossil and humic ages in our case study peatland,

and with even larger differences for humins, fig. 3.7a and 3.7e) indicates that studies reusing existing bulk dates of basal peat should take great care in data interpretation. Some of these studies, which concentrate on regional or global reconstructions of peat initiation (e.g. Tolonen and Turunen, 1996; Macdonald *et al.*, 2006; Ruppel *et al.*, 2013), have important implications for climate research and carbon budgets. Depending on the sample type obtained from the dated basal peat layers, dates are potentially interpreted more safely as terminus-ante-quem dates for peat initiation, or should be subjected to rigorous quality assessment prior to data analysis (Quik *et al.*, 2021).

Higher in the peat profile however, dates of plant macrofossils, humics and humins converge, indicating homogeneity regarding carbon fractions and ages. Some of these dates do not differ significantly, others fall within a (very) short timeframe (fig. 3.7b, 3.7f and 3.7j). We suggest that as water tables started fluctuating less, peat accumulation speed began to increase (compare slope in the P_Sequences, most clearly visible for core S18 in fig. 3.7f), and conditions became more ombrotrophic (start of *Sphagnum* growth, table 3.6). As a result, downward water flow declined and mobility of humics decreased. In line with Törnqvist *et al.* (1992) and Blaauw *et al.* (2004), our findings suggest that when focus is not directed towards the basal peat, but to higher layers in the peat profile that are characterised by more stable water tables and higher accumulation rates, one might obtain accurate dates through bulk sampling (both humics and humins).

In the mineral soil horizons, i.e. those with <40% OM, generally no (above-ground) plant remains could be recognised. Samples from the stratigraphical layers peaty sand/sandy peat and Pleistocene deposits (i.e., the palaeosoil that became covered with peat, table 3.2) could therefore only be radiocarbon dated using the humic and humin fractions. Humic acids are considered to be the most reliable fraction for dating organic matter in soils if no plant remains and (almost) no organic carbon is present (Van der Plicht *et al.*, 2019). Indeed, the humin ages of the Pleistocene layers display poor coherence (fig. 3.7) with frequent stratigraphical inconsistencies. Humic ages in contrast provide results that are stratigraphically consistent. In core S18 for example (fig, 3.7e), the four humic samples between 11.65 to 11.69 m O.D. all date around 5500 cal y BP. This consistency could suggest that these samples represent the slow build-up of organic matter in the sandy soil (i.e., at the time prior to peat growth). Some of the humin dates in the mineral horizons show remarkably young ages, perhaps due to the small amount of total carbon in these samples as mentioned above (tables 3.7 to 3.9), and relatively larger quantities of carbon from other carbon sources. Dating soil organic matter in mineral soils is complicated and involves different processes than peat initiation (see e.g. Goh and Molloy, 1978; Van Mourik *et al.*, 1995; Van der Plicht *et al.*, 2019), further study of these dates is therefore beyond the scope of the present study.

3.4.5 Recommendations for dating peat initiation

Our study highlights that peat initiation is a process rather than an event, which has implications for dating peat initiation and *basal peat*. This process is reflected in the stratigraphy as a gradual boundary between mineral sediments and overlying peat deposits. The mineral-to-peat transition can be characterised using the organic matter gradient ($\frac{dM}{dx}$, fig 3.1b). The use of biostratigraphical indicators to define basal peat, as for instance in the approach used by Törnqvist *et al.* (1998), is not always possible due to limited presence of plant macrofossils and potential lack of testate amoebae. However, if material is present and resources allow, including additional biostratigraphical analyses to characterise the palaeoenvironment of the peat initiation process is valuable.

The layer that is interpreted as *basal peat* should be defined clearly and quantitatively, which ensures reproducibility and eases intercomparison of studies. To move towards a quantitative definition of *basal peat*, a simple parameter such as OM is useful as it is easy to measure at low cost, which enables widespread use. Based on the obtained organic matter gradient ($\frac{dM}{dx}$) that reflects the peat initiation process, a value (M_d) can be chosen for the organic matter percentage above which the material is called *peat*. The first cm that has an OM% equal to or above this value is defined as the *basal peat* layer.

Based on our results, an M_d value of 40% OM would be recommendable to define *basal peat* in areas comparable to our case study peatland. This value agrees very well with the Dutch soil classification (De Bakker and Schelling, 1966), especially given the low clay content of the soils in our study area (table 3.2). However, for peatlands in other regions or with a different botanical composition near the base, LOI-testing may result in a different value for M_d.

As organic matter measurements using LOI require burning the subsample, care should be taken beforehand to ensure sufficient allocation of sample material to all required analyses. Additionally, it should be kept in mind that post-depositional changes such as downgrowth of roots may change OM content, therefore determining the OM gradient over a reach of several cm is useful to contextualise single measurements. We therefore highly recommend to investigate a stratigraphical range to properly contextualise the mineral-to-peat transition and for selecting an OM value to define the *basal peat*.

An additional advantage of organic matter content determination is that this information may help in estimating chances to obtain sufficient amounts of plant macrofossils for ^{14}C dating from specific layers. For the three cores investigated in this study, nearly all (12 out of 14) of the macrofossil samples for dating originated from layers with an organic matter content of 40% or higher. Most of the dated layers with OM below 40% did not contain sufficient macrofossils for dating and were dated solely using humics and humins. Depending on the organic matter gradient and local conditions, this potentially varies between study regions, but may be taken into account for sample selection.

Depending on the timespan of the peat initiation process and apparent accumulation rate, sampling resolution and sample thickness may affect the accuracy of dates in representing the start of peat growth. If accumulation rates are high, a lower vertical sampling resolution or sample size of several cm's might be adequate, whereas lower accumulation rates may require detailed sampling with small sample sizes depending on the research question to be answered. If the timespan of peat initiation and related apparent accumulation rate are unknown, studies aiming to date basal peat with a higher accuracy than several hundred (potentially thousand) years should take great care regarding vertical sampling resolution and sample size, as the assumption of a rapid process is not always valid.

An elaborate dating inventory comparable to the approach of the present study is valuable as it provides detailed information on the peat initiation process and on the accuracy of different carbon fractions for dating. To gain insight in the timespan of peat initiation, and consequently to ensure accurate dates of the peat initiation process and basal peat, dating several vertically spaced samples within one core as a preceding test is very useful. If time allows, such a layered or multi-stage approach for dating peat initiation and lateral expansion is recommendable (also see staged approaches for dating as suggested by Bayliss, 2009 and Piotrowska *et al.*, 2011). For instance, after obtaining the OM gradient dating plant macrofossils and humics of three levels dispersed over the mineral-to-peat transition would allow substantiated choices for sampling size and resolution for subsequent spatial dating schemes. These preliminary dates and insights may be used to run simulations in OxCal to evaluate potential outcomes of alternate approaches for more extensive (spatial) sampling and dating. If a multi-stage approach is not possible and only one level of each core is dated without prior tests, assumptions on the timespan of peat initiation and related choices in sampling resolution and sample size should be explicitly discussed.

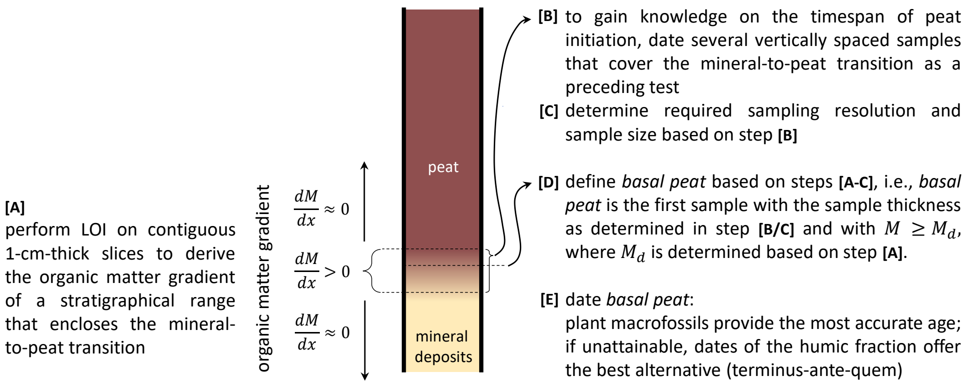
Our findings show that plant macrofossils provide the most reliable age near the mineral-to-peat transition and the basal peat layer, and are therefore recommendable to use for ^{14}C dating. The full ABA pre-treatment of macrofossils lowers the risk of chemical contamination and should be applied when possible. If plant macrofossils are unattainable, either due to poor preservation or limited resources for biostratigraphical analyses, dates of the humic fraction provide the best alternative regarding chronological order. These dates may however deviate from those of plant macrofossils, and our data show that humics can therefore only provide a terminus-ante-quem for the dated levels. If bulk samples are used, it is important to clearly report which fraction was obtained from the sample and used for dating. If marker layers such as tephra are present, these can be used to correlate sites or even provide independent age control if a date can be obtained for the event.

Above the mineral-to-peat transition, our results indicate that dating results of plant macrofossils, humics and humins converge. This implies that humics and humins might be a useful alternative to plant macrofossils for dating peat layers higher in the profile. Justifying this choice would however require a-priori dating knowledge of the peatland under study, and occasional cross-checks with macrofossil dates to ensure accuracy of results.

If the peatland under study is protected as a nature reserve (i.e., not a peat extraction site or location with an outcrop), digging a trench for sampling all the way down to reach the mineral-to-peat transition creates a large disturbance (and would be severely hampered by practical challenges with water infilling). Coring provides an efficient alternative, even though commonly used coring tools such as the Russian corer have a limited sample volume. This limits the options for dating in combination with multiproxy study at a high resolution (Piotrowska *et al.*, 2011). This combination is possible (e.g. as in our study), but requires careful allocation of material to various analyses and involves dating (very) small samples. If chances for obtaining plant macrofossils are encouraging (e.g. based on OM%), one could choose to sacrifice the bulk subsample intended for dating and process it for plant macrofossil analysis. If the expectation regarding plant macrofossils is low, then keeping a bulk sample would offer the possibility to obtain at least a terminus-ante-quem for peat initiation using the humic fraction extracted from the bulk sample.

Textbox 3.1: *Summary of recommendations for dating peat*

- Study the mineral-to-peat transition using the organic matter gradient, and if resources allow, by including biostratigraphical analyses (see [A] in the textbox figure below);
- Take the timespan of the peat initiation process into account when deciding upon sample size and sampling resolution. A layered or multi-stage approach is useful to gain insights on the duration of peat initiation prior to executing elaborate spatial dating schemes (see [B] and [C]);
- Define *basal peat* based on the organic matter gradient to obtain a low-cost, quantitative and reproducible definition that eases intercomparison of studies (see [D]);
- Regarding which fraction to use for ^{14}C dating basal peat (see [E]), our data show that plant macrofossils provide the most accurate age in the mineral-to-peat transition and are therefore recommendable to use. If these are unattainable, dates of the humic fraction provide the best alternative regarding chronological order, but may deviate significantly from the 'true age'. Our results show that humic dates are best interpreted as terminus-ante-quem dates;
- Potentially limited options for sampling and resulting small sample volumes require detailed consideration of allocating material to analyses (see fig. 3.5 for an example).



3.5 Conclusions

3.5.1 Dating peat initiation

In this study we aimed to formulate updated recommendations for dating peat initiation. We based our approach on a conceptual framework (fig. 3.1) that supports the use of the organic matter (OM) gradient for a quantitative and reproducible definition of the mineral-to-peat transition (i.e., the stratigraphical range reflecting the timespan of the peat initiation process) and the layer defined as *basal peat* (i.e., the stratigraphical layer that is defined as the bottom of a peat deposit). Subsequently we analysed the mineral-to-peat transition for a case study peatland in the Netherlands, based on three detailed series of radiocarbon dates that include plant macrofossils, humics and humins. Our findings demonstrate that plant macrofossils, even though their presence in basal peat is often limited, provide the most reliable dating results. If insufficient plant macrofossils are retrieved, the humic fraction provides the best alternative for dating, however dating results are most safely interpreted as a terminus-ante-quem for peat initiation. The potential large age difference between dates of plant macrofossils and humic or humin dates (up to ~1700 years between macrofossil and humic ages, and with even larger differences for humins) indicates that studies reusing existing bulk dates of *basal peat* should take great care in data interpretation. The potentially long timespan of the peat initiation process (with medians of ~1000, ~1300 and ~1500 years within our case study peatland) demonstrates that choices regarding sampling size and resolution need to be well substantiated. Our findings are summarised as a set of recommendations for dating *basal peat* in textbox 3.1.

3.5.2 Palaeoenvironment

Our case study peatland in the Netherlands currently harbours a bog vegetation, but biostratigraphical analyses show that during peat initiation the vegetation was mesotrophic. This vegetation was dominated by sedges, with some presence of *Juncus*. The data indicate that the peat initiation process initially involved fluctuating water tables and that wetter and drier conditions probably alternated. Frequent presence of charred plant remains demonstrates that wildfires occurred regularly. After the peat initiation process, conditions became more oligotrophic, and the vegetation developed probably to an oligotrophic bog with *Calluna vulgaris*, *Erica tetralix* and *Sphagnum* at two of the studied locations and to a moss (*Bryales*) and heather vegetation at the third location.

Author contributions
RvB secured funding for this research. CQ proposed the research outline, which was further improved based on feedback by JW, JC, BM, YvdV, and RvB. JC and CQ explored the study area, performed test corings and decided upon a coring strategy. CQ organised the fieldwork and completed the collection of data and cores in the field with help of several students (see acknowledgements). CQ coordinated all subsequent analyses that were performed on the obtained cores. Cores were opened and subsampled by MvdL and CQ. LK performed the microscopy work for analyses of plant macro remains and selection of datable material. MvdL interpreted and reported the resulting vegetation data. GS analysed the subsamples for testate amoebae. CQ performed the majority of LOI analyses, a small part of the subsamples were analysed by the CBLB (see acknowledgements). SP worked on the radiocarbon dating at the CIO laboratory in Groningen. All resulting data were combined and analysed by CQ. CQ wrote the main body of text, with input from the reports by MvdL and GS, and from discussions with JW, JC, BM, YvdV and RvB. The manuscript was finalized based on feedback from all authors.

Acknowledgements
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Chapter 4

Faded landscape: Unravelling peat initiation and lateral expansion at one of NW-Europe's largest bog remnants

Cindy Quik, Ype van der Velde, Jasper Candel,
Luc Steinbuch, Roy van Beek, Jakob Wallinga
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Abstract

In the mainland of Northwest Europe generally only remnants of former peat landscapes subsist. Due to the poor preservation of these landscapes, alternative approaches to reconstruct peat initiation and lateral expansion are needed compared to regions with intact peat cover. Here we aim (1) to find explanatory variables within a digital soil mapping approach that allow us to reconstruct the pattern of peat initiation and lateral expansion within (and potentially beyond) peat remnants, and (2) to reconstruct peat initiation ages and lateral expansion for one of the largest bog remnants of the Northwest European mainland, the Fochteloërveen. Basal radiocarbon dates were obtained from the peat remnant, which formed the basis for subsequent analyses. We investigated the relationship between peat initiation age and three potential covariates: (1) total thickness of organic deposits, (2) elevation of the Pleistocene mineral surface that underlies the organic deposits, and (3) a constructed variable representing groundwater-fed wetness based on elevation of the mineral surface and current hydraulic head. Significant relationships were found with covariate (1) and (3), which were hence used for subsequent modelling. Our results indicate simultaneous peat initiation at several loci in the Fochteloërveen during the Early Holocene, and continuous lateral expansion until 900 cal y BP. Lateral expansion accelerated between 5,500 – 3,500 cal y BP. Our approach is spatially explicit (i.e., results in a map of peat initiation ages), and allows for a quantitative evaluation of the prediction using the standard deviation and comparison of predictions with validation points. The applied method based on covariate (1) is only useful where remnant peat survived, whereas covariate (3) may ultimately be applied to reconstruct peat initiation ages and lateral peatland expansion beyond the limits of peat remnants.

4.1 Introduction

Peat initiation and subsequent lateral expansion of peatlands represent a significant change in the palaeoenvironment. Knowledge on the timing, process rates and spatial dynamics of peat initiation and expansion is essential to develop our understanding of peatland functioning and development, carbon dynamics, climate change, and long-term human-landscape interactions in peatland environments (e.g. Van der Velde *et al.*, 2021; Tolonen and Turunen, 1996; Van Beek *et al.*, 2015; Van Beek, 2015; Chapman *et al.*, 2013).

Peat initiation may result from terrestrialisation (also called infilling), paludification, or primary mire formation (Charman, 2002c; Rydin and Jeglum, 2013d). Peat deposits form if the decay rate of biomass is slower than the rate of production, i.e. where there is a positive production-decay balance. The decay rate of organic material is mainly influenced by the degree of moisture (Charman, 2002b), which is dependent on a range of factors, including climate (e.g. Weckström *et al.*, 2010), changes in hydrological base level (resulting from sea level rise, e.g. Berendsen *et al.*, 2007; or regional groundwater changes, e.g. Van Asselen *et al.*, 2017), impermeable deposits or resistant layers in the soil profile (e.g. Breuning-Madsen *et al.*, 2018; Van der Meij *et al.*, 2018), landforms and surface topography (e.g. Almquist-Jacobson and Foster, 1995; Mäkilä, 1997; Loisel *et al.*, 2013), and anthropogenic influence (e.g. Moore, 1975, 1993).

Peat initiation can be studied at landscape scale and local scale (fig. 4.1a; Chapter 3). Landscape scale peat initiation refers to the development of peat at a certain locus, i.e. the oldest core of a peatland, that subsequently expands laterally and covers an increasing surface area. At local scale, peat initiation refers to the accumulation of the first organic deposits at this particular site, irrespective of its landscape position, i.e. the site could either be a development locus or become covered with peat through lateral expansion of one or more nearby loci.

Studies on the spatio-temporal dynamics of peat initiation and lateral expansion of peatlands appear to have focused mostly on boreal and circum-arctic peatlands, e.g. in Scandinavia (Mäkilä and Moisanen, 2007; Edvardsson *et al.*, 2014), Siberia (Peregon *et al.*, 2009), Canada (Bauer *et al.*, 2003), and Alaska (Loisel *et al.*, 2013; Jones and Yu, 2010). During the past decades several supra-regional to global syntheses were published that describe large-scale trends (Ruppel *et al.*, 2013; Korhola *et al.*, 2010; Macdonald *et al.*, 2006; Crawford *et al.*, 2003; Morris *et al.*, 2018). So far, limited attention has been paid to the palaeogeographical development of the former extensive peat landscapes of the Northwest European mainland (for an indication of their former extent see, e.g. Vos *et al.*, 2020; Casparie, 1993), with the exception of coastal and alluvial peatlands in the Rhine-Meuse delta (e.g. Berendsen and Stouthamer, 2000, 2001; Hijma, 2009; Cohen *et al.*, 2014; Pierik *et al.*, 2017). This is partly due to their large-scale disappearance following reclamation activities in the past few centuries (e.g. Gerding, 1995), leaving only small peat remnants behind in the current landscape. These remnants are under increasing threat of drainage (e.g. Swindles *et al.*, 2019), pollution (e.g. Limpens, 2003), and locally continuing excavation. The exploitation of their scientific potential is therefore of poignant urgency.

In the range of studies where (boreal) peatland initiation and long-term lateral development are studied, methodologies can roughly be divided in three approaches. In the first category, lateral expansion rates are deduced using transects of basal dates and distance between dating points, but the palaeogeographical pattern of lateral development is not visualised (e.g. Almquist-Jacobson and Foster, 1995; Turunen *et al.*, 2002a; Anderson *et al.*, 2003; Turunen and Turunen, 2003; Peregon *et al.*, 2009; Robichaud and Bégin, 2009; Weckström *et al.*, 2010; Loisel *et al.*, 2013; Zhao *et al.*, 2014). In the second category, transects of basal dates are manually converted to isochrones, i.e. lines of equal age that are deduced from the spatial distribution of obtained ages (fig. 4.1b). The isochrones visualise the pattern and rate of lateral development (e.g. Bauer *et al.*, 2003; Edvardsson *et al.*, 2014; Foster *et al.*, 1988; Korhola, 1994, 1996; Mäkilä, 1997; Mäkilä and Moisanen, 2007). As a third category, numerical peat growth models can be distinguished that are based on hydrological and ecohydrological feedbacks. These simulate vertical peat growth (age-depth) for a peat column (e.g. the Holocene Peat Model, Frolking *et al.*, 2010; the DigiBog model, Baird *et al.*, 2012 and Morris *et al.*, 2012; the coupled DigiBog-STREAM model, Swinnen *et al.*, 2021). However, models that include lateral expansion are so far unavailable (see e.g. discussion on peat models by Baird *et al.*, 2012).

The use of transects of basal dates across a peatland is generally applied in areas where the natural extent of the peatland(s) under study is still intact. In regions where large areas of peatland have disappeared, the placing of such transects is questionable as the orientation of peat remnants within the former extensive peat landscape is unknown (fig. 4.1c). Additionally, peat-cutting (and ongoing excavation) may have damaged basal peat layers. Consequently, an adapted strategy is needed to collect (field) data from peat remnants. The number of studies that focus on peat remnants appears to be very low compared to studies of peatlands of which the extent is still intact (with some exceptions, e.g. the studies by Chapman *et al.*, 2013 and Crushell *et al.*, 2008).

Here we aim (1) to find explanatory variables within a digital soil mapping approach that allow us to reconstruct the pattern of peat initiation and lateral expansion within (and potentially beyond) peat remnants, and (2) to reconstruct peat initiation ages and lateral expansion for one of the largest bog remnants of the Northwest European mainland, the Fochteloërveen, in a former peat landscape of which the majority has been lost during the past centuries. The elevation of the Pleistocene surface relative to its surroundings is likely the primary control on the moment of peat initiation at Fochteloërveen: the lowest points in a region tend to grow over by peat first. However, as a secondary control, large-scale geomorphology may influence local wetness: locations that are situated relatively far from a draining river tend to have higher groundwater tables that come closer to the surface, than locations adjacent to a river. Based on the hypothesis of a two-fold control of peat initiation as discussed above, we investigate the relationship between peat initiation age and three potential covariates: (1) total thickness of organic deposits, (2) elevation of the Pleistocene mineral surface that underlies the organic deposits, and (3) a constructed variable based on elevation of the mineral surface and hydraulic head. Covariate (1) is only useful where remnant peat survived, whereas covariates (2) and (3) are potentially useful for reconstructing peat initiation age beyond peat remnants. The Holocene period up to 900 cal y BP (i.e., approximate start of the High Middle Ages in the study area) forms the temporal scope for our study, because of increased human influence from then onwards (see section 4.2.2).

4.2 Study area

4.2.1 Selection and description of study area

The Fochteloërveen peatland in the Netherlands (fig. 4.2) was chosen as case study area. The Fochteloërveen (~ 2,500 ha) is the largest Dutch bog reserve (Joosten *et al.*, 2017a), and one of the largest bog remnants in the Northwest European mainland. It was part of an extensive peat landscape (fig. 4.2c) and is protected as a Natura 2000 area (Provincie Drenthe, 2016). The widespread occurrence of its mineral substrate and characteristic climatic conditions (see below) make this peatland area representative for larger parts of the Northwest European mainland. Because of the availability of earlier obtained radiocarbon dating evidence (Quik *et al.*, 2022a) and detailed subsurface data from national databases, we consider the Fochteloërveen as an ideal case study to investigate temperate peatland development. In addition, background information on peat initiation trends in the wider region is available from a recent study based on a large set of legacy radiocarbon dates (Quik *et al.*, 2021). Various important archaeological finds have been done in the vicinity of Fochteloërveen, including a Mesolithic aurochs butchering site (Prummel and Niekus, 2011), wooden trackways from the Iron Age (Casparie, 1985), and a Roman-period settlement site that is assumed to have been deserted due to rising groundwater levels (Van Giffen, 1958).

In the north of the Netherlands a continental ice sheet was present during

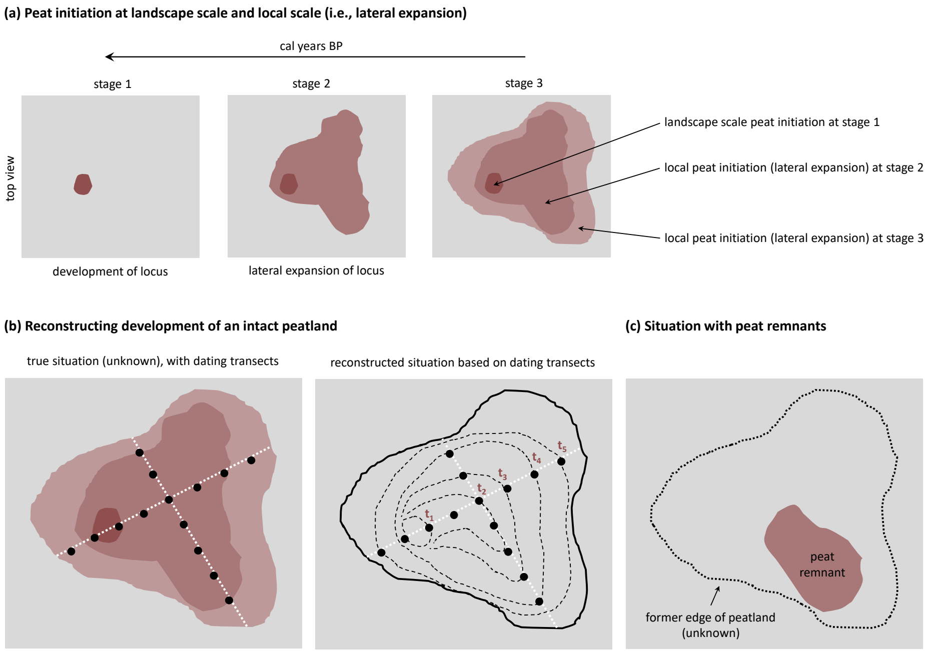


Figure 4.1: *Conceptual illustration of peat initiation and lateral expansion of peatlands. (a) Schematic top-view of a landscape (peat is indicated in brown), showing the meaning of* peat initiation *at the landscape and local scale (redrawn from Chapter 3). (b) Approach to reconstruct peat initiation and the pattern of lateral expansion using dating transects and isochrones for an intact peatland. (c) Situation when only remnants of the former peat landscape remain.*

the Saalian (MIS 6). This led to deposition of glacial till (Rappol, 1987; Rappol *et al.*, 1989; Van den Berg and Beets, 1987; TNO – Geological Survey of the Netherlands, 2021b), on the Drenthe Plateau (Bosch, 1990; Ter Wee, 1972). Deposition of aeolian coversands over Northwest Europe during the Weichselian (OIS 4-2) resulted in formation of the European Sand Belt (Koster, 1988, 2005). Coversands occur with a thickness of approximately 0.5 – 2 m on the Drenthe Plateau (TNO – Geological Survey of the Netherlands, 2021c; Ter Wee, 1979). Fochteloërveen is located close to the western edge of the Drenthe Plateau. Below the coversands a discontinuous till layer with a thickness up to 3.5 m is present underneath the peat remnant (Provincie Drenthe, 2022). Fochteloërveen is part of three catchments (fig. 4.2b). Currently average temperatures are 2.8° C in January and 17.5° C in July, average annual rainfall amounts to 805 mm, and the potential evapotranspiration is 566 mm (KNMI, 2021). Throughout the paper, we indicate elevation in metres O.D., i.e. relative to Dutch Ordnance Datum

(+NAP), which is roughly equal to mean sea level.

Fochteloërveen does not fit within a single definition or classification as it probably formed through coalescence of multiple smaller mires (see results in section 4.4) that formed on a non-coastal and non-alluvial topographic plain. However, in the hydromorphological classification (cf. Charman, 2002c), the resultant composite peatland can probably best be described as a plateau-raised bog. Fochteloërveen started off as a fen (minerogenous mire), but later on transitioned to a bog (ombrotrophic mire) (more information below; Quik *et al.*, 2022a).

Biostratigraphical analyses by Quik *et al.* (2022a) show that the vegetation was mesotrophic during peat initiation. This vegetation was dominated by sedges, with some presence of *Juncus*. Water tables fluctuated during the peat initiation process and wetter and drier conditions probably alternated. Wildfires must have occurred regularly, as indicated by the frequent presence of charred plant remains. Conditions became more oligotrophic after the peat initiation process. The vegetation developed probably to an oligotrophic bog with *Calluna vulgaris*, *Erica tetralix* and *Sphagnum* at two of the locations studied by Quik *et al.* (2022a), and to a moss (*Bryales*) and heather vegetation at the third studied location.

The vegetation of Fochteloërveen is currently dominated by *Sphagnum* mosses occurring in a hummock and hollow topography (Provincie Drenthe, 2016). Species include amongst others *S. magellanicum*, *S. papillosum*, *S. rubellum*, and vascular species typical for ombrotrophic conditions such as *Eriophorum vaginatum*, *Andromeda polifolia* and *Vaccinium oxycoccos*. Fochteloërveen harbours several protected animal species, including the common ringlet (*Coenonympha tullia*), subarctic darner (*Aeshna subarctica*), smooth snake (*Coronella austriaca*), common European adder (*Vipera berus*) and a wide range of bird species. From 2001 onwards, crane birds (*Grus grus*) settled in the area (Provincie Drenthe, 2016). Since the 1980s nature conservation is directed at peatland restoration (Altenburg *et al.*, 2017; Provincie Drenthe, 2016). Main threats for nature conservation include atmospheric nitrogen deposition and desiccation due to intense drainage for surrounding agriculture.

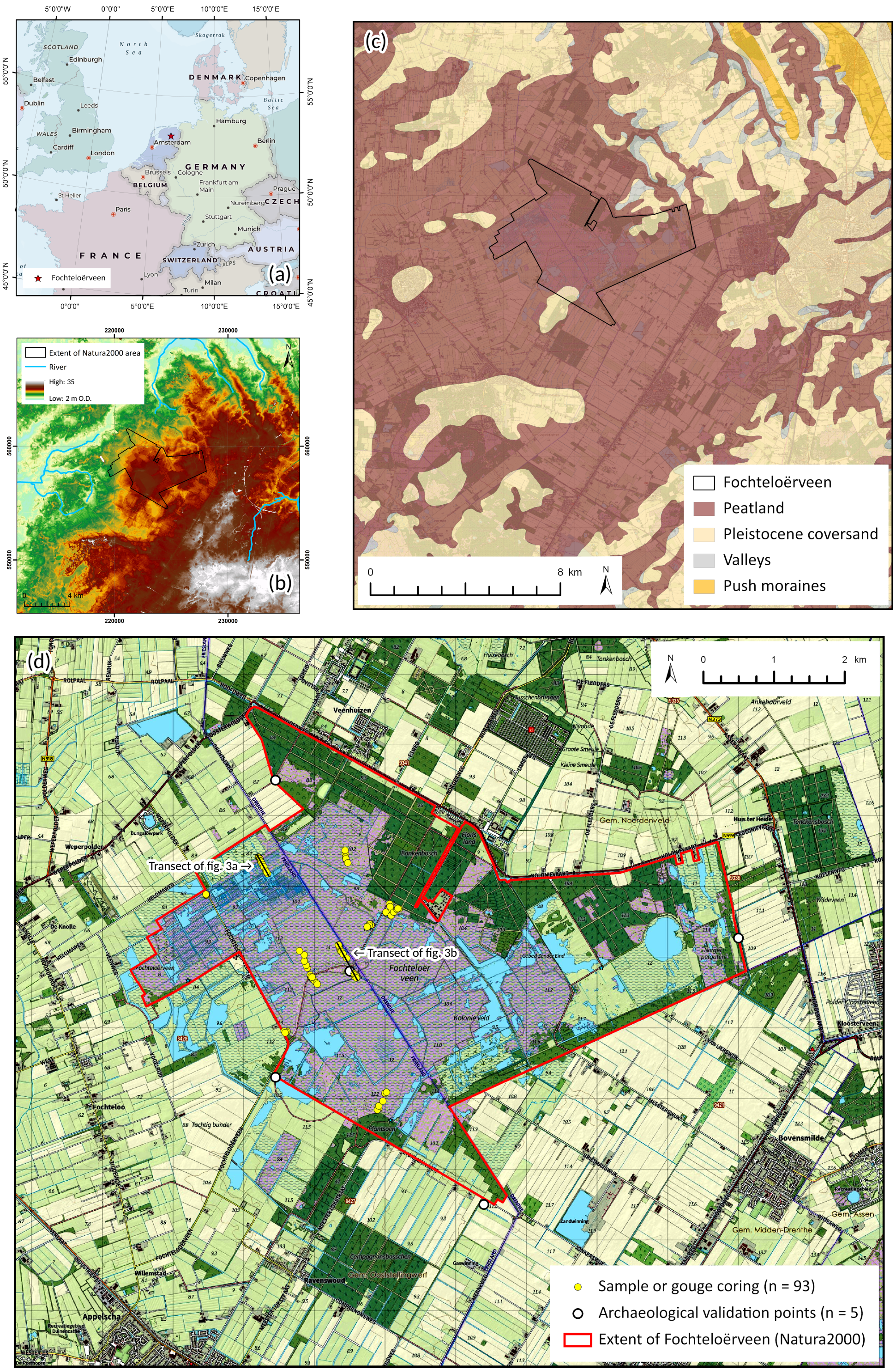

(a)
Fochteloërveen
SCOTLAND
Edinburgh
Belfast
Dublin
Leeds
WALES
Birmingham
Cardiff
London
North Sea
Skagerrak
DENMARK
Copenhagen
Baltic Sea
Hamburg
Berlin
Amsterdam
GERMANY
Brussels
Cologne
BELGIUM
Frankfurt am Main
Prague
St Helier
Paris
Nuremberg
CZECH
Stuttgart
Munich
AUSTRIA
FRANCE
Zurich
SWITZERLAND
ALPS
Lyon
Milan
Turin
CROATIA
5°0'0"W
0°0'0"
5°0'0"E
10°0'0"E
15°0'0"E
55°0'0"N
50°0'0"N
45°0'0"N
(b)
Extent of Natura2000 area
River
High: 35
Low: 2 m O.D.
220000
230000
560000
550000
0
4 km
N
(c)
Fochteloërveen
Peatland
Pleistocene coversand
Valleys
Push moraines
0
8 km
N
(d)
N
0
1
2 km
Transect of fig. 3a →
← Transect of fig. 3b
Fochteloer veen
Veenhuizen
Gem. Noordenveld
Fochteloo
Appelscha
Ravenswoud
Bovensmilde
Gem. Midden-Drenthe
Gem. Assen
Gem. Ooststellingwerf
Sample or gouge coring (n = 93)
Archaeological validation points (n = 5)
Extent of Fochteloërveen (Natura2000)

Figure 4.2: *(Figure on previous page). (a) Location of the Fochteloërveen peat remnant within Europe (ESRI, 2022); (b) Digital Elevation Model (DEM) of the wider area around Fochteloërveen (version AHN3, horizontal resolution 5 m, vertical resolution 0.1 m; AHN, 2021a,b), indicating the main drainage pattern (Ministerie van Verkeer en Waterstaat, 2007). Coordinates are in metres (Dutch RD-new [*Rijksdriehoeksstelsel*] projection). Extent of the Fochteloërveen Natura 2000 area is indicated (Ministerie van Economische Zaken - Directie Natuur & Biodiversiteit, 2018); (c) Palaeogeographical map of Fochteloërveen and surroundings, showing reconstructed situation for 500 BCE (2,450 cal y BP) as indicated by the Dutch national palaeogeographical map series (Vos* et al.*, 2020; RCE, 2022); (d) Topographical map of Fochteloërveen (OpenTopo; Van Aalst, 2022), showing coring locations (see sections 4.3.1.1 and 4.3.1.2) and position of archaeological validation points (for details see table 4.2). Peatland is indicated with purple colours. The area surrounding Fochteloërveen shows the landscape structure that resulted from historical peat colonies, peat-cutting activities and agricultural reclamation.*

4.2.2 Peatland development and decline in the (wider) study area

There is a hiatus between the deposition of coversand during the Weichselian and the formation of peat in the coversand areas in the eastern half of the Netherlands. This can be deduced from the occurrence of soil profiles in coversand (e.g. podzols) underneath the peat, and sometimes by the presence of bog wood (i.e, evidence of previous vegetation cover; Staring, 1983; Jongmans *et al.*, 2013). Theories deviate on the timing when peat growth started in the coversand landscape, on the period when these peatlands expanded, and when they reached their maximum extent (fig. 4.3). Note that in the text below, we repeat the 'old' chronostratigraphic terms that were used in the cited papers. We have added cal y BP ages to ease interpretation and comparison with the new formal subdivision of the Holocene (Walker *et al.*, 2019).

The national palaeogeographic maps created by Zagwijn (1986) indicate that peat formation started during the Early Atlantic (~7,450 cal y BP). By the Late Atlantic (~6,050 cal y BP) large raised bog complexes had formed and reached their maximum extent. From then onwards they remained laterally stable. Zagwijn (1986) placed the reaching of maximum extent in the Late Atlantic, but indicates that the true timing remains uncertain due to lack of data as a result of peat-cutting.

According to the recent palaeogeographic map series by Vos *et al.* (2020), peat initiation also started during the beginning of the Atlantic (~7,450 cal y BP). However, the peatlands continued to expand gradually during the Atlantic and Subboreal, and reached their maximum extent at the beginning of the Subatlantic (~2,450 cal y BP). From ~1500 CE (~450 cal y BP) onwards the peat-covered area rapidly declines according to the map series of Vos *et al.* (2020) due to agricultural reclamation and peat-cutting activities. The national palaeogeographic maps are based on elaborate and detailed data on the development of river deltas and coastal areas in the Netherlands (Vos, 2015b). In contrast, the reconstructions of peatlands in the coversand region have relatively large uncertainty as the amount of data on these areas is low (Vos, 2015a; Van Beek, 2009; Spek, 2004).

Few studies with regional palaeogeographical focus are available for Fochteloërveen and surroundings, but important exceptions include the work of Fokkens (1998) and Waterbolk (2007), who deduce patterns of peatland development based on archaeological find distributions. In doing so, Waterbolk (2007) deduces presence of peat through the absence of archaeological finds, whereas Fokkens (1998) considers an approach using archaeological finds only as terminus-post-quem dates for peat initiation most appropriate (i.e., absence of finds is not used as an indication for presence of peat).

Waterbolk (2007) deduces that large areas were already covered by peat during the Early and Middle Neolithic (4,900 – 2,850 BCE; 6,850 – 4,800 cal y BP). This situation remained stable for several thousand years. Rapid peatland expansion during the Iron Age, which Waterbolk (2007) linked to climate change as discussed by Van Geel *et al.* (1998), left the majority of the area uninhabited during the Roman Period (19 BCE – 450 CE; 1,969 – 1,500 cal y BP). This is in contrast to the conclusions of Fokkens (1998), who assumed that (oligotrophic) peat on the plateau was largely absent during the Middle Neolithic (5,000 cal y BP), except for very local sites.

Until recently, radiocarbon dating evidence from a (near) basal peat layer was only available for a single site in Fochteloërveen (Klaver, 1981; later published by Van Geel *et al.*, 1998), which indicated an age of 2,920 – 2,736 cal y BP (at 95.4% confidence interval). Fokkens (1998) mentions that this site represents the nucleus of the area, and consequently places peat initiation in the Fochteloërveen area between the beginning of the Early Iron Age and the end of the Roman period (800 BCE – 400 CE; 2,750 – 1,550 cal y BP). He also assumes that the maximum extent was reached during this period. Waterbolk (2007) assumes that the peatland reached its maximum extent slightly later during the Early Middle Ages (450 – 1000 CE; 1500 – 950 cal y BP), prior to the onset of systematic reclamation activities.

New dating evidence at three sites presented by Quik *et al.* (2022a) indicates that within the boundaries of the Fochteloërveen nature reserve peat developed from ~9,000 cal y BP onwards and that new areas became covered with peat at least until ~3,500 cal y BP, suggesting that landscape scale peat initiation occurred much earlier than suggested in the studies mentioned above (Vos *et al.*, 2020; Fokkens, 1998; Waterbolk, 2007; Zagwijn, 1986). The substantial differences between the studies discussed above and the overview presented in fig. 4.3 highlights the need to better constrain the timing of peat initiation and the pe-

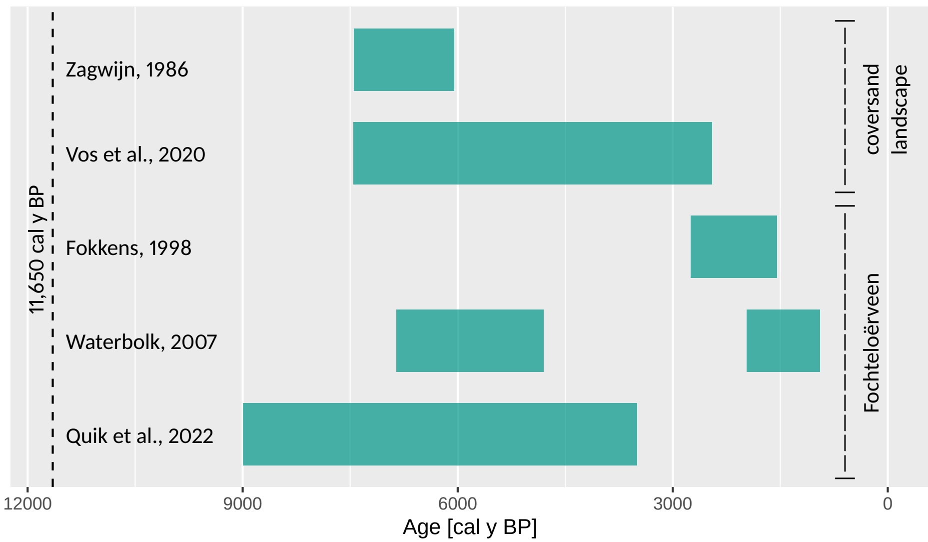


Figure 4.3: *Timing of peat initiation and period of lateral development in the Dutch coversand landscape (upper two) and at Fochteloërveen specifically (lower three), according to different studies. The x-axis is equal to fig. 4.10, to ease comparison with the outcomes of the present study.*

riod of lateral development in the coversand landscape and at Fochteloërveen specifically.

Even though local peat cutting (i.e., on a household level) took place since the Middle Ages, large-scale reclamations of the Fochteloërveen area only started in the 17th century (Gerding, 1995; Douwes and Straathof, 2019). This happened mainly for turf production, and lasted (in the last decades on a smaller scale) until the 1970s. In a large part of the area superficial peat layers are affected by buckwheat cultivation, which was at its height in the late 18th and 19th century (Douwes and Straathof, 2019). However, this practice did not affect the basal peat layers that are of interest to our study. Data from the 18th century indicate that peat thickness at Fochteloërveen has locally declined with as much as 7 m during the past three centuries (Douwes and Straathof, 2019).

4.3 Methods

4.3.1 Methods Part 1: Collection of field data and radiocarbon dating evidence

4.3.1.1 Field approach and site selection

Our field approach is directed at obtaining an extensive set of basal radiocarbon dates, which forms the basis for subsequent modelling steps. Testing the influence of the elevation of the Pleistocene surface and large-scale geomorphology requires insight both in vertical and horizontal landscape dimensions within the Fochteloërveen peat remnant. Transects of basal peat dates are generally used for reconstructions of peat initiation and lateral development (fig. 4.2b). In sea level research, where focus lies on the vertical dimension, it is custom to date basal peat samples that overlie compaction-free sediments where the groundwater level that steered peat growth can be related to former sea level (e.g. Törnqvist *et al.*, 1998). To obtain the required insight in vertical and horizontal landscape dimensions at Fochteloërveen, we chose a hybrid approach that combines spatially distributed transects with elevation gradients in the (compaction-free) mineral deposits underlying the organic deposits (also see Chapman *et al.*, 2013).

Our field exploration consisted of 93 gouge corings, mostly grouped in transects of 185 to 575 m long that were placed perpendicular to the elevation gradients of subsurface coversand ridges and depressions (fig. 4.2d and fig. 4.4). At a few sites a central gouge coring was surrounded by four corings in a radial pattern to derive the subsurface topography. For each core the stratigraphy was described (see Quik *et al.*, 2022a for details). After the field exploration 21 sites were selected for sampling, taking the distribution over the study area into account. Additionally, it was ensured that the combination of sample sites stretched the elevation range of the mineral surface underlying the organic deposits (samples cover an elevation range of 7.2 – 11.7 m O.D.). Collection and subsampling of cores, (bio)stratigraphical analyses, selection of dating samples, and radiocarbon dating procedures followed Quik *et al.* (2022a) and are summarized in sections 4.3.1.2 – 4.3.1.4.

4.3.1.2 Collection and subsampling of cores

Cores were collected in 2019 with a hand-operated stainless-steel peat corer (Russian type) with a core volume of 0.5 dm^3 (Eijkelkamp Soil & Water, 2018). Prior to sampling the corer was cleaned with deionised water. After retrieving the core it was carefully packaged in a PVC half-pipe and placed in a refrigerator of 3° C within 12 hours. Location and elevation of all sampling sites were recorded with a Topcon 250 Global Navigation Satellite System (GNSS) receiver, with a horizontal precision of ~5 mm and vertical precision of ~10 mm (RTK; TOPCON, 2017).

Directly after opening the cores the stratigraphy was described (additional to field descriptions) and the approximate mineral-to-peat transition (following Quik *et al.*, 2022a) was determined through visual inspection. Around this transition 6 to 12 contiguous 1-cm-thick slices were cut from the core. Outer edges of these slices were carefully cleaned to avoid contamination. From each slice a subsample of ~2 cm^3 was collected for loss-on-ignition; all remaining material (~5 cm^3) was reserved to select plant macrofossils for radiocarbon dating after subsample selection (see section 4.3.1.3).

4.3.1.3 (Bio)stratigraphical analyses and selection of dating samples

The organic matter (OM) content was measured using loss-on-ignition. Sample dry weight was determined after drying for 24 hours at 105° C, followed by combustion at 550° C. After obtaining the OM% for the range of slices cut from a particular core, the lowermost slice that contained ≥40% OM was defined as the *basal peat* layer (following Quik *et al.*, 2022a). Charred and uncharred plant macrofossils (aboveground tissues) were selected at BIAX Consult in Zaandam, the Netherlands for radiocarbon dating (table 4.1). For 12 cores radiocarbon samples were obtained from the *basal peat* slice. These basal dates form the calibration dataset for subsequent modelling Quik *et al.*, 2022a. In addition, five radiocarbon samples were obtained from slices of five cores that represent terminus-ante-quem (TAQ) and terminus-post-quem (TPQ) dates for peat initiation (i.e., from slices with >40% OM and slices with <40% OM respectively). The TAQ and TPQ dates are part of our validation dataset (together with archaeological validation data, see section 4.3.2.2. A table with organic matter gradients on which selection of dating samples is based, and a table with all encountered plant macrofossils (i.e., including material not selected for dating) are available online (see reference to the dataset on page 105). For three additional cores, dating information of the basal peat layer is available from Quik *et al.* (2022a,b).

4.3.1.4 Radiocarbon dating

Radiocarbon measurements were performed at the Centre for Isotope Research of the University of Groningen (the Netherlands). A full description of the methods used at this laboratory can be found in Dee *et al.* (2020); methods applied to our samples are only concisely explained below. Samples were either pre-treated using the acid-base-acid ($n = 9$) method, or only with acid ($n = 5$), or not pre-treated in case of very small and delicate samples ($n = 3$) (see reference to the dataset on page 105 for details per sample). Samples were measured using a MICADAS Accelerator Mass Spectrometer (Ionplus AG; Synal *et al.*, 2007).

Depending on sample weight after the pre-treatment, samples were measured as graphite in a regular batch (in case of 1.0 - 2.5 mg C), in a batch for small-sized graphite samples (0.1 - 1.0 mg C), or measured directly as CO_2 after combustion ($<$ 0.15 mg C). $F^{14}C$ and ^{14}C age were calculated according to the conventions (Stuiver and Polach, 1977). Results are corrected for isotopic fractionation using the $\delta^{13}C$ value measured with AMS. Dates were calibrated using IntCal20 (Reimer *et al.*, 2020) in the OxCal program (version 4.4, Ramsey, 1995).

Table 4.1: *Overview of the aboveground plant remains that were selected for radiocarbon dating. When a number is given, this is the exact amount encountered, cf. = resembles, + = present, ++ = frequent, NA = not available.*

Core	Subsample	From (m O.D.)	To (m O.D.)	Aboveground plant remains for ^{14}C dating (charred unless indicated otherwise)
S1	M4	10.53	10.54	*Calluna vulgaris* (stem 2 fragments [charred, very small fragments])
S1	M5	10.54	10.55	Ericaceae (twig fragments 3); *Erica tetralix* (leaf 1)
S2	M9	10.79	10.80	*Erica tetralix* (leaf 1, leaf 1 [un-charred]); *Calluna/Erica* (twig fragments +)
S3	M2	10.12	10.13	*Eriophorum vaginatum* (leaf and stem fragments with sclerenchyma tissue and epidermis ++, stem base (corm) with spindles 1, isolated spindles ++ [all un-charred])
S4	M9	7.16	7.17	*Carex* cf. *riparia* (5 [un-charred]), *Carex* cf. *pilulifera* (6 fragments [un-charred]; Ericaceae (twig 1 fragment); undetermined (herbaceous stem 3 fragments)
S5	M5	10.13	10.14	*Erica tetralix* (leaves 7); cf. *Erica* (twig fragments +)
S6	M8	9.74	9.75	*Erica tetralix* (leaves 8); Ericaceae (twig 3 fragments); *Carex* (3 fragments [un-charred])
S7	M7	10.55	10.56	*Eriophorum vaginatum* (spindle 1); undetermined (herbaceous stem 1 fragment)
S7	M8_9	10.56	10.58	Cf. Ericaceae (stem base/root 2 fragments); *Persicaria* (1 fragment [un-charred]); undetermined (herbaceous stem 2 fragments);
S8	M3	11.55	11.56	*Erica tetralix* (leaves 2); cf. *Erica* (flower 1); *Andromeda polifolia* (seed 1 [un-charred]); undetermined (herbaceous stem fragments +)
S9	M1	10.59	10.60	NA
S9	M2	10.60	10.61	*Reseda luteola* (seed 1 [un-charred]); undetermined (herbaceous stem 2 fragments)
S10	M6	10.78	10.79	*Eriophorum vaginatum* (spindles 3); Ericaceae (stem base 1); undetermined (herbaceous stem fragments +)
S12	M7	10.91	10.92	Ericaceae (stem base 4 fragments); *Sphagnum* (stem 1 fragment [un-charred]); undetermined (herbaceous stem fragments +)

Continued on next page

Table 4.1 – *Continued*

Core	Subsample	From (m O.D.)	To (m O.D.)	Aboveground plant remains for ^{14}C dating (charred unless indicated otherwise)
S13	M10	8.99	9.00	*Calluna vulgaris* (twig fragments ++, leaves +); *Erica tetralix* (leaves 4, twig fragments +); undetermined (herbaceous stem fragments +)
S14	M10	8.65	8.66	*Calluna vulgaris* (twigs with leaves ++, stem 1 fragment [un-charred]); *Erica tetralix* (leaves ++); *Calluna/Erica* (flowers +); *Sphagnum* (stem 1 fragment)
S15	M5	8.13	8.14	*Erica tetralix* (leaves 3, stem base 1); undetermined (herbaceous stem fragments +)
S16	M2	7.57	7.58	Undetermined (herbaceous stem fragments +)
S16	M4	7.59	7.60	NA
S19	M8	10.44	10.45	Cyperaceae (stem 2 fragments); undetermined (herbaceous stem fragments +)

4.3.2 Methods Part 2: Reconstructing peat initiation age spatially

4.3.2.1 Covariates and construction of covariate maps

The relationship with median peat initiation age was tested for: (1) the total thickness of organic deposits [O], (2) the elevation of the Pleistocene mineral surface [z_P] underlying the organic deposits, and (3) a constructed variable based on elevation of the mineral surface and hydraulic head, that captures the effect of groundwater-fed wetness that results from geomorphological position (fig. 4.5). The latter covariate, denoted with z_PH, is defined as the peat initiation height (i.e., the elevation of the Pleistocene mineral surface, z_P) at location x minus the current hydraulic head (H_{t0}) at location x.

Two Dutch national databases with subsurface data, managed by the Dutch Geological Survey (TNO-GDN), were consulted (see below) for the construction of the covariate maps. Geological coring data for a region surrounding Fochteloërveen (see extent of corings in fig. 4.4a) were downloaded from DINOloket (DINOloket - TNO, 2022) and selected for presence of peat or gyttja (n = 485). In addition, information from gouge corings (n = 71) and sample corings (n = 21) from the fieldwork (see section 4.3.1.2) was used. For each coring (total n = 577), the elevation of the Pleistocene surface [z_P] and total thickness of organic deposits [O] was registered (for geological corings the sum was used of peat and gyttja if present). Using ArcGIS Pro (version 2.3.3), a palaeoDEM of the Pleistocene surface was interpolated based on the z_P values through Inverse Distance Weighing (IDW). In addition, a map of the total thickness of organic deposits was interpolated through IDW based on the O values. The resulting rasters have a resolution of 50 x 50 m and a support of ~10 datapoints/km^2.

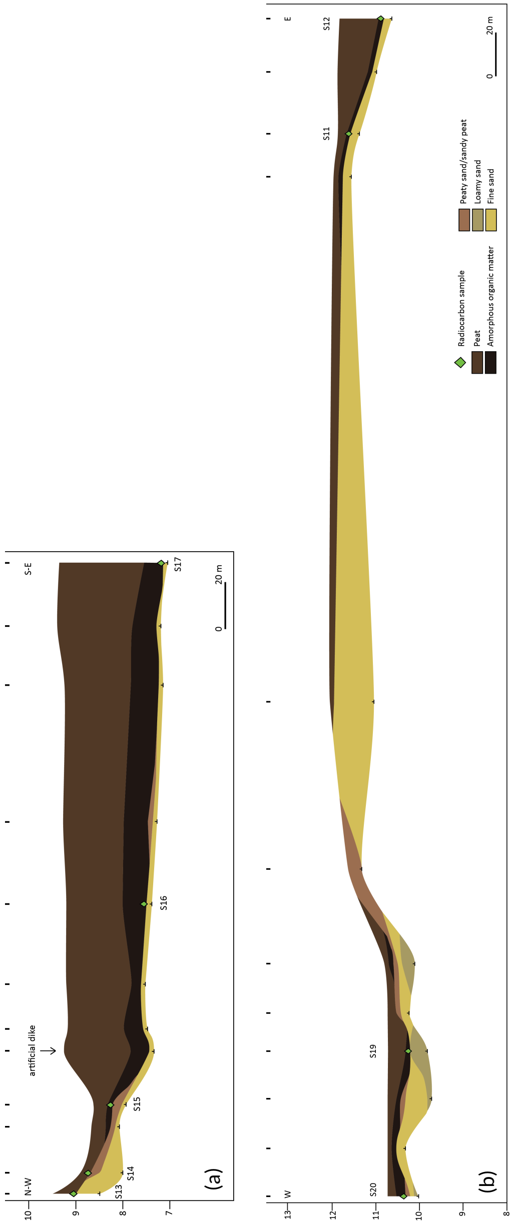


Figure 4.4: *Two cross sections showing example transects perpendicular to coversand ridges underlying the organic deposits in the Fochteloërveen peat remnant. See fig. 4.2 for location of the transects; (a) transect covering one side of a ridge, and (b) transect covering both sides of a ridge. Corings are indicated with vertical bars at the top of each cross section. The numbers (of the format Sxx) refer to the sampling site codes (see table 4.1 and table 4.3).*

For the current hydraulic head [H_{xt0}] the map of the upper layer of the national hydrological model was downloaded from Grondwatertools (Grondwatertools - TNO, 2022), reflecting the phreatic groundwater level (the upper unconfined aquifer). This raster has a resolution of 250 x 250 m. To enable maps of peat initiation age with a 50 x 50 m resolution, the H_{xt0} raster was resampled to 50 x 50 m and smoothed through focal statistics (using the mean with a neighbourhood of 3 x 3 cells). A $z_P H$ raster was calculated by subtracting the H_{xt0} raster from the z_P palaeoDEM. For each coring location (n = 577) the value of $z_P H$ was obtained to be used in linear regression analysis (see section 4.3.2.2). Covariate maps and a table with all used coring data are available online (see reference to the dataset on page 105).

4.3.2.2 Linear regressions and prediction maps of peat initiation age

Using R, the relationships between median peat initiation age and each of the three covariates [O, z_P, $z_P H$] were analysed with linear regression. Based on several checks (including the normality of the residuals, homoscedasticity, and leverage) the assumptions underlying linear regression were deemed valid for our data (results not shown but available through the R script, (see reference to the dataset on page 105). The three linear models were assessed based on their p-value and adjusted R^2; those with significant results were used for subsequent predictions of peat initiation age.

Using the linear models, covariate maps were converted to prediction maps of peat initiation age using the R "raster" package. The corresponding standard deviation maps were obtained from the limits of the prediction interval of the regressions. The resulting rasters were exported as geotiffs and opened in ArcGIS Pro (2.3.3). Values <900 cal y BP were set to 'No Data'. Isochrones (contour lines) with an interval of 1000 years were added to the map to show the pattern of modelled peatland expansion.

A histogram and density function of the predicted peat initiation ages were created to visualize the acceleration in lateral expansion through time. A cumulative density function was created to show the increase in peat covered area through time within the boundaries of the Fochteloërveen peat remnant.

4.3.2.3 Assessment of modelling results

To evaluate the agreement between the predictions of peat initiation age, the resulting prediction rasters were subtracted from each other. In addition, predictions were evaluated using validation points consisting of radiocarbon dates of peat samples that indicate a terminus-ante-quem (n = 3) and terminus-post-quem

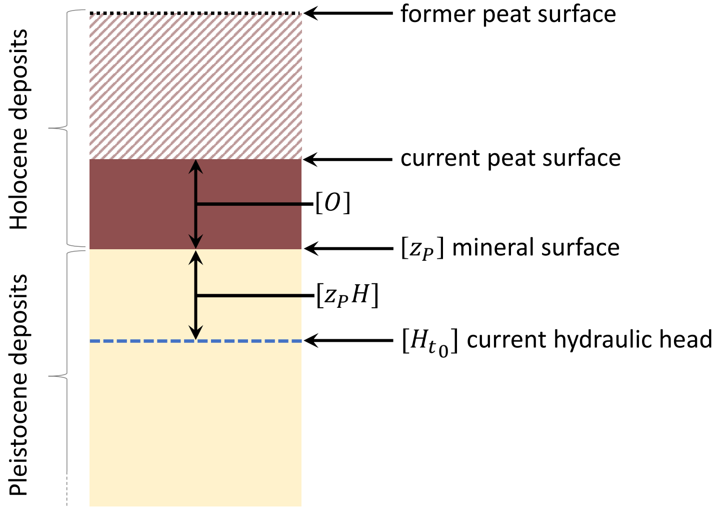


Figure 4.5: *Schematic depiction of the covariates [O, z_P, $z_P H$]. For explanation see text.*

(n = 2) for peat initiation, and archaeological sites that indicate a terminus-post-quem for peat initiation (n = 4; fig. 4.2d and table 4.2). Predicted peat initiation ages at the locations of validation points were obtained and compared with the TPQ/TAQ information of these points. To ease interpretations the predicted ages and TPQ/TAQ validation ages were plotted in OxCal (version 4.4, Bronk Ramsey, 1995). Confidence intervals of the validation points are presented both as one- and two-sigma intervals.

Table 4.2: *Archaeological validation points within the study area. Identification numbers can be used to obtain detailed find information from Archis III (RCE, 2019). Coordinates are in metres (Dutch RD-new [*Rijksdriehoeksstelsel*] projection). As the exact find location is not entirely certain, coordinates are only approximate. TPQ = terminus-post-quem, TAQ = terminus-ante-quem. Ages in BCE are indicated with a minus sign.*

Identification Archis III	**RD-x**	**RD-y**	**Location, *toponym***	**Concise description**	**Interpretation**	**Constraint for peat initiation**	**Archaeological period**	**From (BCE/CE)**	**To (BCE/CE)**	**From (cal y BP)**	**To (cal y BP)**
2929700100	221450	556300	Appelscha	Late Palaeolithic and Mesolithic flint material.	Habitation was possible during the Mesolithic (imprecise date).	TPQ	Late Palaeolithic to Mesolithic	-15000	-5000	16950	6950
3010261100	222500	557800	Fochteloo, *De Bonghaar*	Cluster of Mesolithic flint material.	Habitation was possible during the Mesolithic (imprecise date).	TPQ	Mesolithic	-8000	-5000	9950	6950
2929758100	224400	554500	Ravenswoud	Cluster of Late Neolithic flint artefacts.	Habitation was possible during the Late Neolithic.	TPQ	Late Neolithic	-2850	-2000	4800	3950
2688418100	228000	558270	Norgervaart, *Norgervaart 09*	Single find of a silver coin dated to the first half of the 9th century.	Human activity in or after 9th century. Unclear if this find points to habitation.	?	Early Middle Ages	814	840	1136	1110
3030577100	221450	560500	Veenhuizen, *De Bieuw*	Find assemblage of high medieval pottery.	Habitation was possible during the High Middle Ages.	TPQ	High Middle Ages	900	1300	1050	650

4.4 Results

4.4.1 Results Part 1: Collection of field data and radiocarbon dating evidence

A table with all collected coring data is available online (see reference to the dataset on page 105). The dating results for the obtained samples from the cores are listed in table 4.3. Both peat initiation dates and terminus-post-quem/terminus-ante-quem dates for validation are included. Ages range from 1650 ± 40 yrBP (1690 – 1411 cal y BP at 95.4% confidence interval) to 8305 ± 30 yrBP (9433 – 9142 cal y BP at 95.4%), indicating that the period of peat initiation and subsequent lateral expansion stretched over at least ~7.500 calendar years.

4.4.2 Results Part 2: Reconstructing peat initiation age spatially

The linear regressions of median peat initiation age versus the total thickness of organic deposits $[O]$ is highly significant (p-value $<$ 1e-3) and explains a reasonable amount of variation with an adjusted R^2 of 0.57 (fig. 4.6a). The linear regression of median peat initiation age versus the elevation of the Pleistocene mineral surface underlying the organic deposits $[z_P]$ has a p-value of 0.09 and and adjusted R^2 of 0.14. Based on these values, this covariate was rejected for further analyses. For the third covariate that was tested, groundwater-fed wetness that results from geomorphological position $[z_P H]$, the linear regression has an adjusted R^2 of 0.61 and is again highly significant (p-value $<$ 1e-3) (fig. 4.6b).

The interpolated Pleistocene surface underlying the organic deposits ($[z_P]$, fig. 4.7a) indicates that the mineral substrate covers an elevation range of 6 – 13 m O.D.. The thickness of organic deposits ($[O]$, fig. 4.7b) varies from 0.0 – 3.5 m. Using the Pleistocene surface ($[z_P]$, fig. 4.7a) and present-day hydraulic head ($[H_{t0}]$, fig. 4.7c), the covariate raster for groundwater-fed wetness that results from geomorphological position ($[z_P H]$, fig. 4.7d) was calculated (see section 4.3.2.1).

Using the covariate maps in fig. 4.7b and 4.7d and the linear regressions in fig. 4.6, the prediction maps of peat initiation age in fig. 4.8 were generated. Standard deviations of the predictions are shown in insets in fig. 4.8. The higher the standard deviation at a particular location, the less certain the prediction of peat initiation age is for that point. Lower certainty mainly occurs at points with a predicted peat initiation age $\geq$ 6,000 cal y BP and at points with an age of $\leq$ 1,500 cal y BP, as the number of datapoints above and respectively below these ages are limited (see data points in fig. 4.7). Overall, both predictions in fig. 4.8 show a similar pattern. The difference between both predictions as shown in fig. 4.9a, demonstrates that they deviate near the edge of the Fochteloërveen area and mostly in the northern part of the area. As this northern part is currently forested (see fig. 4.2d), present-day groundwater levels may not reflect a natural pattern here, causing deviations in the prediction based on $z_P H$. The validation points indicate that for the three terminus-ante-quem radiocarbon dates (fig. 4.9b), which should be younger than the predicted peat initiation ages, two are indeed younger than the mean of the predictions and one is slightly older but falls within the 1-sigma confidence interval of the predictions. Of the terminus-post-quem radiocarbon dates (fig. 4.9b), which are expected to be older than the predicted peat initiation ages, one has a comparable age as the mean of the predictions, and one is older than the mean of the predictions. Of the terminus-post-quem archaeological validation points (fig. 4.9c), three are indeed older. One is younger than the mean of the predictions but still falls within the 2-sigma confidence interval for the prediction based on O and within the 1-sigma confidence interval for the prediction based on $z_P H$. Overall, comparison with the validation points suggests validity of the predictions.

Loci of early peat initiation are distributed over the lower central, west and northwest parts of the Fochteloërveen area (fig. 4.8a and 4.8b), indicating that landscape scale peat initiation (see fig. 4.1a) occurred simultaneously at multiple sites. The west and northwest loci are located on low-lying topography ($\leq$7.0 m O.D.) of the Pleistocene surface (compare with fig. 4.7a), but the loci in the lower central part of the area are located on somewhat higher ground (between 9.0 and 10.5 m O.D.). Even on the highest parts of the Pleistocene surface (between 12.0 and 13.0 m O.D.), both predictions indicate a peat cover from about 3,000 cal y BP onwards. This suggests that as the peat cover grew with time, even coversand ridges that initially protruded above the peat landscape became covered with peat as time progressed. The distance between the isochrones in fig. 4.8a and 4.8b indicates the rate of lateral expansion. Where isochrones are drawn close together, the peat cover expanded slowly. This is the case in the blueish coloured parts of the maps, pointing to initial slow expansion of peat initiation loci. Later in time the peat-covered area expanded more rapidly, with the strongest expansion between 5,500 – 3,500 cal y BP (see fig. 4.10c; 5,500 – 3,500 cal y BP for the prediction based on O, and 5,500 – 3,000 cal y BP for the prediction based on $z_P H$). Half of the Fochteloërveen area was covered with peat by ~4,000 cal y BP according to the prediction based on O (fig. 4.10c), and by ~3,500 cal y BP according to the prediction based on $z_P H$. Peat covered nearly the entire area by ~2,500 and ~900 cal y BP respectively.

Table 4.3: *Dating results. NA = not available. All samples consist of charred or uncharred plant remains, only sample S20-M5 consists of the humic fraction. Samples are from 1-cm thick slices, apart from sample S7-M8_9 for which two slices were combined. More details of these samples are available online (see reference to the dataset on page 105). Dating results for S17-M11, S18-M8 and S20-M5 are from* Quik et al. *(2022a,b).*

From (m O.D.)	To (m O.D.)	Sample name	Date expectancy	Lab-ID	$F^{14}C$	± (1σ)	^{14}C age (yrBP)	± (1σ)	$\delta^{13}C$ (permil; IRMS)	± (1σ)	%C	95.4 % confidence interval From (cal y BP)	To (cal y BP)
10.53	10.54	S1-M4	Peat initiation date	GrM-26893	0.5649	0.0024	4585	45	-26.75	0.15	42.5	5462	5051
10.79	10.80	S2-M9	Terminus-post-quem	GrM-26883	0.5621	0.0038	4630	50	-27.07	0.15	48.1	5566	5073
10.12	10.13	S3-M2	Terminus-ante-quem	GrM-26574	0.8065	0.0024	1728	24	-25.86	0.15	49.9	1700	1545
7.16	7.17	S4-M9	Peat initiation date	GrM-27195	0.7096	0.0022	2756	26	-27.89	0.15	70.4	2930	2775
10.13	10.14	S5-M5	Peat initiation date	GrM-26575	0.7954	0.0021	1839	22	-26.01	0.15	77.4	1823	1705
9.74	9.75	S6-M8	Peat initiation date	GrM-26576	0.7488	0.0022	2323	26	-25.88	0.15	61.2	2365	2183
10.55	10.56	S7-M7	Peat initiation date	GrM-26787	0.5471	0.0053	4840	80	NA	NA	NA	5742	5326
10.56	10.58	S7-M8_9	Terminus-ante-quem	GrM-26895	0.6975	0.0029	2893	35	-28.83	0.15	38.2	3160	2888
11.56	11.57	S8-M3	Peat initiation date	GrM-26884	0.8144	0.0040	1650	40	-27.86	0.09	52.4	1690	1411
10.60	10.61	S9-M2	Terminus-ante-quem	GrM-26792	0.5196	0.0055	5260	80	NA	NA	NA	6277	5898
10.78	10.79	S10-M6	Peat initiation date	GrM-26577	0.5385	0.0027	4972	27	-26.51	0.15	62.0	5841	5601
10.91	10.92	S12-M7	Peat initiation date	GrM-26578	0.6921	0.0021	2956	24	-26.23	0.15	61.1	3209	3004
8.99	9.00	S13-M10	Peat initiation date	GrM-26579	0.7347	0.0028	2477	30	-27.92	0.15	69.1	2720	2374
8.65	8.66	S14-M10	Peat initiation date	GrM-26580	0.6966	0.0021	2904	24	-27.70	0.15	61.8	3150	2960
8.13	8.14	S15-M5	Peat initiation date	GrM-27196	0.5621	0.0021	4630	30	-27.17	0.08	53.9	5464	5305
7.57	7.58	S16-M2	Peat initiation date	GrM-26885	0.4607	0.0023	6225	40	-27.00	0.08	24.8	7255	6999
7.20	7.21	S17-M11	Peat initiation date	GrM-23525	0.3556	0.0013	8305	30	-25.42	0.15	63.1	9433	9142
11.73	11.74	S18-M8	Peat initiation date	GrM-23827	0.6863	0.0020	3024	24	-27.69	0.15	64.0	3339	3149
10.44	10.45	S19-M8	Terminus-post-quem	GrM-27197	0.5441	0.0022	4890	35	-25.80	0.09	53.4	5717	5492
10.30	10.31	S20-M5	Peat initiation date	GrM-24021	0.6419	0.0022	3561	27	-28.77	0.15	46.7	3966	3725

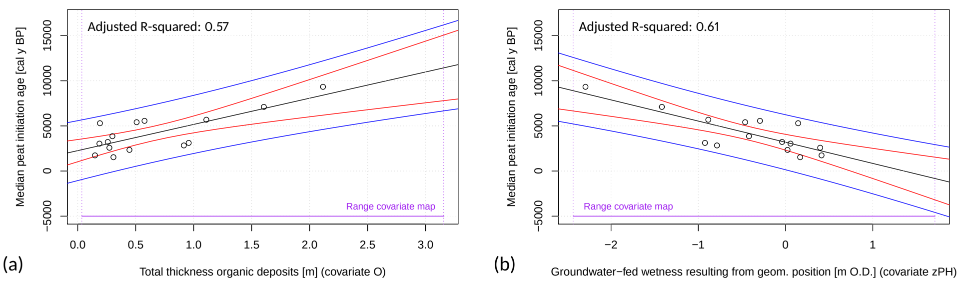
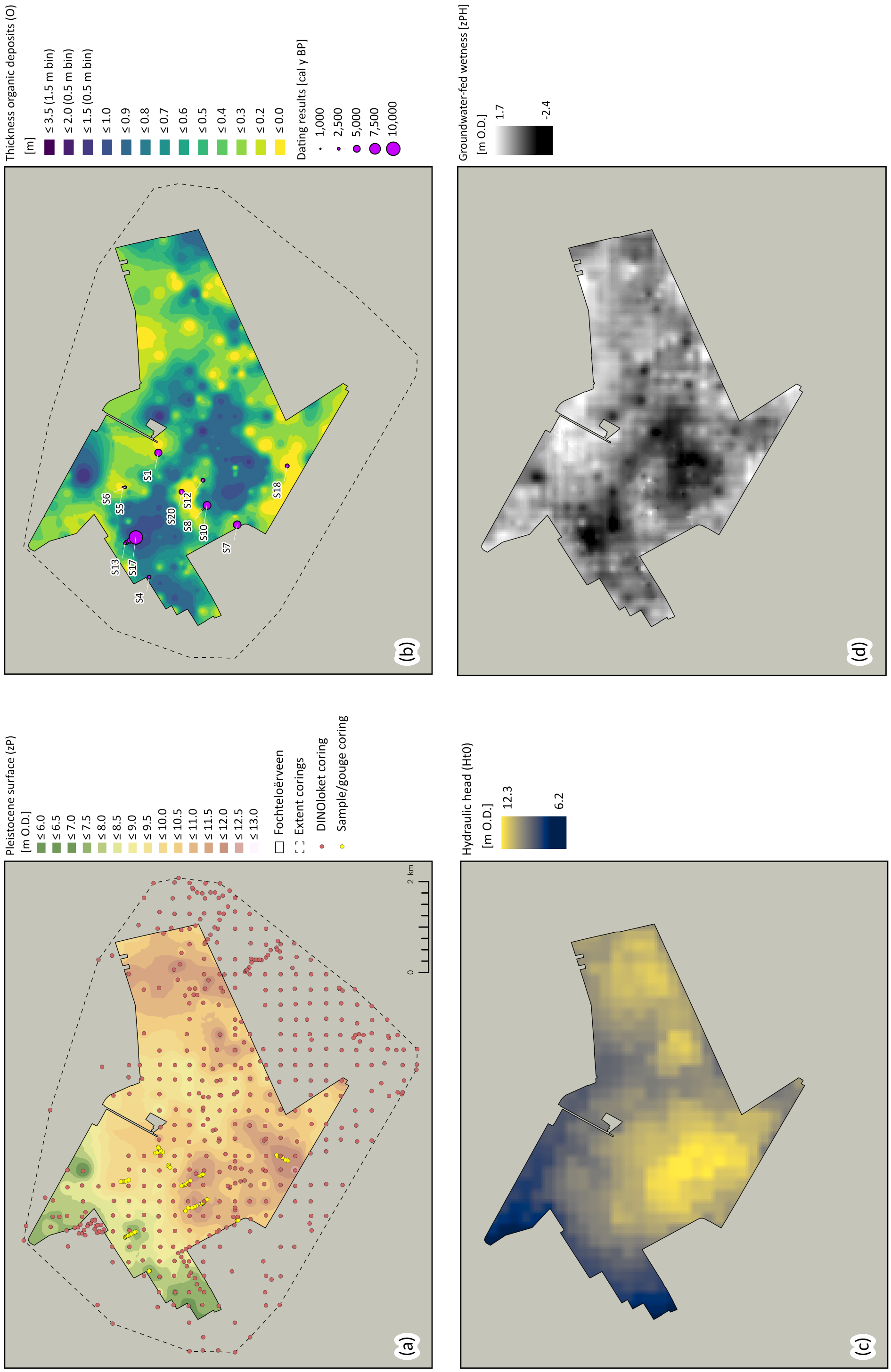


Figure 4.6: *Linear regressions, showing the relationships between median peat initiation age and (a) the total thickness of organic deposits [O], and (b) groundwater-fed wetness that results from geomorphological position [$z_P H$]. Both regressions were significant with p $<$ 1e-3. Observations are indicated by the black circles. The regression line is shown in black, the 95% confidence interval of the regression line is indicated in red, and the 95% prediction interval in blue. The range of the covariate maps is indicated in purple and also visible in fig. 4.7b and 4.7d.*

Figure 4.7: *(Figure on next page). (a) Interpolated elevation of the Pleistocene surface [z_P] based on data obtained through sample/gouge corings and DINOloket corings (DINOloket - TNO, 2022). (b) Interpolated current thickness of organic deposits [O] based on data obtained through sample/gouge corings and DINOloket corings (DINOloket - TNO, 2022). Radiocarbon dates of basal peat samples show peat initiation ages (see section 4.4.1). (c) Current hydraulic head [H_{t0}] based on the LHM model (Grondwatertools - TNO, 2022), resampled to 50 x 50 m and smoothed through focal statistics. (d) Groundwater-fed wetness that results from geomorphological position, calculated by subtracting the hydraulic head [H_{t0}] in (c) from the Pleistocene surface [z_P] in (a). For further details on each map see section 4.3.2.1.*


(a)
Pleistocene surface (zP)
[m O.D.]
≤ 6.0
≤ 6.5
≤ 7.0
≤ 7.5
≤ 8.0
≤ 8.5
≤ 9.0
≤ 9.5
≤ 10.0
≤ 10.5
≤ 11.0
≤ 11.5
≤ 12.0
≤ 12.5
≤ 13.0
Fochteloërveen
Extent corings
DINOloket coring
Sample/gouge coring
0
2 km
(b)
Thickness organic deposits (O)
[m]
≤ 3.5 (1.5 m bin)
≤ 2.0 (0.5 m bin)
≤ 1.5 (0.5 m bin)
≤ 1.0
≤ 0.9
≤ 0.8
≤ 0.7
≤ 0.6
≤ 0.5
≤ 0.4
≤ 0.3
≤ 0.2
≤ 0.0
Dating results [cal y BP]
1,000
2,500
5,000
7,500
10,000
S1
S4
S5
S6
S7
S8
S10
S12
S13
S17
S18
S20
(c)
Hydraulic head (Ht0)
[m O.D.]
12.3
6.2
(d)
Groundwater-fed wetness [zPH]
[m O.D.]
1.7
-2.4

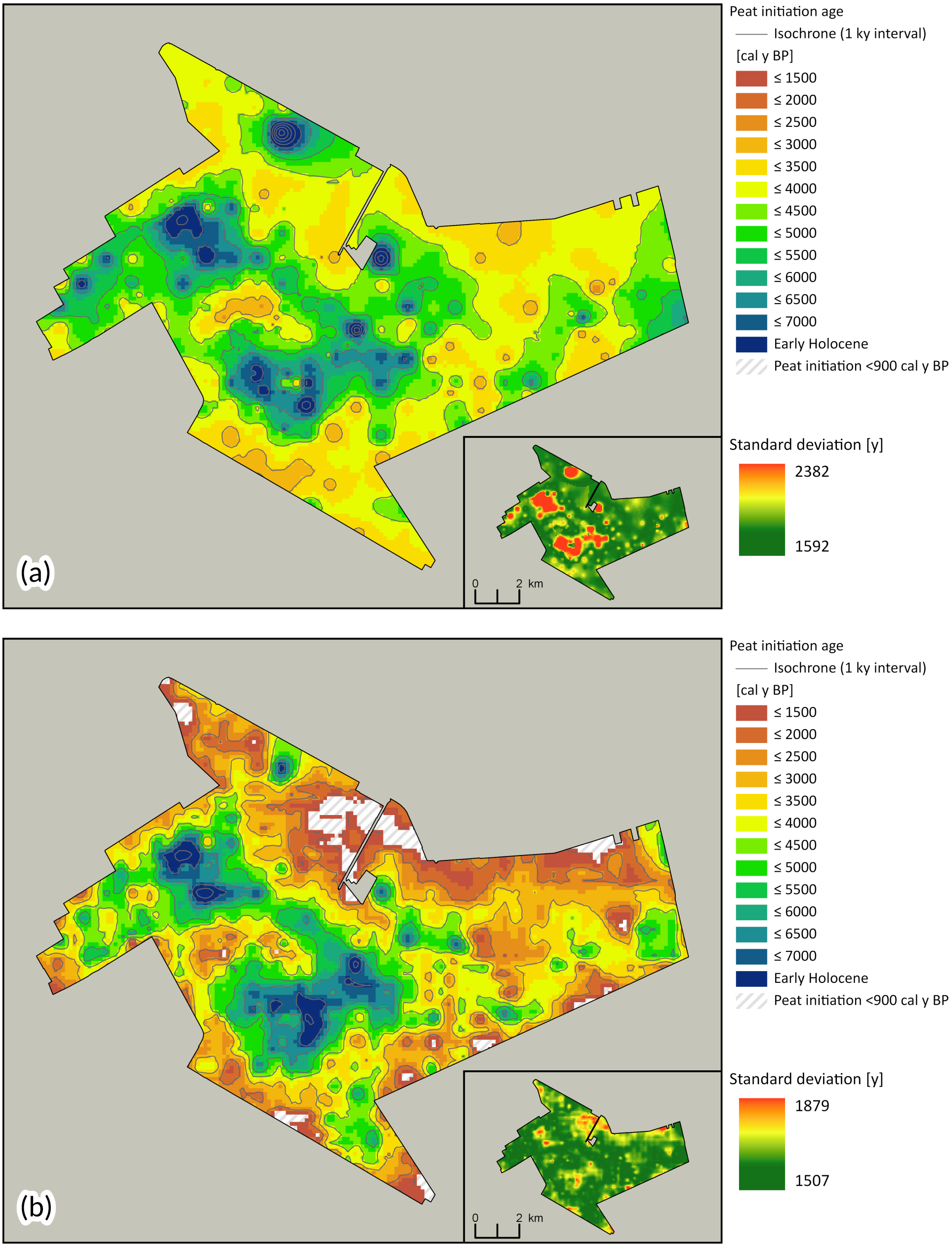
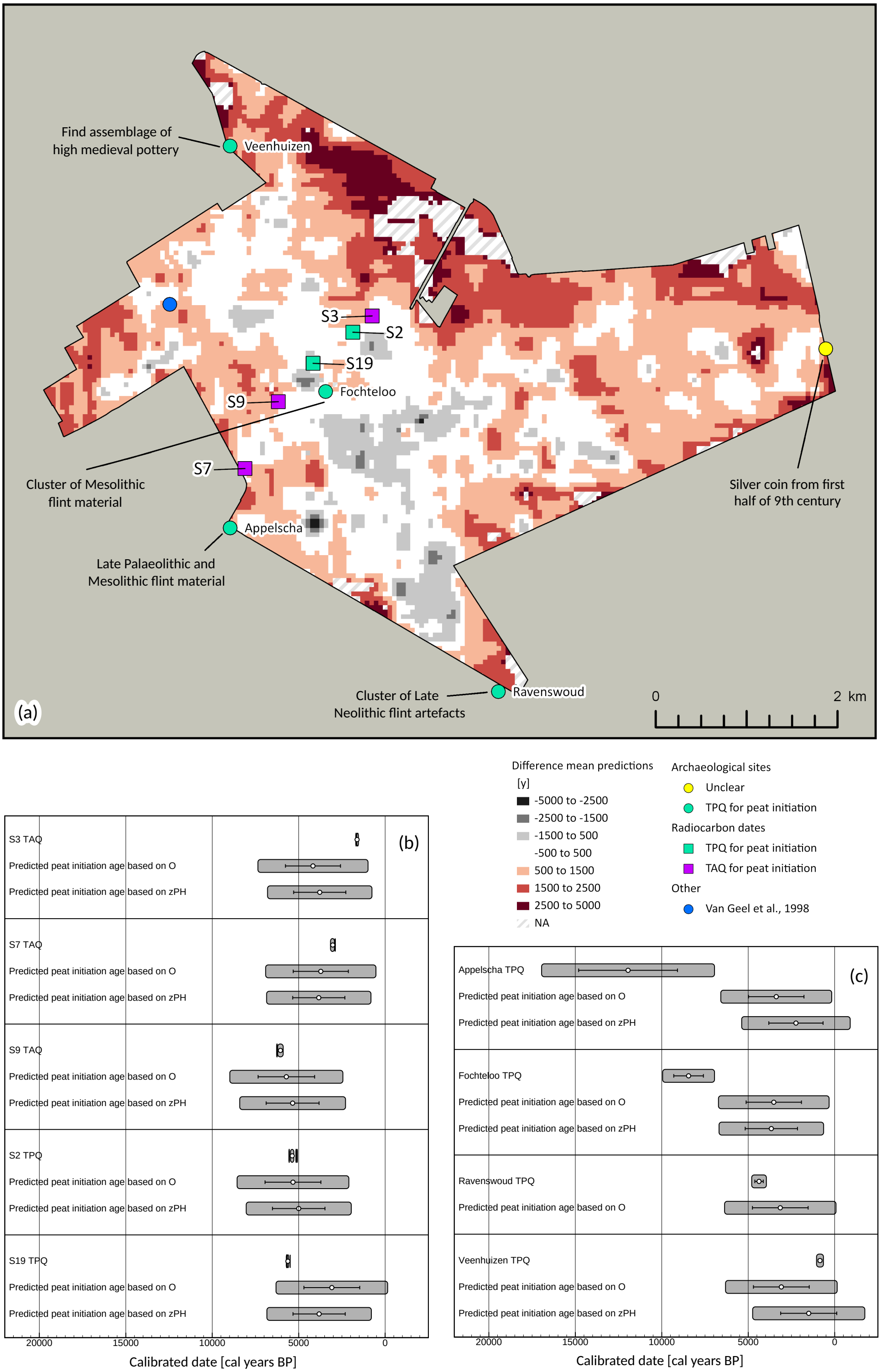


Figure 4.8: *(a/b) Reconstructed peat initiation ages for Fochteloërveen, with (a) based on thickness of organic deposits [O] (see fig. 4.7b), and (b) based on groundwater-fed wetness that results from geomorphological position [$z_P H$] (see fig. 4.7d). Contours represent isochrones (lines of equal age) and have an interval of 1000 years. Note that peat initiation age legends are equal, but that legends of the standard deviation of the prediction differ.*



Find assemblage of high medieval pottery
Veenhuizen
S3
S2
S19
Fochteloo
S9
S7
Cluster of Mesolithic flint material
Appelscha
Late Palaeolithic and Mesolithic flint material
Silver coin from first half of 9th century
Cluster of Late Neolithic flint artefacts
Ravenswoud
(a)
0
2 km
Difference mean predictions [y]
-5000 to -2500
-2500 to -1500
-1500 to 500
-500 to 500
500 to 1500
1500 to 2500
2500 to 5000
NA
Archaeological sites
Unclear
TPQ for peat initiation
Radiocarbon dates
TPQ for peat initiation
TAQ for peat initiation
Other
Van Geel et al., 1998
(b)
S3 TAQ
Predicted peat initiation age based on O
Predicted peat initiation age based on zPH
S7 TAQ
S9 TAQ
S2 TPQ
S19 TPQ
20000
15000
10000
5000
0
Calibrated date [cal years BP]
(c)
Appelscha TPQ
Fochteloo TPQ
Ravenswoud TPQ
Veenhuizen TPQ

Figure 4.9: *(Figure on previous page). (a) Difference between the mean predictions of peat initiation age in fig. 4.8a and 4.8b (i.e., prediction of fig. 4.8a minus prediction of fig. 4.8b). The locations of the validation points (of which results are presented in panels (b) and (c)) are also indicated on this map (for further details on the archaeological sites see table 4.2). In (b) and (c) validation points are compared with the predicted peat initiation age as predicted by both covariates (i.e., each validation point is compared with the prediction of fig. 4.8a and with the prediction of fig. 4.8b). The central circles show the mean, bars indicate 1-sigma confidence interval, and grey-coloured blocks the 2-sigma confidence interval. Note that terminus-ante-quem validation points should be older than the prediction, whereas terminus-post quem validation points should be younger (see section 4.4.2). (b) Validation points consisting of radiocarbon dates of peat samples that indicate a terminus-ante-quem ($n = 3$) and terminus-post-quem ($n = 2$) for peat initiation. (c) Validation points consisting of archaeological sites that indicate a terminus-post-quem for peat initiation ($n = 4$; for one archaeological site the relationship with peat growth is unclear, therefore this site was not included here, see table 4.2 for details).*

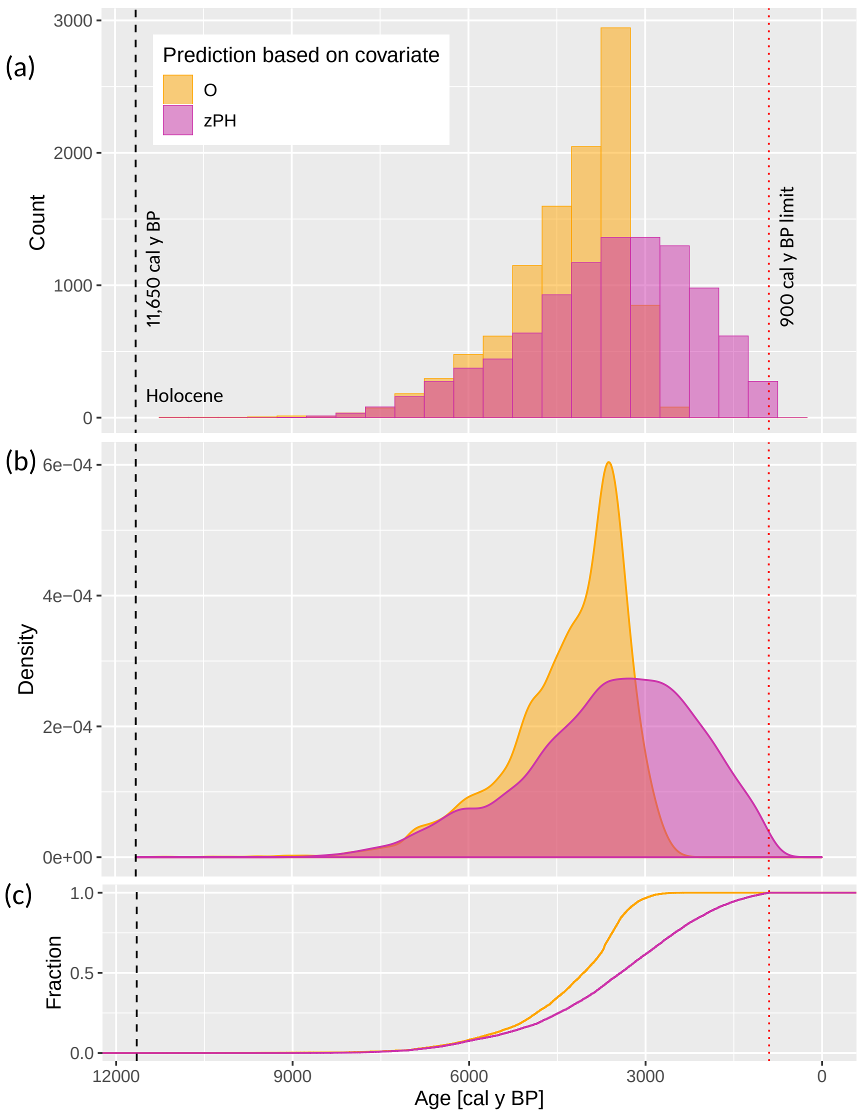


Figure 4.10: *(a) Histogram of predicted peat initiation ages for Fochteloërveen, showing results for the prediction based on thickness of organic deposits [O] (see fig. 4.8a), and for the prediction based on groundwater-fed wetness that results from geomorphological position [z_PH] (see fig. 4.8b). Start of the Holocene follows Walker et al. (2009). Temporal scope of the predictions runs to 900 cal y BP. Note that certainty of both predictions is different, see standard deviation maps in fig. 4.8a and fig. 4.8b. (b) Density plot of predicted peat initiation ages for Fochteloërveen (i.e., normalised to a graph surface area of one). (c) Plot showing cumulative fraction of peat-covered area within the Fochteloërveen area as indicated by the two predictions.*

4.5 Discussion

Here we discuss peat initiation and lateral expansion at Fochteloërveen as indicated by our predictions (section 4.5.1), followed by an evaluation of our approach (section 4.5.2).

4.5.1 Peat initiation and lateral expansion at Fochteloërveen

Peat initiation results from terrestrialisation, paludification and/or primary mire formation (Charman, 2002b; Rydin and Jeglum, 2013d). As the substrate in the study region has been deglaciated and exposed at the surface since the penultimate Glacial (OIS6, see section 4.2.1), primary mire formation is not the case here. The question then remains whether peat initiation resulted from paludification or terrestrialisation, or both. Gyttja is often found at the base of terrestrialisation sequences. We did not encounter gyttja in the gouge and sample corings of the field survey, but in part of the DINOloket coring descriptions gyttja is mentioned. However, interpretation and terminology of the amorphous peat layer (highly humified; *sapric* cf. IUSS Working Group WRB, 2015; see table 3.2 in Chapter 3, page 68) that is regularly found near the bottom of peat deposits may differ. The lithology of this layer can be described as peat with blackish-brown colouring, greasy consistency and very few recognisable plant remains. Depending on definitions used, it is plausible that in the DINOloket corings reference is made to a similar facies as the amorphous peat layer with the term gyttja. Proximity of some of the DINOloket corings with gyttja in the description to our sample corings with an amorphous peat layer suggests that both terms refer to the same layer. As this layer does not meet the requirements of true gyttja (an organic lacustrine deposit) according to Bos (2010) and Bos *et al.* (2012), we conclude that peat initiation in the study area was largely caused by paludification, i.e. waterlogging of previously unsaturated sediments. Note that we used an OM percentage of 40% to define peat based on Quik *et al.* (2022a), which is important to keep in mind for comparison of results with other studies.

Trophic status is used in many peatland classification systems. Reference can be made to the current trophic status (suffix 'trophic'), and to trophic status during peatland initiation (suffix 'genous') (Charman, 2002c). Geogenous or minerogenous conditions indicate that a peat-forming vegetation receives groundwater or surface runoff, i.e. water that has been in contact with mineral soil. Ombrogenous conditions are present when a peat-forming vegetation receives water solely from precipitation (Rydin and Jeglum, 2013c; Charman, 2002c; Joosten and Clarke, 2002; IPS, 2022). The water source during formation of the organic deposits at Fochteloërveen could be deduced from the botanical data (table 4.1, see reference to the dataset on page 105). Of the peat initiation samples five can be classified as geogenous, nine as transitional from geogenous to ombrogenous, and only one as truly ombrogenous. This suggests that peat initiation was strongly influenced by groundwater and surface runoff, and only to a limited degree by perched groundwater tables that result from precipitation and poor drainage caused by impermeable (sub)surface layers (i.e., glacial till which can be found close to the surface, see section 4.2.1).

The weak linear relationship between elevation of the Pleistocene mineral surface and peat initiation age (p-value $= 0.09$, adjusted $R^2 = 0.14$) shows that not all basal peat layers of equal elevation are of the same age. In contrast, the relationship between peat initiation age and groundwater-fed wetness that results from geomorphological position is highly significant (p-value $<$ 1e-3, adjusted $R^2 = 0.61$). This demonstrates that the influence of groundwater in initiating peat growth at Fochteloërveen cannot be explained solely by elevation, but that it is strongly related to groundwater-fed wetness resulting from position within the large-scale geomophology of high topographic plains and insized valleys. Sea level was rising during the entire period of peat development at Fochteloërveen (Meijles *et al.*, 2018). As a result, the isohypse pattern gradually rose through time.

Transects of basal peat dates are useful to distinguish development loci from lateral expansion areas (e.g. Mäkilä, 1997; Mäkilä and Moisanen, 2007; Chapman *et al.*, 2013). At Fochteloërveen, landscape scale peat initiation (fig. 4.1) occurred simultaneously at multiple sites (fig. 4.8). Some of the loci of peat initiation are located at positions that are lower compared to surrounding topography (areas of accumulated flow or sinks). Our predictions indicate that even cover sand ridges eventually became covered with peat (fig. 4.8), suggesting that lateral expansion was not slope-limited in this area or below its threshold. The pattern (fig. 4.8) and pace (fig. 4.10b and 4.10c) of lateral expansion show that after initial slow lateral growth of peat initiation loci, lateral growth accelerated. The strongest expansion occurred between 5,500 – 3,500 cal y BP.

Some of these findings are contrasting with previous palaeogeographic reconstructions by Fokkens (1998), Waterbolk (2007) and Vos *et al.* (2020). Fokkens (1998) placed peat initiation in the Fochteloërveen area between the beginning of the Early Iron Age and the end of the Roman period (800 BCE – 400 CE; 2,750 – 1,550 cal y BP). This is much later than our dating results (table 4.1) and predictions (fig. 4.8) demonstrate. Waterbolk (2007) on the other hand assumes that large areas were already covered by peat during the Early and Middle Neolithic (4,900 – 2,850 BCE; 6,850 – 4,800 cal y BP). This is roughly in agreement with our results; according to our predictions half of the Fochteloërveen area was covered with peat by ~4,000 cal y BP (fig. 4.10c). However, Waterbolk (2007) concludes that this situation remained stable for ~3,000 years followed by rapid peatland expansion, which left the area largely abandoned by the Roman Period (19 BCE – 450 CE; 1,969 – 1,500 cal y BP). This is in strong contrast with our findings, which do not indicate a period of stability that precedes further lateral expansion. In the national-scale reconstructions by Vos *et al.* (2020), it was assumed that peatlands expanded gradually until they reached their former maximum extent, but the authors indicate that this is mainly due to a lack of data. Our results demonstrate that peat loci at Fochteloërveen probably expanded in a non-gradual fashion, with a phase of accelerated lateral expansion between 5,500 – 3,500 cal y BP (fig. 4.10b and 4.10c).

Ruppel *et al.* (2013) analysed an extensive dataset of basal radiocarbon dates reflecting both peat initiation and lateral expansion in Northern Europe and in North America. Their data on lateral growth demonstrate that the expansion of existing peatlands accelerated between approximately 5,000 – 3,000 ka, both in Northern Europe and in North America (Ruppel *et al.*, 2013). Similarly, Korhola *et al.* (2010) found that high-latitude peatlands in Europe expanded most drastically after 5 ka. Our data fit within this large-scale trend as they indicate a phase of accelerated lateral expansion at Fochteloërveen between 5,500 – 3,500 cal y BP (fig. 4.10b and 4.10c). Ruppel *et al.* (2013) suggest that this trend may be related to Neoglacial cooling (Wanner *et al.*, 2008).

In a core from Fochteloërveen studied by Klaver (1981); Van Geel *et al.* (1998), a radiocarbon date of a plant macrofossil sample collected near the visual mineral-to-peat transition indicated an age of 2920 – 2736 cal y BP (95.4% confidence interval, uncalibrated age of 2690 $\pm$ 50 BP; core location indicated in fig. 4.9a). Based on this and a comparison with several other regions, Van Geel *et al.* (1998) infer an influence of the 2.8 ka event where a change in climate results in peat initiation on previously unsaturated soils. However, our predictions of peat initiation age (fig. 4.8) indicate that the site studied by Van Geel *et al.* (1998) probably became covered with peat through lateral expansion, and does not reflect landscape scale peat initiation (fig. 4.1). An effect of the 2.8 ka event does not become clear from our results (fig. 4.10).

4.5.2 Evaluation of approach

Palaeogeographical studies of former extensive peat landscapes are challenging as vast areas have lost their former peat cover, affecting the natural archive formed by the peat and thus limiting the options for collecting field data (fig. 4.1b and 4.1c). Consequently, alternative approaches are needed to reconstruct peatland development on the Northwest European mainland and other areas where peat is poorly preserved. Our field strategy consisted of spatially distributed transects that were placed perpendicular to elevation gradients in the mineral subsurface underlying the organic deposits. This resulted in an extensive set of basal radiocarbon dates that stretches both the lateral and vertical dimensions of the Fochteloërveen peat remnant, and as such formed the basis for subsequent modelling steps. This approach was found useful when options for transects covering a whole peatland (as in fig. 4.1b) are hampered by limited a-priori knowledge on the position of peat remnants within the former peat landscape (fig. 4.1c). The availability of coring data within national databases (see section 4.3.2) was highly useful for constructing a palaeoDEM of the Pleistocene mineral surface underneath the organic deposits. For areas where comparable data are not available, the sampling scheme may need to be expanded as it must also provide sufficient data for interpolation to a palaeoDEM (for examples where basin morphometry is studied, see e.g. Anderson *et al.*, 2003; Bauer *et al.*, 2003; Chapman *et al.*, 2013).

To reconstruct peat initiation age for non-sampled sites within the peat remnant, we applied a digital soil mapping approach. For data-intensive approaches such as geostatistics (Oliver and Webster, 2014) or random forests (Breiman, 2001) the amount of data (specifically radiocarbon dates) is generally too low. Therefore, a digital soil mapping technique was needed that is less data-intensive. In our study, we found linear regression to be the best option as it involves only few assumptions, which were valid for our dataset.

Advantages of this approach are that it is spatially explicit (i.e., results in a map of predicted peat initiation ages), and it offers a quantitative alternative compared to manual deduction of isochrones from transects of basal dates (e.g. as in Bauer *et al.*, 2003; Foster *et al.*, 1988; Korhola, 1994, 1996; Mäkilä, 1997; Mäkilä and Moisanen, 2007). In addition, our approach allows for a quantitative evaluation of the prediction using the standard deviation and comparison of predicted ages with validation points.

To the best of our knowledge, digital soil mapping approaches have so far hardly been explored for reconstructing peat initiation and lateral expansion. An important exception is the work of Chapman *et al.* (2013), who made use of second-order polynomial regression to reconstruct peat initiation ages based on empirical relationships between basal peat age and DEM-derivatives for two remnants of a floodplain raised mire (Hatfield and Thorne Moors, UK). They tested relationships between peat initiation age and (1) elevation, (2) proximity to river courses, and (3) flow accumulation. Similar to our results, they found a weak relationship between peat initiation age and elevation (R^2 values of 0.15 and 0.20 for linear and second-order polynomial regression respectively (p-value not reported), compared to an adjusted R^2 of 0.14 and p-value of 0.09 for the linear regression in our study). Proximity to rivers also yielded a weak relationship, whereas flow accumulation produced an R^2 of 0.39 for linear regression and of 0.91 for second-order polynomial regression. Hence they apply the second-order polynomial relationship with flow accumulation as covariate to reconstruct peat initiation ages for their study area. Unfortunately, they do not provide an indication of certainty of their prediction, but do compare the prediction result with five validation points. Based on the relationship with flow accumulation, they conclude that peat growth initiated in the area at locations where surface run-off accumulates and results in a terrestrialisation process.

In our study, we reasoned with two points in mind, and used a combination of process-informed choices within a statistical approach. Firstly, we hypothesized that peat initiation at Fochteloërveen would be subjected to a two-fold control consisting of elevation and position within the large-scale geomorphology of high topographic plains and insized valleys. Secondly, we valued a covariate that is independent of peat presence or thickness, as this may have the potential to estimate peat initiation age for areas that are no longer covered by peat. Based on the assumption that the current isohypse pattern within the Fochteloërveen peat remnant reflects the isohypse pattern of the past (but in the past positioned at lower elevation due to lower sea level), we constructed the variable $z_P H$ based on elevation of the mineral surface and present-day hydraulic head. This covariate then allows to explain peat initiation with groundwater-fed wetness that results from geomorphological position.

As stated above, in our model based on $z_P H$, we assume that the current isohypse pattern reflects the natural situation as it was once present in the area (but with the pattern as a whole currently positioned at higher elevation). Within the boundaries of the Fochteloërveen peat remnant this assumption is largely true, as nature conservation measures require high groundwater tables. In addition, hydraulic conductivity within the area is not subjected to change (i.e. for the deposits underneath the peat). However, as groundwater levels in the surrounding area are much lower due to artificial drainage, an edge effect is probably present near the border of the peat remnant. This is reflected in the prediction map of peat initiation ages based on $z_P H$ in fig. 4.8b, which shows much younger ages near the edges (especially in the north) compared to the prediction map based on O in fig. 4.8a. This is also suggested by the modelling results if we would not hold on to our temporal scope with 900 cal y BP as limit. In that case, the $z_P H$ model predicts that peat near the edges of Fochteloërveen is of very recent age and locally even later than 0 cal y BP (i.e., these are otherwise set to 'No Data'). However, an historical map of 1664 CE indicates that peat was probably present at these locations (Pynacker, 1664). We encountered a comparable problem during an exploratory attempt to reconstruct peat initiation ages outside the peat remnant, which results in peat initiation ages that are likely too young. This shows that to obtain a reliable prediction, the method requires the isohypse pattern to reflect the natural pattern as closely as possible, and cannot predict peat initiation ages for areas that are subject to strong artificial drainage.

Our model based on total thickness of organic deposits [O, is based on the concept that the thicker the organic deposit, the longer ago peat was initiated at that location. This is of course dependent on peat growth rates, decay rates, and degree of compaction. However, despite these complicating factors, our regression model of peat initiation age versus total thickness of organic deposits is highly significant (p-value $<$ 1e-3) and has a decent fit (adjusted $R^2 = 0.57$). We made use of newly collected and existing coring data to obtain thickness values, which reflect the thickness of the peat layer that is still present. If the natural peat thickness (from before the onset of reclamations and peat-cutting) would be known, perhaps the fit would increase further.

Where remnant peat survived, covariate O is useful and may provide an estimation of the peat initiation age based on the thickness of the remaining peat layer. Covariate $z_P H$ is potentially useful for reconstructing peat initiation age beyond peat remnants, given that the data on which this covariate is constructed reflect the natural situation. A combination of both may offer new options to reconstruct peatland development within and beyond peat remnants. For the $z_P H$ model, this requires data on the natural topography of the mineral surface that used to be covered with peat (where peat is lost, the mineral surface may have been subject to levelling activities) and on the natural isohypse pattern. If this pattern could be derived for the region surrounding a peat remnant using hydrological modelling, the $z_P H$ model could provide insights in peatland initiation and lateral development for areas where this information cannot be collected from the field. It is important to keep in mind that complicating factors may have played a role during peatland development, for instance where peat growth in valleys changes regional base level or where the formation of peat domes affects drainage divides. As peat may be largely absent outside (protected) peat remnants, options to obtain radiocarbon dates to verify model results are probably very limited. Another option would be to use TAQ and TPQ dates obtained from archaeological data. In the example of Fochteloërveen, the surrounding area contains a fairly large number of archaeological finds which could offer a regional-scale validation dataset.

4.6 Conclusion

Reconstructions of peat initiation and lateral expansion in areas where the former peat cover is largely lost, such as the Northwest European mainland, are severely hampered by the limited options for collecting field data. In this study we aim (1) to find explanatory variables within a digital soil mapping approach that

allow us to reconstruct the pattern of peat initiation and lateral expansion within (and potentially beyond) peat remnants, and (2) to reconstruct peat initiation ages and lateral expansion for one of the largest bog remnants of the Northwest European mainland, the Fochteloërveen in the Northern Netherlands. Basal radiocarbon dates that were obtained from the peat remnant formed the basis for subsequent analyses. Significant relationships were found between peat initiation age and total thickness of organic deposits, and between peat initiation age and a constructed covariate on groundwater-fed wetness based on the present-day hydraulic head relative to the mineral palaeosurface underneath the peat cover. In contrast, a weak relationship was found between peat initiation age and elevation of the mineral palaeosurface. These findings indicate a strong influence of position within large scale geomorphology (high plains and insized valleys) on peat initiation at Fochteloërveen. The digital soil mapping approach based on thickness of organic deposits is only useful where remnant peat survived, whereas the constructed covariate on groundwater-fed wetness may ultimately be applied beyond the limits of peat remnants. Thereby this novel approach has the potential to shed light on the pattern, timing and pace of peatland initiation and lateral expansion in areas where this information can no longer be obtained from the field. For the Fochteloërveen our results indicate simultaneous peat initiation at several loci during the Early Holocene, and continuous lateral expansion until 900 cal y BP. Lateral expansion accelerated between 5,500 – 3,500 cal y BP.

Author contributions
RvB secured funding for this research. CQ proposed the research outline and adjusted it based on discussions with JC, YvdV, JW and RvB. JC and CQ explored the study area, performed test corings and decided upon a coring strategy. CQ organised the fieldwork and completed the collection of data and cores in the field with help of several students (see Acknowledgements). CQ subsampled the cores and coordinated all subsequent analyses on the subsamples. CQ analysed the data with input from YvdV, JC, JW and RvB; LS advised and assisted with the statistical analysis. CQ wrote the main body of text. The manuscript was finalized based on feedback from all authors.

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Chapter 5

General synthesis

5.1 Introduction

In the first chapter of this PhD thesis I identified two key research deficits, regarding (I) the need for methodological developments to constrain the spatio-temporal development of peatlands more accurately, and (II) the limited understanding of spatio-temporal trends in and steering factors for peatland initiation and lateral development in the coversand landscape of the Northwest European mainland. In this chapter, I synthesize and reflect on the methodological advances that were developed in this thesis (section 5.2), and on the knowledge that was gained regarding peatland development (section 5.3). Subsequently, I summarise the main conclusions (section 5.4), discuss recommendations for future research (section 5.5), and end with implications of the thesis results (section 5.6).

5.2 Methodological advances

5.2.1 Reuse of existing radiocarbon dates in peatland geochronology

In the geosciences, data rescue and reuse are of increasing interest (Wyborn *et al.*, 2015). However, for geochronological peat research no overviews exist of factors that need to be taken into consideration for reuse of radiocarbon dates, and standardized workflows or designs for quality assessments of peat dates are lacking (section 1.2 and 1.3). In Chapter 2, I developed a workflow for data rescue and reuse of legacy radiocarbon dates in peatland studies, including a rigorous quality assessment. The latter is intended to provide insight in potential sources of error and enables working with confidence levels based on subsets of data with increasing uncertainty. In this way, accuracy and robustness of conclusions can be verified. The developed workflow consists of:

i. A database set-up that can be tailored as required by the study scope;

ii. A complementary set of quality criteria with flexible weights to suit specific research questions;

iii. A script for automated quality assessment of the recorded legacy data using the weights defined in point (ii), to make the approach suitable for evaluating large legacy datasets.

In the quality assessment of point (ii), a penalty is assigned to each date based on criteria that consider taphonomic quality (i.e., sample provenance) and dating quality (i.e., sample material and method used). The degree to which a radiocarbon date represents the event of interest is determined by its dating and taphonomic quality. The quality criteria cover two types of information, i.e. aspects that are considered negative, and the availability of information about a certain property. The first type is based on 'best practices' in scientific literature regarding methodological aspects of dating (for comparable approaches, see e.g. Small *et al.*, 2017). For example, dates based on bulk samples are generally considered to be less accurate than those based on plant macrofossil samples (Törnqvist *et al.*, 1992, 1998; Piotrowska *et al.*, 2011). The second type considers whether sufficient information is available to make informed choices with regard to data analysis. Here the focus is not on the property itself (for instance, the location itself is not judged), but on knowledge about the property (do we know the location well or not).

In Chapter 2, the value of the workflow was demonstrated through application to a case study area, for which the northern Dutch coversand landscape was selected. Data rescue for the case study proved to be cost-efficient and provided access to information of which part is no longer available in the field. The comprehensive dataset for the case study area and overarching trends in peat growth that emerged from the meta-analyses highlight the potential of data reuse for palaeogeographic reconstructions.

5.2.2 Defining and dating basal peat

The lack of a universally applicable and quantitative definition for basal peat, combined with multiple concerns that have been raised previously regarding the radiocarbon dating of peat, may result in apparent ages that are either too old or too young for the timing of peat initiation (section 1.2 and 1.3). To contribute to resolving these challenges, I analysed a detailed series of radiocarbon dates in Chapter 3, comparing ages of multiple organic fractions from the mineral-to-peat transition in three cores obtained at Fochteloërveen. The approach was based on a conceptual framework (fig. 3.1) explaining the difference between local and landscape scale peat initiation, the issues with defining the mineral-to-peat-transition (which reflects the timespan of peat initiation) and basal peat layer, the challenges in sample selection, and the datable fractions and potential contaminants.

Chapter 3 illustrated the value of studying the mineral-to-peat transition using the organic matter gradient, and to base the definition of *basal peat* on this gradient. The timespan of the peat initiation process that is reflected in the mineral-to-peat transition (a stratigraphical distance of 6, 7 and 8 cm in the studied cores), lasted for 1343, 1073 and 1510 years (medians) respectively. It is important to take this significant timespan into account when deciding upon a sample size and sampling resolution. The *basal peat* layer can be defined using the organic matter gradient to provide a quantitative and reproducible definition that can be obtained through a simple protocol and at low-cost.

The dating results presented in Chapter 3 demonstrate that the ages obtained from plant macrofossil samples are most accurate in the mineral-to-peat transition and are therefore recommendable to use. However, the mineral-to-peat transition may be low in plant macrofossil content. If plant macrofossil samples cannot be obtained, dates of the humic fraction provide the best alternative regarding chronological order, but may deviate significantly from the 'true age' and are most safely interpreted as terminus-ante-quem dates. As the options for collecting dating sampling samples might be limited and resulting sample volumes might be small, it is important to assign material to analyses based on a comprehensive (sub)sampling scheme. The findings of Chapter 3 were summarised as a set of recommendations for defining and dating peat initiation that can be applied in various peatland settings (see Textbox 3.1 in Chapter 3 on page 57).

5.2.3 Reconstructions based on peat remnants

Adapted strategies are needed to obtain field data and to model peat initiation and lateral expansion based on peat remnants (section 1.2 and 1.3). To contribute to addressing this need, I searched for explanatory variables within a digital soil mapping approach in Chapter 4. I found significant linear relationships between median peat initiation age and the total thickness of organic deposits, and between median peat initiation age and a constructed covariate on groundwater-fed wetness. The latter was based on the present-day hydraulic head relative to the mineral palaeosurface underneath the peat cover.

To reconstruct peat initiation age for non-sampled sites within the Fochteloërveen peat remnant, a digital soil mapping approach was applied where either a map of total thickness of organic deposits or a map of groundwater-fed wetness was converted into a map of peat initiation ages using the abovementioned significant relationships. Key benefits of this method are that it directly results in a map of predicted peat initiation ages, and a quantitative evaluation of the prediction can be obtained using the standard deviation of the prediction and comparison of predicted ages with validation points. As such, it offers an alternative where uncertainty is quantified compared to manual deduction of isochrones from transects of basal dates (e.g. as in Foster *et al.*, 1988; Korhola, 1994, 1996; Mäkilä, 1997; Bauer *et al.*, 2003; Mäkilä and Moisanen, 2007).

The use of total thickness of organic deposits as covariate is only useful where remnant peat survived and a thickness of this layer can be derived. In contrast, use of the constructed covariate on groundwater-fed wetness may ultimately be applied beyond the limits of peat remnants, as it does not require information from peat deposits. As such, this novel approach enables reconstructions of the pattern, timing and rate of peatland initiation and lateral expansion in areas where the peat cover is (largely) lost.

For the reconstruction based on groundwater-fed wetness, we made the assumption that the current isohypse pattern reflects the natural situation as it was once present in the area, but with the pattern as a whole currently positioned at higher elevation. This assumption is reasonable within the boundaries of the Fochteloërveen nature reserve where groundwater levels are kept high (Provincie Drenthe, 2016; Altenburg *et al.*, 2017). However, in the surrounding area artificial drainage causes much lower groundwater levels. The results presented in Chapter 4 illustrate that this probably causes the prediction of younger ages near the boundary of Fochteloërveen. During a trial to reconstruct peat initiation ages outside the peat remnant, which by default has to be modelled based on groundwater-fed wetness as organic deposits are lacking, we came across a similar issue with modelling results indicating peat initiation ages that are likely too young. This underlines the importance that the isohypse pattern must reflect the natural pattern as closely as possible to obtain a reliable prediction, and that the method is not applicable to areas where groundwater levels are artificially lowered.

5.2.4 Relevance and integration of methodological tools

The methodological tools presented in this thesis aim to advance science on peatland reconstructions. Depending on research objectives, they can be applied separately, or concurrently in a complementary manner.

Relevance

The workflow for data reuse and quality assessment (Chapter 2) were designed with adaptability in mind, making them suitable for application in studies with divergent research questions and study regions. To obtain this flexibility, weights were applied to the quality criteria that may be adjusted based on research focus. Depending on which information can be retrieved (and the resulting penalty score and confidence level), data may be filtered prior to data analysis (for example, first including only sites with well-known location, then analysing sites with uncertain location as well). This allows a purposeful assignment of dates to various analyses and helps to ensure veracity of conclusions. To make the workflow and quality assessment suitable for analysis of large datasets, the quality assessment was scripted in Python to automatically assign a penalty score and confidence level to each date.

The recommendations for defining and dating basal peat (Chapter 3) are of relevance for a wide range of peatland studies. To move towards a quantitative definition of *basal peat*, organic matter content is a simple parameter that is easy to measure at low cost, which enables widespread use. Based on the organic matter gradient, a value can be chosen for the organic matter percentage above which the material is called peat. This value may differ between studies, but the described approach ensures that it is reproducible and eases comparison with other studies. The proposed steps for dating basal peat consider the timespan of peat initiation and consequences for sampling size and resolution. Application of the recommendations ensures that dating efforts are embedded in a conceptual framework and helps to obtain accurate dating evidence for peat initiation.

The application of digital soil mapping approaches in reconstructing peat initiation and lateral expansion (Chapter 4) is a field that has so far hardly been explored. A notable exception is the work of Chapman *et al.* (2013), who used second-order polynomial regression to reconstruct peat initiation ages based on empirical relationships with DEM derivatives. However, in their analysis the uncertainty of the prediction is not quantified, which is one of the key advantages of the approach in Chapter 4. The two covariates offer options for reconstructing peat initiation and lateral expansion within and potentially beyond the boundaries of peat remnants. Similar relationships between median peat initiation age and these covariates may be obtained for peat remnants elsewhere, enabling new options for peatland reconstructions in areas where large parts of the peat cover are lost.

Integration

The case study presented in Chapter 2 illustrated that the benefit of such meta-analyses is first and foremost dependent on the success of data retrieval. Retrieval of legacy data may require a high level of thoroughness, and registration of retrieved information may be a meticulous task. Based on the experiences with the case study in Chapter 2, I therefore emphasise the great importance of FAIR sharing (Wilkinson *et al.*, 2016) information on basic properties of dating samples to prevent further data loss from natural archives at risk of decline. Key properties to share information about include location, elevation and stratigraphy, and details about radiocarbon dating (following Millard, 2014) including the laboratory measurement as a conventional radiocarbon age in ^{14}C yr BP, the laboratory code, the sample material, and pre-treatments. The conceptual framework and recommendations presented in Chapter 3 may further help to clearly report information on dating samples.

The large age difference between dates of plant macrofossils and humic or humin dates that was found in Chapter 3 (up to ~1700 years between macrofossil and humic ages, and with even larger differences for humins) indicates that studies reusing legacy bulk dates of basal peat should take great care in data interpretation. Depending on sample details, dates are potentially interpreted more safely as terminus-ante-quem dates for peat initiation. Alternatively, they should be subjected to rigorous quality assessment prior to data analysis as proposed in Chapter 2.

The digital soil mapping approach presented in Chapter 4 requires a radiocarbon dataset for studies on regions with different properties than the Fochteloërveen peatland to obtain the required linear relationships. The effort and resources needed to obtain such a dataset may form an impediment to use the presented approach. However, current methodologies based on basal transects and isochrones require a similar dataset. Potentially the need for a radiocarbon dataset might be covered through reuse of legacy data (Chapter 2). If new data are obtained, a multi-stage dating approach is recommendable (also see staged approaches for dating as suggested by Bayliss, 2009; Piotrowska *et al.*, 2011). The first stage may consist either of an elaborate dating inventory comparable to the approach in Chapter 3 or of a more restricted preceding test (e.g., dating plant macrofossils and humics of three levels dispersed over the mineral-to-peat transition). The former provides detailed information on the peat initiation process and on the accuracy of different carbon fractions for dating, whereas the latter only provides the necessary insights on the duration of peat initiation and may consequently inform choices for sampling size and resolution before performing extensive spatial dating schemes as in Chapter 4.

5.3 Advances in understanding initiation and lateral development of peatlands in the Northwest European mainland

In this section, I will zoom out from the microtope (Chapter 3; section 5.3.1) to meso- and macrotope (Chapter 4; section 5.3.2) and beyond the macrotope level (Chapter 1; section 5.3.3). I end with a hypothesis regarding the steering factors for peat formation in coversand landscape of the Northwest European mainland (section 5.3.3).

5.3.1 Palaeoenvironment in the Fochteloërveen area during peat initiation

The biostratigraphical analyses presented in Chapter 3 and 4 demonstrate that the initial peat-forming vegetation at Fochteloërveen was mesotrophic and dominated by sedges (*Carex* spp.), with some presence of *Juncus*. For each location where a peat initiation date was obtained, the source of water during the formation of the first organic deposits could be deduced from the botanical data (Chapter 3 and 4). Of the fifteen peat initiation samples, five can be classified as geogenous, nine as transitional from geogenous to ombrogenous, and only one as truly ombrogenous (for definitions, see Textbox 1.1 in Chapter 1). These findings indicate that the initial formation of peat took place primarily under the influence of groundwater and surface runoff (Charman, 2002c).

As was discussed in Chapter 3, several levels of the three studied cores contained sclerotia of *Cenococcum geophilum*. This mycorrhizal fungus that usually lives in the sandy subsoil, may indicate rather dry conditions when encountered in peat (Van Geel, 1978). The investigated levels contained very little amoebae, but remains of *Difflugia* species were found in a few samples which points to very wet conditions. Interestingly, *C. geophilum* and *Difflugia* did not occur simultaneously in any of the investigated levels (see table 3.6 in Chapter 3). This suggests that water tables may have fluctuated and that drier (*C. geophilum*) and wetter (*Difflugia*) conditions alternated during the timespan of the peat initiation process. Periods with drier conditions may have caused the limited preservation of uncharred plant macrofossils, as these circumstances probably allowed increased decomposition of organic material. Charred plant macrofossils were encountered in the majority of the investigated levels of the three vertical sequences under study in Chapter 3, and in all but one of the dated levels in Chapter 4. This almost ubiquitous presence of charred organic material demonstrates that (local) fires must have occurred on a regular basis.

The mineral-to-peat transition, which resulted in the formation of mesotrophic fen peat, was followed by a fen-bog transition due to ombrotrophication (for general information on fen-bog transitions see Hughes, 2000; Charman, 2002a; Rydin and Jeglum, 2013d; for examples see e.g. Almquist-Jacobson and Foster, 1995; Hughes and Barber, 2004; Loisel and Bunsen, 2020. As the cores studied in Chapter 3 were directed at obtaining the mineral-to-peat transition, they did not fully contain the higher-positioned fen-bog transition. However, the botanical analyses of the upper layers of the cores indicate that at sites S17 and S18 the peat-forming vegetation developed to an oligotrophic bog with *Calluna vulgaris*, *Erica tetralix* and *Sphagnum*. For site S20 the record contained in the core does not clearly contain the fen-bog transition, but it seems that the vegetation became dominated by heathers and mosses (*Bryales*). At different locations within a peatland, fen-bog transitions may take place at different timings (Väliranta *et al.*, 2017), which is also the case at the three Fochteloërveen sites. At site S17 the transition took place probably at or after ~5000 cal y BP, at site S18 at or after ~1800 cal y BP, and at site S20 after ~2000 cal y BP (compare table 3.6 and fig. 3.7 in Chapter 3). A full description of the palaeoecological development at

Fochteloërveen will be presented in Van Beek *et al.* [in prep].

5.3.2 Peat initiation and lateral expansion at Fochteloërveen and the northern Dutch coversand landscape

An overview of the peat initiation data that were obtained in this thesis is presented in fig. 5.1. As demonstrated in Chapter 4, landscape scale peat initiation (following the conceptual framework in fig. 3.1 in Chapter 3) in the Fochteloërveen area took place at several loci during the Early Holocene (>7000 cal y BP). The reconstructions in fig. 4.8 indicate that these simultaneous peat initiation sites were located in the lower central, west and northwest parts of the area. The rate of lateral expansion can be derived from the distance between isochrones: where the distance between isochrones is small, the rate of lateral growth was low, and vice versa. In the reconstructions of Fochteloërveen, isochrones are mostly lying close to one another in the oldest peat-covered areas, indicating that peat initiation loci initially expanded slowly (see fig. 4.8/4.10 in Chapter 4, and fig. 5.1 below). As time progressed, lateral expansion accelerated, with the most pronounced period of expansion between 5,500 – 3,500 cal y BP. Sustained lateral expansion resulted in a peat cover for half of the Fochteloërveen area by 4,000 – 3.500 cal y BP, and for nearly the entire area between 2,500 – 900 cal y BP. The findings from Chapter 4 indicate that Fochteloërveen is a composite peatland that probably formed through coalescence of multiple smaller mires that formed on a topographic plain.

The meta-analysis of the legacy dataset in Chapter 2 shows a bimodal distribution of basal peat dates (fig. 2.8 and fig. 5.1). The legacy basal dates reflect peat initiation at the local scale (following the conceptual framework in fig. 3.1 in Chapter 3). Unfortunately, initiation loci or sites of lateral expansion could not be distinguished from one another, as it often remained unclear whether legacy basal dates originated from the same peatland (this would require a-priori a clear view of their palaeogeography). As a result, the analysis provides information about peat initiation and lateral expansion combined. The first phase of peat initiation (and lateral expansion) started during the Late Pleniglacial from ~16,000 cal y BP and lasted until ~12,000 cal y BP (depending on which certainty level is followed in fig. 5.1b). The second phase started ~9,000 cal y BP and continued until ~1,000 cal y BP, with a peak at approximately ~4,500 cal y BP. Peat initiation (and lateral expansion) data were separately analysed for different landform groups, which revealed several trends (fig. 2.9). River valleys were subject to Late Glacial peat growth, which continued during the Holocene. Peat growth on plains and ridges on the other hand started much later at ~6,000 cal y BP and lasted to ~2,000 cal y BP. Topographic depressions such as pingo remnants and deflations in coversand are characterized by an erratic pattern of peat growth through time. For sites with unclear palaeo-landform underlying the organic deposits, the data fit within the bimodal distribution that was found for the complete dataset. The dating evidence and modelling results for Fochteloërveen fit within the second phase of peat growth (fig. 5.1b/c).

5.3.3 Process of peat initiation and steering factors for peat growth

Peat initiation results from terrestrialisation, paludification and/or primary mire formation (see Textbox 1.2 in Chapter 1; Charman, 2002a; Rydin and Jeglum, 2013d). Peat formation in the northern Dutch coversand landscape is not connected with primary mire formation, as this region has been deglaciated and exposed at the surface since the penultimate Glacial (Ter Wee, 1962). Terrestrialisation typically results in gyttja (an organic lacustrine deposit) at the base of the organic deposits. To assess the prevalence of terrestrialisation versus paludification in the northern Dutch coversand landscape, the registered sample material of legacy basal dates ($n = 74$) was evaluated for presence of gyttja (see section 2.3.2.2 and table 2.5). Gyttja was only present in six samples. For Fochteloërveen, an amorphic organic layer was encountered at the mineral-to-peat transition, but this layer does not meet the requirements of true gyttja (following Bos *et al.*, 2012). Based on these findings, I conclude that paludification was the most prominent process of peat formation in the northern Dutch coversand landscape (and Fochteloërveen), with local occurrence of terrestrialisation sites. In the subsequent discussion of steering factors for peat growth, I will therefore focus on potential drivers of the paludification process.

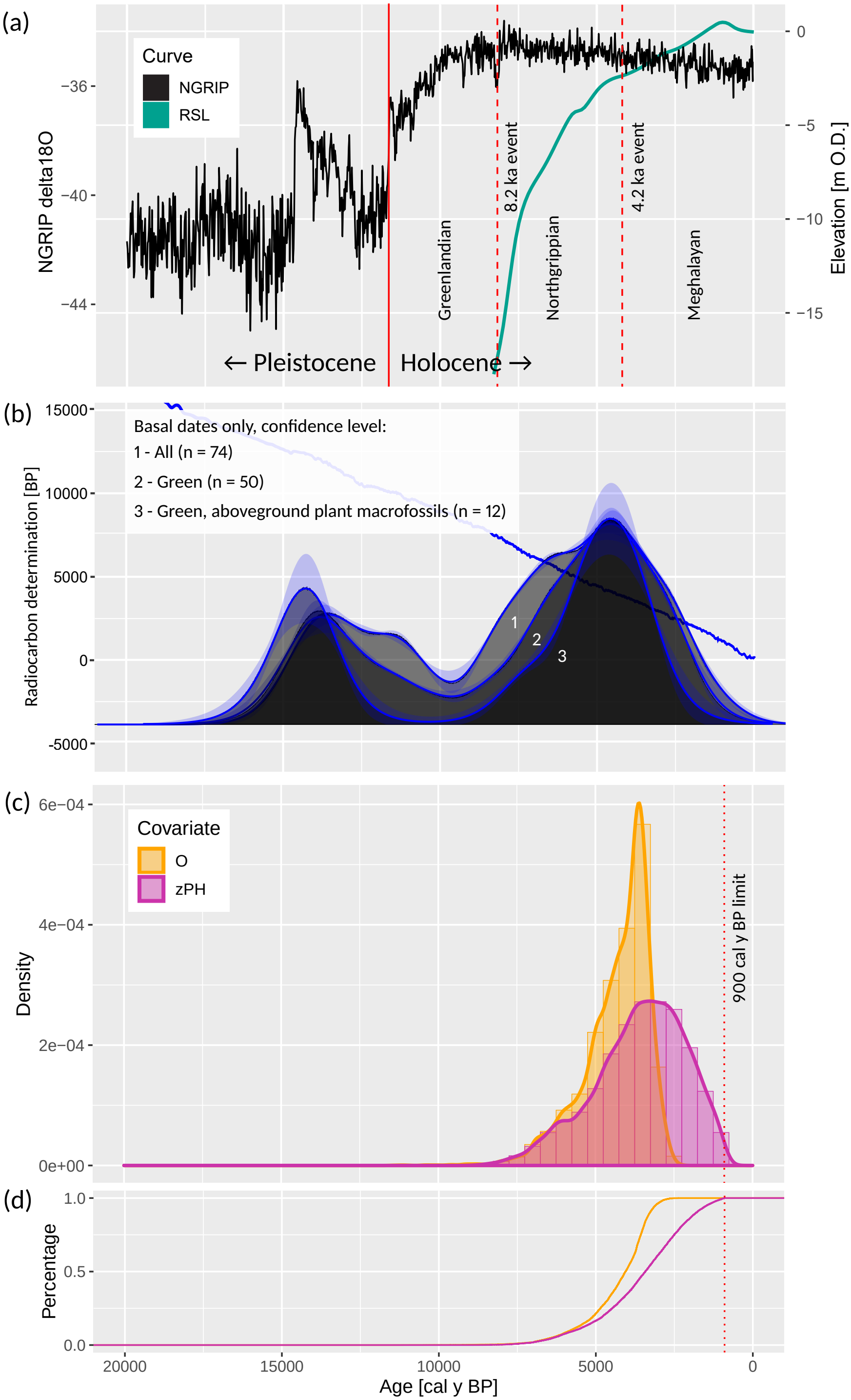
Peat formation in Northwest Europe is listed as a process with “cause under debate” in the summary chart of environmental and cultural changes during the Holocene by Roberts (2014). The work presented in this thesis points to several environmental factors that may have led to paludification, consequent peat initiation and subsequent lateral expansion. In the subsequent paragraphs I will discuss the potential effects of climate changes during the Last Termination and Holocene, sea level rise during the Holocene, impermeable (sub)surface layers, and human influence. I end with a hypothesis on the steering factors for paludification and peat growth in the Northwest European mainland.

Climate change

The bimodal distribution in fig. 5.1b shows that the first phase of peat growth started around ~16,000 cal y BP, peaked at ~14,000 cal y BP and lasted until ~12,000 cal y BP, followed by a distinct low at approximately ~9,500 cal y BP. This first phase of peat growth started after the Last Glacial Maximum during the

Late Pleniglacial (fig. 5.1a/b). Its peak coincides with the onset of the Bølling–Allerød interstadial (14.7 – 12.9 cal ky BP; Rasmussen *et al.*, 2006; cal ky BP ≈ ka b2k). The analysis of datasets with different confidence levels indicates unclarity about the duration of this phase. When considering only data with a green confidence level (i.e., most reliable), the phase ends around ~12,000 cal y BP, but the datasets that include data with lower confidence levels point towards ending of this phase around ~10,000 cal y BP (fig. 5.1b). It remains uncertain whether growth continued during the Younger Dryas (12.9 – 11.7 cal ky BP; Lowe and Walker, 2015) and Greenlandian Stage of the Holocene (11.7 – 8.2 cal ky BP; Walker *et al.*, 2019). However, the data subset with green confidence level suggests that peat growth was halted during this time. Peat growth continued during a second phase starting at ~9,000 cal y BP, which peaked at ~4,500 cal y BP and lasted until ~1,000 cal y BP. The rise of this second phase fully overlaps with the Northgrippian Stage (8.2 – 4.2 cal ky BP; Walker *et al.*, 2019). It coincides partly with the hypsithermal or Holocene Thermal Maximum (9,000 – 6,000/5,000 cal y BP; Wanner *et al.*, 2008; Renssen *et al.*, 2009) and with strong Holocene sea level rise (fig. 5.1a/b). The peak of the second phase may have been coeval with the 4.2 cal ky BP event and overlaps with the period of neoglacial cooling (6,000/5,000 cal y BP – pre-industrial time; Wanner et al., 2008). The recession of peat growth falls within the Meghalayan Stage (4.2 cal ky BP – present; Walker *et al.*, 2019) and neoglacial cooling. These findings led to the tentative conclusion in Chapter 2 that the first phase of peat growth was mostly driven by climate, whereas the second was probably the result of climatic conditions favourable to peat growth in combination with Holocene sea level rise and related rise in groundwater levels.

Figure 5.1: *(Figure on next page). Overview of peat initiation data obtained for the northern Dutch coversand landscape and Fochteloërveen. (a) δ^{18}O curve (GICC05 NGRIP δ^{18}O data accessed through OxCal), climatic division and events from Walker* et al. *(2009, 2019). Relative Sea Level (RSL) curve for the Northern Netherlands from Meijles* et al. *(2018). (b) Results from the kernel density estimation models presented in Chapter 2, showing the bimodal distribution of peat initiation dates (basal peat dates) in the northern coversand landscape of the Netherlands. The dark grey area indicates the sampled KDE estimated distribution. The blue line shows the mean of the KDE distribution, the lighter blue band shows the $\pm 1\sigma$ range. The calibration curve is indicated for reference (Reimer* et al.*, 2020). (c) Histogram and density plot of predicted peat initiation ages for Fochteloërveen presented in Chapter 4, showing results for the prediction based on the current total thickness of organic deposits [O], and for the prediction based on groundwater-fed wetness [$z_P H$]. Predictions were limited at 900 cal y BP due to onset of peatland reclamations (see Chapter 4). (d) Plot presented in Chapter 4, showing cumulative percentage of peat-covered area within the Fochteloërveen area.*


(a)
Curve
NGRIP
RSL
NGRIP delta18O
-36
-40
-44
0
-5
-10
-15
Elevation [m O.D.]
8.2 ka event
4.2 ka event
Greenlandian
Northgrippian
Meghalayan
← Pleistocene
Holocene →
(b)
Radiocarbon determination [BP]
15000
10000
5000
0
-5000
Basal dates only, confidence level:
1 - All (n = 74)
2 - Green (n = 50)
3 - Green, aboveground plant macrofossils (n = 12)
1
2
3
(c)
Density
6e-04
4e-04
2e-04
0e+00
Covariate
O
zPH
900 cal y BP limit
(d)
Percentage
1.0
0.5
0.0
20000
15000
10000
5000
0
Age [cal y BP]

The results of Chapter 4 indicated that lateral expansion at Fochteloërveen accelerated most rapidly between 5,500 – 3,500 cal y BP (fig. 5.1c/d). This overlaps with the peak of the second peat growth phase in fig. 5.1b. Similarly, Korhola *et al.* (2010) found that high-latitude peatlands in Europe expanded most drastically in the period between 5,000 – 3,000 cal y BP. In addition, the meta-analysis of Ruppel *et al.* (2013) demonstrated that lateral expansion accelerated during this time, both for peatlands in Northern Europe and in North America. Ruppel *et al.* (2013) propose that this large-scale trend of accelerated lateral expansion could be related to neoglacial cooling.

Previously, two phases of climate-induced peat initiation for the Netherlands were described by Casparie and Streefkerk (1992). However the evidence for these phases remains implicit and the assumed timing of the phases differs from the results obtained in this thesis. Casparie and Streefkerk (1992) state that the first phase lasted from 7,000 – 6,500 BCE (~9,000 – 8,500 cal y BP) and that the second took place around 5,000 BCE (~7,000 cal y BP). Both of these periods overlap with the rise and peak of the second phase in fig. 5.1b, suggesting that they are only parts of what is in fact one larger phase of peat growth.

Based on a basal peat date of 2920 – 2736 cal y BP (95.4% confidence interval) obtained from a core from Fochteloërveen, and a comparison with data obtained for other regions, Van Geel *et al.* (1998) propose a major effect of the 2.8 ka cal ky BP event leading to peat initiation on previously unsaturated soils. A significant effect of the 2.8 cal ky BP event does not become clear from the bimodal distribution of the legacy data (fig. 5.1b). In addition, the site studied by Van Geel *et al.* (1998) became covered with peat through lateral expansion as indicated by the models of peat initiation age presented in Chapter 4 (fig. 4.6), i.e., the site reflects only local and not landscape scale peat initiation (following the conceptual framework in fig. 3.1 in Chapter 3).

Sea level rise

The results from Chapter 2 and 4 suggest that, in addition to a potential climate effect, Holocene sea level rise may be (partly) responsible for the development of non-coastal and non-alluvial peatlands in the coversand landscape of the Northwest European mainland. Peat growth in coastal plains and in tidally influenced floodplains is directly controlled by sea level (e.g. Törnqvist and Hijma, 2012). Peatlands in the Dutch coversand area are considered to be fundamentally different (e.g. Pons, 1992: 7), suggesting that for these peatlands sea level is of lower relevance. In Chapters 3 and 4 however, the source of water during the formation of initial organic deposits could be deduced from the botanical data. This indicated that peat formed primarily under geogenous conditions (also see section 5.3.1, for definitions see Textbox 1.1 in Chapter 1), i.e., under influence of groundwater and surface runoff (Charman, 2002c). This points towards a strong influence of position within large scale geomorphology (high plains and incised valleys) on peat initiation, related groundwater-fed wetness (Chapter 4) and a potential indirect effect of Holocene sea-level rise (fig. 5.1a).

Impermeable (sub)surface layers

Some studies emphasise the relevance of impermeable (sub)surface layers or soil horizons in peat formation, which may cause accumulation of rainwater and perched groundwater tables (e.g. Everts *et al.*, 2002; Van der Meij *et al.*, 2018; Jansen *et al.*, 2019; Sevink, 2019). Geology and soils may influence the hydrological status during peat initiation (Charman, 2002b). Impermeable geological layers, such as boulder clay (which is present as a discontinuous layer underneath the northern Dutch coversand landscape and Fochteloërveen; Provincie Drenthe, 2022), form a boundary condition for drainage. In contrast, soil layers that are characterized by low permeability may form over the course of time, leading to an alteration in drainage conditions (Charman, 2002b). For instance, Sevink (2019) discusses multiple types of soil forming processes that may result in impermeable horizons, such as accumulation of humus and/or oxides during podzolization which results in a spodic horizon (IUSS Working Group WRB, 2015), that may develop to a degree where the horizon becomes impermeable to water.

Podzols are one of the most frequently occurring soils in the Dutch coversand landscape (Alterra, 2014). However, the results from Chapter 3 and 4 indicated that peat formed primarily under geogenous conditions (discussed above). It therefore seems likely that impermeable (sub)surface layers or soil horizons and related perched groundwater tables only affected paludification and peat growth locally, but are not responsible for large scale formation of peat in the studied region.

Human influence

In the Northwest European Plain, the transition from hunter-gatherers to early farming communities took place gradually (Raemaekers, 1999). Analysis of the archaeological record of Fochteloërveen and its wider surroundings (Van Beek *et al.* [in prep]), shows that from the second half of the 4th millennium BCE onwards (~5,500 cal y BP) agrarian communities had settled in multiple parts of the region. This is supported by palynological evidence, which shows a decline in arboreal pollen and the emergence of cereal pollen from ~5,500 cal y BP onwards (Van Beek *et al.* [in prep]). Also for other areas in the northern Dutch coversand landscape an increase in human landscape impact was recorded around ~5,500 cal y BP. For instance, palynological investigations in the Bargerveen peat remnant showed that human influences can be traced in arboreal pollen data from 5,500 cal years

BP onwards (Dupont, 1986). Also for the Gietsenveentje peatland agricultural activity increased at this time (Bakker, 2003). Arboreal pollen further decreases until the lowest percentage is reached during the Roman Period (~1,700 cal y BP) (Van Beek *et al.* [in prep]).

Zagwijn (1986) and Spek (2004: 116–117) suggested that deforestation by humans may have contributed to a rise in groundwater tables due to a decrease in evapotranspiration following forest clearing. The decline in arboreal pollen (Van Beek *et al.* [in prep]) may reflect a combined effect of deforestation and a natural decrease in forest cover due to groundwater levels that rose in response to non-human factors (see discussion in the section below). Deforestation could be an additional factor that facilitated peat growth. I expect that deforestation could have played a role during the second phase of peat growth (fig. 5.1b).

Hypothesis on steering factors for peat growth

In the following section I present a hypothesis of the process and steering factors for peat growth (visualised schematically in fig. 5.2), based on the discussion above and inspired by the outcomes of this thesis.

During the Bølling-Allerød, minerogenous peat began to grow primarily in valleys (alluvial settings) during a first phase of peat growth (fig. 5.2a; Chapter 2). During the Younger Dryas and Greenlandian Stage peat initiation and/or lateral expansion halted (fig. 5.2b; Chapter 2). Peat that formed in valleys potentially degraded during this period as a result of oxidation. In the Northgrippian Stage, peat growth restarted (fig. 5.2c; Chapter 2, 3 and 4). The climatic conditions during the hypsithermal facilitated peat growth. In areas close to the coast, minerogenous peat formation is directly controlled by sea level rise (e.g. Törnqvist and Hijma, 2012). A higher position in the landscape will reduce the relative importance of sea level for peat formation; topographic factors (depth of valley incision and distance between valleys) are then progressively more influential. In a landscape setting where the distance between valleys is relatively small, minerogenous peat will form in valleys. Due to relative proximity of the watershed limit to the valley, drainage is sufficient to prevent formation of watershed mires on the small plateaus between the valleys. In a landscape setting where distance between valleys is relatively large (as in fig. 5.2), peat will form on the plateaus due to poor drainage at the watershed limits. Peat formation in valleys is generally considered as one of the processes leading to poor drainage in the higher areas of the Dutch coversand landscape and ultimately as a facilitating factor in the formation of peat (Vos, 2015a: 58; Douwes and Straathof, 2019). Holocene sea level rise during the Northgrippian, in combination with poor drainage due to growing peat deposits in valleys, and a potential facilitating effect caused by deforestations, led to a rise in regional groundwater levels. This caused a groundwater influence near

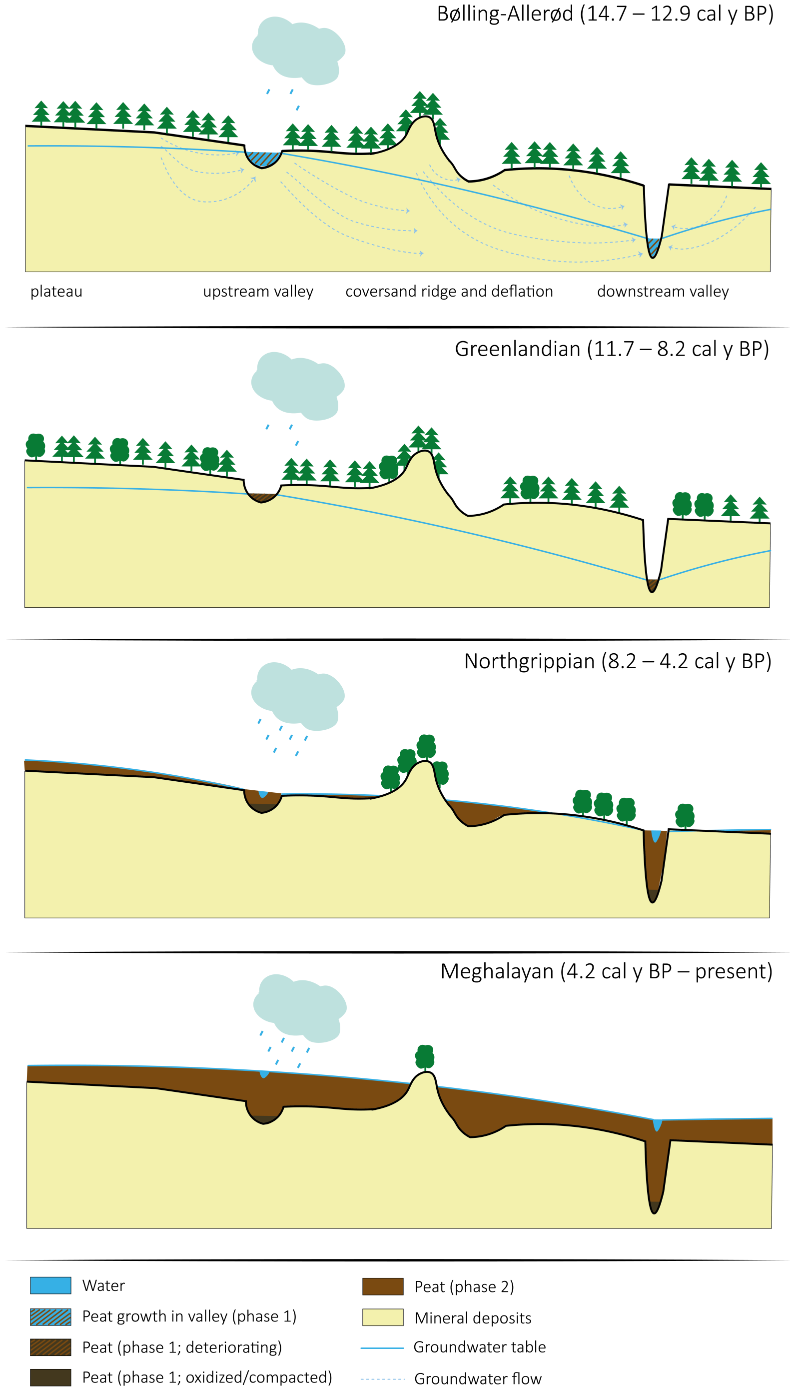


Figure 5.2: *Schematic hypothesis regarding the factors and processes responsible for the development of peatlands in the coversand landscape of the Northwest European mainland (for more information see text).*

the surface of the plateaus and resulting minerogenous peat formation (Chapter 3 and 4). Evapotranspiration of a peat-covered landscape is lower than the evapotranspiration of forests (Van der Velde *et al.*, 2021), leading to a positive feedback loop for peat formation and a shift from a forested landscape to a peat landscape. This is supported by descriptions of remnants of a drowned oak forest adjacent to the Fochteloërveen nature reserve (De Telegraaf, 1897; Popping, 1935: 21, 39–43). Initially, conditions on the well-drained plateau slopes remained favourable for forests. In the course of time, and as sea level continued to rise, valley mires grew beyond the valley sides and mires on the plateaus expanded laterally, eventually resulting in an extensive composite peat landscape (fig. 5.2d). Vertical peat growth beyond groundwater level on the plateaus caused ombrotrophication and resulted in (asynchronous) fen-bog transitions (Chapter 3; not shown in fig. 5.2d).

5.4 Conclusions

In this thesis I identified two key research deficits (Chapter 1), regarding the need for (I) methodological developments to constrain the spatio-temporal development of peatlands more accurately, and (II) improved understanding of the timing, pace and pattern of the initiation and lateral development of peatlands in the coversand landscape of the Northwest European mainland. The main contributions of this thesis to resolving these research deficits are listed below.

With respect to methodological advances:

- A workflow for reuse of legacy radiocarbon dates in peatland studies was developed (Chapter 2). This workflow includes a rigorous quality assessment, where a penalty is assigned to each date based on criteria that consider taphonomic quality (i.e., sample provenance) and dating quality (i.e., sample material and method used). The workflow and quality assessment can be tailored to specific research questions and study regions.

- A conceptual framework was provided (Chapter 3) that supports the use of the organic matter (OM) gradient for a quantitative and reproducible definition of the mineral-to-peat transition (i.e., the stratigraphical range reflecting the timespan of the peat initiation process) and the layer defined as *basal peat* (i.e., the stratigraphical layer that is defined as the bottom of a peat deposit). A list of recommendations for dating peat initiation was presented based on detailed analyses of three radiocarbon sequences (Chapter 3).

- An approach for modelling peat initiation and lateral expansion through time and space was presented (Chapter 4), where digital soil mapping techniques are applied using one out of two covariate options. Key benefits are that the approach results in a map of peat initiation ages (spatially explicit) and that it provides a quantitative evaluation of the prediction using the standard deviation. The use of total thickness of organic deposits as covariate is only useful where remnant peat survived, whereas the constructed covariate on groundwater-fed wetness may ultimately be applied to reconstruct peat initiation ages and lateral peatland expansion beyond the limits of peat remnants.

With respect to the initiation and lateral development of peatlands in the coversand landscape of the Northwest European mainland:

- Meta-analyses of legacy data show a bimodal distribution of basal peat dates (Chapter 2). The first phase of peat initiation (and lateral expansion) started during the Late Pleniglacial at ~16,000 cal y BP, peaked at ~14,000 cal y BP, and lasted until ~12,000 cal y BP. The second phase started ~9,000 cal y BP and continued until ~1,000 cal y BP, with a peak at approximately ~4,500 cal y BP. River valleys were subject to Late Glacial peat growth, which continued during the Holocene. Peat growth on plains and ridges started much later at ~6,000 cal y BP and lasted to ~2,000 cal y BP. Topographic depressions such as pingo remnants and deflations in coversand are characterized by an erratic pattern of peat growth through time.
- Landscape scale peat initiation in the Fochteloërveen area took place at several loci during the Early Holocene (>7000 cal y BP). As time progressed, the rate of lateral expansion began to accelerate, with the most pronounced period of expansion between 5,500 – 3,500 cal y BP. Sustained lateral expansion resulted in a peat cover for half of the Fochteloërveen area by 4,000 – 3,500 cal y BP, and for nearly the entire area between 2,500 – 900 cal y BP (Chapter 4). The dating evidence and modelling results for Fochteloërveen fit within the second phase of peat growth (Chapter 2).
- Biostratigraphical analyses (Chapter 3 and 4) demonstrate that the initial peat-forming vegetation at Fochteloërveen was mesotrophic and the majority of the peat initiation samples could be classified as geogenous. These findings indicate that the initial formation of peat took place primarily under the influence of groundwater and surface runoff. During the timespan of the peat initiation process, water tables probably fluctuated with alternating drier and wetter conditions. The mineral-to-peat transition was later in time followed by a fen-bog transition (Chapter 3).

- Paludification was the most prominent process of peat formation in the northern Dutch coversand landscape (and Fochteloërveen), with local occurrence of terrestrialisation sites. A hypothesis regarding the factors and processes responsible for the development of peatlands in the coversand landscape of the Northwest European mainland was presented to offer direction for future research. Based on combined findings from Chapters 2 – 4 and the synthesis in Chapter 5, I tentatively conclude that the first phase of peat growth was mostly driven by climate, whereas the second was probably the result of climatic conditions favourable to peat growth in combination with Holocene sea level rise and related rise in groundwater levels.

5.5 Recommendations for future research

In this section I first discuss recommendations for methodological advances and subsequently directions for future peatland research in the Northwest European mainland.

5.5.1 Recommendations for methodological developments

Regarding methodological advances, I see three developments that have great potential for future research.

Ages of carbon compounds

The first one (associated with Chapter 3) is directed at gaining more knowledge on the ages of the various carbon compounds in the mineral-to-peat transition. The source of the younger carbon in the humin fraction, and the cause for the incoherence that was recorded in the humin dates, remained unclear. A potential explanation is the effect of inclusion of roots in the bulk samples, which were not removed prior to pre-treatment for radiocarbon dating. Downgrowth of roots could be a relevant factor especially where (fen) peat accumulates slowly (Streif, 1972; Törnqvist *et al.*, 1992), as is the case in the studied cores during the mineral-to-peat transition. Additional dating may shed light on the influence of in- or excluding roots in bulk samples, and may help to gain more insight in the mobility of different carbon fractions and their source within the peat profile. Research on this topic has already started in a collaboration by Sanne W.L. Palstra (Centre for Isotope Research, University of Groningen), Marjolein van der Linden (BIAX Consult, Zaandam), and the author of this PhD thesis. So far, the dating procedure has been completed for this study and the results await further analyses.

Dating the pre-peat landscape
The second recommendation (also related to Chapter 3) proposes an alternative way to constrain the age of peat initiation by making use of Optically Stimulated Luminescence (OSL) dating (see e.g. Preusser *et al.*, 2008 for more background on OSL dating, and Galbraith and Roberts, 2012 for more information on age models such as the Minimum Age Model (MAM), referred to below).

Dating bioturbation processes is a recently developed application of OSL (Reimann *et al.*, 2017). As OSL involves dating of the mineral substrate, it cannot date peat deposits directly as is done in radiocarbon dating. However, it could be used to obtain the age when bioturbation in the mineral soil underlying peat deposits ceased due to paludification. Peat formation started as a result of paludification, and as such OSL ages could provide terminus-post-quem dates for peat initiation. An initial exploration of this concept was performed during MSc thesis research by Koudijs (2022; supervised by Jakob Wallinga and the author of this PhD thesis). For this purpose, equivalent dose distributions were analysed as function of depth for samples obtained from directly underneath the mineral-to-peat transition. Vertical series of MAM ages, and percentages of grains that could be assigned to the MAM over the investigated depths, point towards termination of bioturbation. The OSL results were compared with radiocarbon ages that were obtained in Chapter 3 and 4 of this thesis and correspond quite well. These promising results show the potential of this approach for constraining the timing of peat initiation. As this method does not require preservation of organic material, it could potentially be applied to obtain age information on the timing of paludification in areas where the peat cover is lost or highly degraded, given that the mineral substrate is intact. To develop this method further, dating studies of additional OSL cores of Fochteloërveen (for which complementary radiocarbon dating evidence is already available) would be valuable to gain more insights in the responsible bioturbation processes and potential confounding effects through other processes of soil formation, for instance cessation of bioturbation caused by acidification and podzolization. As a next step, the method could be applied to a mineral soil with a degraded peat cover, to test the potential for obtaining dating evidence beyond peat remnants.

Model extrapolation
A third recommendation (building on Chapter 4) is to extrapolate the model that builds on groundwater-fed wetness as predictor of peat initiation age beyond peat remnants. The isohypse pattern must resemble the natural (i.e., not artificially drained) groundwater level as closely as possible for this model to reliably predict peat initiation, as was emphasized in Chapter 4 and section 5.2.3. As the current groundwater levels outside Fochteloërveen (and probably also in the vicinity of

other peat remnants) are artificially lowered, their pattern cannot be used for extrapolation. Hydrological modelling techniques could offer a solution for this problem, to obtain the natural (not human-modified) groundwater levels based on Pleistocene surface topography, hydraulic conductivity of the mineral subsurface, Holocene climate data and data on Holocene sea-level rise. While modelling the natural hydrological pattern, it is important to keep in mind that peatland development may cause complications, for example where peat growth in valleys changes regional base level or where the formation of peat domes affects drainage divides.

If the natural isohypse pattern of the landscape surrounding a peat remnant could be derived through hydrological modelling techniques, the digital soil mapping approach based on groundwater-fed wetness could provide new insights in peatland initiation and lateral development in regions where this information cannot be collected from the field. Additionally, this may improve process understanding and provide insights in the hydrological and climatological boundary conditions that allowed peat formation to take place. As this involves modelling peat initiation ages based on modelled hydrological data (with related uncertainties), uncertainty propagation techniques (e.g. Heuvelink, 2018) might be useful to constrain the resulting (un)certainty of the reconstructed ages of peat initiation.

In Chapter 1 and Chapter 4 I discussed three approaches for reconstructing spatio-temporal peatland dynamics. Unfortunately, so far no numerical models seem to be available that can model the lateral dimension of peat growth (see e.g. the comprehensive discussion of peat models by Baird *et al.*, 2012). If in the future numerical peatland models would be expanded with functionalities to model lateral expansion, the digital soil mapping approach proposed in Chapter 4 could potentially be used for validating these numerical modelling outputs.

5.5.2 Recommendations for peatland research in the Northwest European mainland

I see several opportunities for further study, considering the palaeoenvironment of Fochteloërveen, steering factors for peat growth and the genesis of composite peat landscapes in the Northwest European mainland, and integration of peatland research in interdisciplinary contexts.

Palaeoenvironment of Fochteloërveen

As discussed in section 5.3.1, the highly abundant presence of charred organic material in the investigated levels of the Fochteloërveen cores suggests that (local) fires must have occurred regularly. Further study of physical and chemical properties of the organic matter and ash content of the cores may shed more light on ignition conditions and type of burning (flaming or smouldering). This may be relevant for understanding the time span of peat initiation (to what degree is organic material lost due to fires), for characterizing the interplay with hydrological processes, and could have climatological implications (e.g. Zaccone *et al.*, 2014). In addition, it may be relevant for interdisciplinary integrations that consider human landscape influence (see below). For more information on (palaeo)fires in peatlands see e.g. Nelson *et al.* (2021).

Steering factors for peat growth and genesis of composite peat landscapes
A key direction for future research is to improve understanding of the steering factors for peat growth in the coversand landscape of the Northwest European mainland. The hypothesis presented in section 5.3.3 offers guidance for this. Additionally, the recommendation to use hydrological modelling to extrapolate the digital soil mapping approach beyond peat remnants (sections 5.2.3 and 5.5.1) offers a starting point to move towards understanding of processes and feedbacks in the development of peat landscapes in this region.

Another element related to this, is to expand the research scope to include both peatlands that developed on non-coastal and non-alluvial topographic plateaus, and peatlands that developed in valleys (alluvial settings) that intersect these plateaus. Study of the landscape connections between peat on plateaus and valley peat, may yield new knowledge and an integrated understanding of the genesis of the former extensive composite peat landscapes of the Northwest European mainland. As an initial step, the stratigraphy and chronology of one of the upper reaches of the Peizerdiep, named the Slokkert (i.e., draining water from the Fochteloërveen in northern direction), was studied by Jasper Candel and the author of this PhD thesis. The obtained ages along the valley side (unpublished data) fall within the Late Glacial period and mostly within the Bølling-Allerød interstadial. The development of peat during this period fits within the first phase of peat growth (fig. 5.1b). In addition, two dates suggest that a renewed phase of peat growth started approximately synchronous with the 8,2 cal y BP event. Further study of this site, especially a vertical sequence of radiocarbon dates, may shed more light on the timeframe that is captured in the peat deposit in the valley, which may reflect both peat growth phases of fig. 5.1b.

Lastly, data rescue and meta-analysis for other major bog remnants in the Northwest European mainland may help to further substantiate the regional character of the phases of peat growth (fig. 5.1b) and consequently increase understanding of the steering factors for peat growth.

Interdisciplinary integration
A key interdisciplinary integration is of peatland palaeogeography and palaeoecol-

ogy with archaeological data on human land use and habitation. The interplay between peatland initiation and lateral expansion, human habitation and vegetation dynamics is not well understood (Van Beek *et al.*, 2015; Van Beek, 2015). A study that aims to contribute to this knowledge deficit is currently in preparation (Van Beek *et al.* [in prep]) and uses the Fochteloërveen area (including both the peat remnant and adjacent mineral soils) as a case study (incorporating findings from Chapters 3 and 4). Main aims are to analyse how the initiation and lateral expansion of the Fochteloërveen peatland relates to human habitation patterns through time and space, how the vegetation of the area (locally and regionally) developed over time, and in which ways humans contributed to landscape or vegetation changes. The period between the Late Palaeolithic and the Early High Middle Ages (~15,000 BCE – 1,000 CE) forms the scope of the study.

In addition to the interdisciplinary study mentioned above, further research on levels of the Fochteloërveen peat cores that contain the period from ~8,000 to 6,000 cal y BP (~6,000 to 4,000 BCE; e.g. cores S9, S10, S16, S17, S19) may help to further constrain the Mesolithic to Neolithic transition and agricultural activity of the Swifterbant and Funnel Beaker cultures (Raemaekers, 1999; Bakker, 2003).

The abovementioned suggestions which focus on the Fochteloërveen, may serve as examples for similar interdisciplinary peatland studies in the wider Northwest European mainland. The information that can be obtained from the peat archives offers unique opportunities to analyse the environmental context of (changes in) human-landscape interactions. Many studies on archaeological finds from peatlands have a strong focus on material culture, and attention for environmental and socio-cultural contexts has been limited (cf. Chapman, 2015; Van Beek *et al.*, 2019). Interdisciplinary integration of archaeological studies with research on peatland palaeogeography and palaeoecology may therefore yield new insights in past human behaviour (Van Beek *et al.*, 2019).

5.6 Implications

5.6.1 Peatlands and ecosystem services

The transition from dryland to wetland and to peatland represents a huge landscape change that has major impacts for landscape functioning and ecosystem services. Ecosystem services provided by peatlands include amongst others carbon storage (Joosten and Couwenberg, 2008), greenhouse gas fluxes (Sirin and Laine, 2008), and biodiversity (Minayeva *et al.*, 2008). Changes in future climate, especially rising temperatures and changes in water availability, are expected to significantly affect the ecosystems services provided by peatlands (Charman *et al.*, 2008; Parish *et al.*, 2008b).

Peatlands play an important role in the global carbon cycle (Yu *et al.*, 2011) and form the largest long-term carbon store in the terrestrial biosphere (Joosten and Couwenberg, 2008). Peatland extent forms a fundamental boundary condition in the carbon dynamics of peatlands (Loisel *et al.*, 2013) and in calculations of peatland carbon fluxes the spatial extent of peatlands is a fundamental parameter (Korhola *et al.*, 2010; Yu *et al.*, 2010). Reconstructing the development and size of carbon storage in peatlands throughout the Holocene is an active field of research and debate, as was illustrated recently by the differences in estimating the carbon storage of northern peatlands between the studies by Nichols and Peteet (2019) and Ratcliffe *et al.* (2021). Increased understanding of the age and palaeogeography of peatlands (as in this thesis) may contribute to these ongoing developments and is vital for improving the accuracy of models on past, present and future carbon storage and release.

5.6.2 Nature conservation and restoration

The vast losses in peat cover (Chapter 1) and continuous threats to the survival of peatlands in Europe and elsewhere (e.g. Bragazza *et al.*, 2006; Swindles *et al.*, 2019) pose the need to protect the peatland areas that are left. From a scientific point of view, these exceptional archives of the past environment may satisfy future demands for information about the past (cf. Greiser and Joosten, 2018). The study by Greiser and Joosten (2018) offers examples of how to evaluate the value of peat archives based on predefined criteria, as a way to include archive value in decisions on conservation and restoration. The age of the peat archive, as was studied in this thesis, is a key limitation on information that the archive may contain. Therefore knowledge on the timing of peat initiation (and lateral expansion) is of great significance in assessing archive content and value.

Furthermore, evidence-based narratives of palaeoenvironmental and palaeoecological development are needed as dynamic references for nature conservation and restoration goals (Gillson *et al.*, 2021). Such longer-term data is fundamental to understand natural variability and ecosystem resilience, and to contextualize changes that are observed today (Gillson *et al.*, 2021). Knowledge on the age, palaeogeography and palaeoecology of Fochteloërveen may provide this reference for nature conservation and restoration goals in this area. Current assumptions by nature conservation organisations highly underestimate the age of the Fochteloërveen peat remnant, and may be updated based on the outcomes of this thesis. For instance, Altenburg *et al.* (2017) state that Fochteloërveen developed from 800 BCE onwards, and Provincie Drenthe (2016) and Douwes and Straathof (2019) describe that its development started from approximately 1000 BCE onwards. In addition, currently only the southern central area is recognized as the old core of the peatland (Altenburg *et al.*, 2017), whereas the findings of this thesis indicate that several Early Holocene loci of peat initiation are present within the area.

In the 'Assessment on Peatlands, Biodiversity and Climate Change', Parish *et al.* (2008a,b) state that reducing drainage and improving water management in peatlands is the most important step to prevent peatland degradation, to protect biodiversity, to reduce the risk of fire and to stop carbon dioxide emissions from peat. In Fochteloërveen, nature restoration efforts from the 1980s onwards have mainly been directed at improving water retention in the area. In addition, aims were to reduce the occurrence of *Molinia caerulea* (presence of *M. caerulea* strongly increased in the second half on the twentieth century due to nitrogen deposition), and to increase the amount of vascular bog plant species and *Sphagnum* mosses (Provincie Drenthe, 2016; Altenburg *et al.*, 2017). The palaeoecological data that were obtained in this thesis (and in the work of Van Beek *et al.* [in prep]) could assist in re-evaluating the value of areas with a vegetation in which the presence of *Sphagnum* is low. Some of these mesotrophic habitats might be comparable to the palaeoenvironment during and shortly after peat initiation and as such reflect the long-term history of the Fochteloërveen.

5.6.3 Cultural history and heritage management

Information on the palaeogeographical and palaeoenvironmental development of peatlands plays a vital role in understanding and contextualising long-term human habitation patterns (Van Beek *et al.*, 2015), and in the analysis of single archaeological sites (either discovered in the distant past or still present in-situ; e.g. Plunkett *et al.*, 2009; Chapman *et al.*, 2019; Van Beek *et al.*, 2019). The knowledge that this thesis provides on the age, palaeogeography and palaeoenvironment of peatlands may serve as direct input for interdisciplinary studies on the changes in human-landscape interactions (section 5.5.2).

In addition, insights in the age and character of peat deposits may be highly informative for cultural heritage management purposes and archaeological prospection, as peat layers may cover or contain well-preserved waterlogged archaeological sites that are unparalleled in dryland environments. The sustainable management of cultural heritage in (former) raised bogs has received relatively little attention in the Netherlands. Several wetland-oriented heritage management projects have been issued by the Dutch Cultural Heritage Agency, but all with a focus on coastal areas (Van Dockum *et al.*, 2001). A key objective of the overarching *Home Turf* project is therefore to develop a proactive strategy for the management of cultural heritage in raised bogs (Paulissen and Van Beek [in prep]). The need to consolidate and advance cross-domain research and pressing lack for joint efforts in natural and cultural heritage management has been recognized for several decades (Buckland, 1993; Gearey and Chapman, 2004) and is still relevant today (Gearey and Everett, 2021). Recently, it has been suggested that cultural heritage should be included within the ecosystem services framework (Tengberg *et al.*, 2012; Gearey *et al.*, 2014; Hølleland *et al.*, 2017), as a way to pose heritage along other potentially competing conservation interests (Gearey *et al.*, 2014). The current management plan of Fochteloërveen (Provincie Drenthe, 2016) does not include heritage management, but restoration practices are adjusted for sites that are marked as archaeological monument. For instance, the central sand ridge ('Bonghaar') in the Fochteloërveen is not subjected to removal of sods (Dutch: *plaggen*) to eliminate nutrients, but grazed for this purpose. The results of this PhD thesis, along with the findings by Van Beek *et al.* [in prep], could offer further points of reference for integrating natural and cultural heritage management in the area. The work by Paulissen and Van Beek [in prep] provides a framework for mapping cultural remains in (former) peatlands and for integrated management of natural and cultural heritage.

5.6.4 Peatlands in environmental education and science communication

Peatlands are landscapes with great potential to feature in environmental education, both in formal educational contexts and in science communication with the general public. The long-term development of peatlands is relevant for students of physical geography, ecology, archaeology, history, and for applied disciplines that are concerned with landscape management such as forestry, landscape architecture, and environmental policy. In response to this thesis project and the research outcomes on the long-term development of Fochteloërveen, bog landscapes are included in a course of the earth science curriculum at WUR from the academic year 2021 – 2022 onwards, and illustrated through a field excursion to Fochteloërveen (Candel and Makaske, 2022).

Adequate training of peatland researchers is fundamental to ensure accurate and timely decision-making in nature and climate policy (Meleisea, 2022). In addition, in the policy paper by Erwin (2009), which was produced at the request of the Ramsar Convention on Wetlands, the need for education of public and private sectors about the protection and restoration of wetlands is listed as a point of action. One of the obstacles to translate scientific evidence to policy and management practice is that it is not always synthesized and communicated in a way that is useful for decision-makers (Meleisea, 2022). To make research outcomes more accessible, Van Beek *et al.* [in prep] have converted scientific results into two artist impressions, i.e., digital landscape renders created by a renowned artist based directly on research data. The artist impressions show what the surroundings of Fochteloërveen looked like during the Mesolithic and Roman Period. The outcomes of this thesis are also included in both artist impressions. The artist impressions will be presented to the Province of Drenthe and to Natuurmonumenten (the nature conservation organisation that manages the Fochteloërveen area). This approach may serve as inspiration for peatland researchers to communicate their findings to policy makers and management organisations, and also as a way to showcase research to the general public.

Peat is not renewable (IMCG, 2022) and peat landscapes reflect thousands of years of history (this thesis). The ability to tell the long-term development story of a landscape (this thesis) and the way humans interacted with it (Van Beek *et al.* [in prep]) may help to increase public support for conservation and restoration. The research of this thesis project was presented to a non-scientific audience through several outreach activities, including a television broadcast on Fochteloërveen (ROEG!, 2021), a documentary on Fochteloërveen (Story Driven, 2022), and through a series of exchanges between science and art focused on peatlands (Foster, 2022; ISRIC World Soil Museum, 2022a,b). Comparable science communication efforts on peatland research in the Northwest European mainland and elsewhere may help to show the value, history and beauty of these unique landscapes, and the importance of protecting and restoring peat remnants.

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Summary

Peatland initiation through time and space

Peatlands comprise 50 – 70% of all global wetlands, making them the most prevalent wetland type. Peat deposits consist of organic material that accumulated under more or less water-saturated conditions, and form a natural archive of past environmental changes. For Europe, it is estimated that over 50% of the peatland area was lost during the twentieth century. For the Netherlands, only 1% of the former peatland area is left today. These tremendous losses in peatland surface area, and ongoing threats to their existence in Europe and elsewhere, pose the urgency to accumulate the knowledge that is contained in the peat archives, and the need to protect the areas that are left. One of the biggest changes recorded in the peat archives, the transition to peat growth itself, is underexposed in scientific research. The transition from dryland to wetland (and to peatland) represents however a huge landscape change, with major impacts for landscape functioning, ecosystem services and human-landscape interactions.

Reconstructing the period, pace and pattern of peat initiation and lateral expansion requires dating the bottom of peat deposits overlying mineral sediment, often called the basal peat. To obtain dating information for reconstructions, one can either look back in the scientific record to build on and integrate existing information, or obtain new data from the field. The huge losses of peat landscapes in Europe call for reuse of existing data, which may contain information that can no longer be obtained from the field. However, for geochronological peat research no overviews exist of factors that need to be taken into consideration for reuse of radiocarbon dates, and standardized workflows or designs for quality assessments of peat dates are lacking. When obtaining new information from the field, accurately dating basal peat is key. However, the lack of a universally applicable and quantitative definition for basal peat, combined with multiple concerns that have been raised previously regarding the radiocarbon dating of peat, may result in apparent ages that are either too old or too young for the timing of peat initiation. Furthermore, in areas where large areas of peatlands are lost, an adapted strategy is required to collect field data based on peat remnants. Alternative methods of analysis are needed to reconstruct peat initiation and lateral expansion in a way that uncertainty is quantified, which is especially relevant when reconstructing a former landscape of which large parts are lost.

In this thesis I focus on mires and peatlands that formed on non-coastal (located above mean sea level) and non-alluvial topographic plains in the coversand landscape of the temperate Northwest European mainland. The spatio-temporal

development of these peatlands remains uncertain, probably as a result of their large-scale disappearance following reclamation activities in the past few centuries and consequent limited amount of data for these areas. In addition, existing information on the age of the former peatlands in the coversand landscape of the Northwest European mainland is not yet fully synthesized. I identified two key research deficits, namely (I) methodological developments are needed to constrain the spatio-temporal development of peatlands more accurately; and (II) understanding of the timing, pace and pattern of the initiation and lateral development of peatlands in the coversand landscape of the Northwest European mainland is limited, and responsible steering factors are not well understood. In this thesis I aim to reconstruct peat initiation and lateral expansion in the coversand landscape of the Northwest European mainland, and to develop the required methodological tools, which can be applied irrespective of the case study region.

Each thesis chapter (2 – 4) focuses on elements of research deficits (I) and (II). The period after the Last Glacial Maximum to the present (Late Pleniglacial and Holocene) forms the temporal scope of the thesis. The northern part of the Dutch coversand area was selected as case study region, which contains one of the largest bog remnants of the Northwest European mainland, the Fochteloërveen. This PhD-study is part of the NWO-Vidi project '*Home Turf. An integrated approach to the long-term development, cultural connections and heritage management of Dutch raised bogs*', led by Roy van Beek. This project has an interdisciplinary design and consists of several interlinked project elements: landscape archaeology (by Roy van Beek), historical geography (by Maurice Paulissen), ore geology (by Aukjen Nauta), and palaeogeography (this thesis).

In Chapter 2, I developed a workflow for reuse of legacy radiocarbon dates in peatland studies, including a rigorous quality assessment that can be tailored to specific research questions and study regions. In the quality assessment, a penalty is assigned to legacy dates based on criteria that consider taphonomic quality (i.e., sample provenance) and dating quality (i.e., sample material and method used). The weights of the quality criteria may be adjusted based on the research focus, and resulting confidence levels may be used in further analyses to ensure robustness of conclusions. I applied the proposed approach to the northern Dutch coversand landscape, to synthesize existing data for this area and to gain insight in regional peat growth trends. The data search for this area yielded 313 radiocarbon dates from the 1950s to 2019. Based on the quality assessment, the dates –of highly diverse quality– were assigned to four confidence levels. Results indicate a bimodal distribution of peat initiation and lateral expansion, with a first phase of peat growth that peaked at ~14,000 cal years BP, followed by a distinct low at approximately ~9,500 cal years BP, and a second phase that peaked at ~4,500 cal years BP. This chapter highlights the potential of legacy data for palaeogeographic reconstructions, as it is cost-efficient and provides access to information that is (partly) no longer available in the field. However, data retrieval may be challenging, and reuse of data requires that basic information on location, elevation, stratigraphy, sample and laboratory analysis are documented irrespective of the original research aims.

In Chapter 3, I provide a conceptual framework that supports the use of the organic matter (OM) gradient for a quantitative and reproducible definition of the mineral-to-peat transition (i.e., the stratigraphical range reflecting the timespan of the peat initiation process) and the layer defined as basal peat (i.e., the stratigraphical layer that is defined as the bottom of a peat deposit). I analysed the mineral-to-peat transition based on three highly detailed sequences of radiocarbon dates from cores obtained at Fochteloërveen, including dates of plant macrofossils and the humic and humin fractions obtained from bulk samples. Fochteloërveen currently harbours a bog vegetation, but biostratigraphical analyses show that during peat initiation the vegetation was mesotrophic. Results show that plant macrofossils provide the most accurate age in the mineral-to-peat transition and are therefore recommendable to use for ^{14}C dating basal peat. If these are unattainable, the humic fraction provides the best alternative and is interpreted as a terminus-ante-quem for peat initiation. The potential large age difference between dates of plant macrofossils and humic or humin dates (up to ~1700 years between macrofossil and humic ages, and with even larger differences for humins) suggests that studies reusing existing bulk dates of basal peat should take great care in data interpretation. The potentially long timespan of the peat initiation process (with medians of ~1000, ~1300 and ~1500 years at the three studied sites) demonstrates that choices regarding sampling size and resolution need to be well substantiated. I summarise all findings as a set of recommendations for dating basal peats, and advocate the widespread use of OM determination to obtain a low-cost, quantitative and reproducible definition of basal peat that eases intercomparison of studies.

In Chapter 4, I searched for explanatory variables within a digital soil mapping approach that enables reconstructions of the pattern of peat initiation and lateral expansion within (and potentially beyond) peat remnants, with quantified uncertainty. Basal radiocarbon dates were obtained from the Fochteloërveen peat remnant, which formed the basis for subsequent analyses. I investigated the relationship between peat initiation age and three potential covariates: (1) total thickness of organic deposits, (2) elevation of the Pleistocene mineral surface that underlies the organic deposits, and (3) a constructed variable representing groundwater-fed wetness based on elevation of the mineral surface and current hydraulic head. Significant relationships were found with covariate (1) and (3), which were hence used for subsequent modelling. Results indicate simultaneous peat initiation at several loci in the Fochteloërveen during the Early Holocene, and continuous lateral expansion until 900 cal y BP. Lateral expansion accelerated between 5,500 – 3,500 cal y BP. The presented approach is spatially explicit (i.e., results in a map of peat initiation ages), and allows for a quantitative evaluation of the prediction using the standard deviation and comparison of predictions with validation points. The applied method based on covariate (1) is only useful where remnant peat survived, whereas covariate (3) may ultimately be applied to reconstruct peat initiation ages and lateral peatland expansion beyond the limits of peat remnants.

The methodological tools presented in this thesis may help to advance science on peatland reconstructions. Depending on research objectives, they can be applied separately, or concurrently in a complementary manner.

Peat initiation results from terrestrialisation, paludification and/or primary mire formation. Based on the findings of this thesis, I conclude that paludification was the most prominent process of peat formation in the northern Dutch coversand landscape (and Fochteloërveen), with local occurrence of terrestrialisation sites. The work presented in this thesis points to several environmental factors that may have led to paludification, consequent peat initiation and subsequent lateral expansion. I present a hypothesis on the steering factors for paludification and peat growth in the Northwest European mainland, that offers starting points for further research.

Increased understanding of the age and palaeogeography of peatlands is highly relevant for research on ecosystem services provided by peatlands (such as carbon dynamics), for nature conservation and restoration, and for cultural history and heritage management. Carbon dynamics form a key ecosystem service provided by peatlands. The age and spatial extent of peat deposits are crucial parameters for modelling past and future carbon storage. In addition, knowledge on the timing of peat initiation is of great significance in assessing archive content and value, and may provide long-term palaeoenvironmental and palaeoecological references for nature conservation and restoration goals. Information on the palaeogeographical development of peatlands plays a vital role in contextualising long-term human habitation patterns, and in the analysis of single archaeological sites. In addition, insights in the age and character of peat deposits may be highly informative for cultural heritage management purposes and archaeological prospection, as peat layers may cover or contain well-preserved waterlogged archaeological sites that are unparalleled in dryland environments. The knowledge on the palaeogeographical and palaeoenvironmental development of peatlands in the Northwest European mainland that was gained in this thesis is directly incorporated in interdisciplinary studies within the overarching *Home Turf* project. Peatlands are landscapes with a strong potential to feature in environmental education, both in formal educa-

tional contexts and in science communication with the general public. Science communication efforts on peatland research in the Northwest European mainland and elsewhere may help to show the value, history and beauty of these unique landscapes, and the importance of protecting and restoring peat remnants.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities).

Review/project proposal (8.5 ECTS)

- Reconstructing Holocene spatio-temporal bog developments

Post-graduate courses (5.4 ECTS)

- Pre-conference workshop: Spatial sampling for mapping; Pedometrics Conference, Wageningen (2017)
- Bayesian statistics; Wageningen Graduate Schools (2017)
- Radiocarbon dating and Bayesian chronological analysis; Oxford Department for Continuing Education (2018)
- Groundwater processes; VU Amsterdam (2018)
- Resilience of living systems - From fundamental concepts to interdisciplinary applications; Graduate Schools PE&RC and WIAS (2018)

Deficiency, refresh, brush-up courses (3.4 ECTS)

- Spatial modelling and statistics; WUR (2017)
- The fourth dimension; WUR (2018)

Laboratory training and working visits (1 ECTS)

- Peatland workshop; Hyytiälä Forestry Field Station, University of Helsinki, Finland (2018)

Competence strengthening/skills courses (4.71 ECTS)

- Effective behaviour in your professional surroundings; Wageningen Graduate Schools (2017)
- Orientation on teaching for PhD candidates; Wageningen Graduate Schools (2017)
- IT Workshop online samenwerken; WUR (2018)
- Scientific artwork - Vector graphics and images; Wageningen Graduate Schools (2020)
- Career orientation; Wageningen Graduate Schools (2020)

- Visual communication; WUR (2021)

Scientific integrity/ethics in science activities (0.6 ECTS)

- Research integrity; Wageningen Graduate Schools (2017)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.1 ECTS)

- PE&RC First years weekend (2017)
- PE&RC Last year afternoon; online (2020)

Discussion groups/local seminars or scientific meetings (5.23 ECTS)

- Field visit to a peatland site in the Binnenveld area with RCE (2019)
- Excursion to Schokland with Home Turf and Wetfutures teams and guest researchers (2019)
- Excursion to Bargerveen and Drents Museum with Home Turf team and guest researchers (2018)
- Peatland exchanges (2022)
- Other activities related to peatland science (2017-2022)
- Young WUR seminars (2017-2022)
- Land Dynamics Discussion Group (2017-2022)
- R Users meeting (2017-2022)
- Other activities related to the wider scientific field (2017-2022)
- Member hiring committee for a postdoc position at WUR and for a PhD position at WUR (2018, 2020)
- Participation as PhD-representative in the Soil Science Cluster review (2021)

International symposia, workshops and conferences (5.8 ECTS)

- Symposium of the Netherlands Centre for Luminescence dating; oral presentation; Utrecht, the Netherlands (2017)
- 23rd Annual meeting of the European Association of Archaeologists; oral presentation; Maastricht, the Netherlands (2017)
- Symposium RCE/Deltares/TNO; oral presentation; Amersfoort, the Netherlands (2020)
- Reuvens-digi-dag door Stichting Reuvens; oral presentation; online (2020)

Societally relevant exposure (3.44)

- Creating a website for our project: www.boglandscapes.eu (2017)
- Co-writing an article for Nature Today (2018)

- NBV Themadag: Bodem & Archeologie (presentatie voor breder publiek) (2019)
- Filmed interview about my research for a documentary on Fochteloërveen (‘Et Fochtelervene - Van Iestied Naor Wieshied’) (2020)
- Filmed interview about my research for the tv-series ‘ROEG!’ (2021)
- Oral presentation during Session 1 of the seminar series ‘Peatland Exchanges’ (about science and art) (2022)

Committee work (0.75 ECTS)

- Member of the General Board of the Dutch Soil Society (Nederlandse Bodemkundige Vereniging, NBV) (2017-2022)

Lecturing/supervision of practicals/tutorials (11.83 ECTS)

- Integration course soil, water and atmosphere (2017)
- Environmental data collection and analysis (2017)
- Soils and landscapes of the Netherlands (2017, 2018, 2019)
- Introduction soil, water, atmosphere (2017, 2018)
- Landscape geography (2017, 2018, 2019)
- Introduction to Soil Geography (2018, 2019)
- Coastal oceanography and delta geology (2019, 2020, 2021)
- Evaluator at BSc symposium (2020)

BSc/MSc thesis supervision (5.61 ECTS)

- Best practices for creating high-resolution 3D pre-peat landscapes
- Sacrificing with wet feet? An environmental reconstruction of the Bolleveen area (Drenthe, the Netherlands) in the Roman period (12 BC – AD 400)
- The spatial and temporal distribution of bog bodies in Northwestern Europe
- Constraining peat initiation by OSL-dating the pre-peat landscape
- Problems and solutions of conventional peat meadow farmers in the Netherlands (internship at Stichting Boerengroep)

List of publications

Manuscripts in preparation

- Van Beek R, **Quik C**, Van der Linden M. Drowning landscapes revisited. Correlating peatland expansion, human habitation trends and vegetation dynamics in the Northwest European mainland. In preparation.

Peer-reviewed articles

- **Quik C**, Van der Velde Y, Candel JHJ, Steinbuch L, Van Beek R, Wallinga J, 2023. Faded landscape: unravelling peat initiation and lateral expansion at one of northwest Europe's largest bog remnants. *Biogesciences* 20, 695–718, https://doi.org/10.5194/bg-20-695-2023.

- Van Beek R, **Quik C**, Bergerbrandt S, Huisman F, Kama P, 2023. Bogs, bones and bodies. The deposition of human remains in European mires (9000 BC – AD 1900). *Antiquity* 1-21, https://doi.org/10.15184/aqy.2022.163.

- **Quik C**, Palstra SWL, Van Beek R, Van der Velde Y, Candel JHJ, Van der Linden M, Kubiak-Martens L, Swindles GT, Makaske B, Wallinga J, 2022. Dating basal peat: The geochronology of peat initiation revisited. *Quaternary Geochronology* 72, 1-22, https://doi.org/10.1016/j.quageo.2022.101278.

- **Quik C**, Harkema T, Van der Plicht J, Quik J, Van der Velde Y, Van Beek R, Wallinga J, 2021. Using legacy data to reconstruct the past? Rescue, rigour and reuse in peatland geochronology. *Earth Surface Processes and Landforms* 46, 2607–2631, https://doi.org/10.1002/esp.5196.

- **Quik C**, Candel JHJ, Makaske B, Van Beek R, Paulissen M, Maas GJ, Verplak M, Spek T, Wallinga J, 2020. Anthropogenic drivers for exceptionally large meander formation during the Late Holocene. *Anthropocene* 32, 1–15, https://doi.org/10.1016/j.ancene.2020.100263.

- Van Beek R, Candel JHJ, **Quik C**, Bos JAA, Gouw-Bouman MTIJ, Makaske B, Maas GJ, 2019. The landscape setting of bog bodies: Interdisciplinary research into the site location of Yde Girl, The Netherlands. *The Holocene* 29(7), 1206–1222, https://doi.org/10.1177/0959683619838048.

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Datasets

- **Quik C**, Van der Velde Y, Candel JHJ, Steinbuch L, Van Beek R, Wallinga J, 2023. Data from: Faded landscape: unravelling peat initiation and lateral expansion at one of northwest Europe's largest bog remnants. *4TU.Centre for Research Data*: https://doi.org/10.4121/20237958.

- **Quik C**, Steinbuch L, 2022. Workshop FAIR Data and Data Reuse for Environmental Science Group Researchers. *4TU.Centre for Research Data*: https://doi.org/10.4121/21399975.v1.

- **Quik C**, Palstra SWL, Van Beek R, Van der Velde Y, Candel JHJ, Van der Linden M, Kubiak-Martens L, Swindles G, Makaske B, Koudijs R, Wallinga J. 2022. Data from: Dating basal peat: The geochronology of peat initiation revisited. *4TU.Centre for Research Data*: https://doi.org/10.4121/16923358.

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- **Quik C**, Candel JHJ, Makaske B, Van Beek R, Paulissen M, Maas GJ, Verplak M, Spek T, Wallinga J, 2020. Data from: Anthropogenic drivers for the rapid formation of extremely large meanders during the Late Holocene. *4TU.Centre for Research Data*: https://doi.org/10.4121/uuid:c9c892de-4f3f-4c1b-b684-17c700b02f31.

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