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

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Abstract

There is a growing interest in the 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 years BP), dropped during the Boreal (∼9,500 cal years BP) and showed a second peak in the Subboreal (∼4,500 cal years 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.

KEYWORDS

Data rescue, legacy data, meta-analysis, peatlands, quality assessment, radiocarbon dating

1 | INTRODUCTION

Data rescue in the geosciences is a field of rapidly growing interest (Wyborn et al., 2015). Data that have been collected in the past are often referred to as 'legacy' data (Griffin, 2015; Smith et al., 2015). Many researchers are realising 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, 2015). 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. Ruppel et al., 2013; Tolonen & Turunen, 1996) and can 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 | 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.

2.1 | Legacy data in geoscience

In the geosciences, legacy data may play a role when analysing 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 bird's-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 | 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, 2002a). 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 & Foster, 1995; Loisel et al., 2013; Mäkilä, 1997), 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; Moore, 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, 2002a; Rydin & Jeglum, 2013a). 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, 2002b; Rydin & Jeglum, 2013a). These fen–bog transitions may occur at various timings (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, 2002b), 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-GSN, 2021a]). 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. Chapman et al., 2013;

Mäkilä, 1997; Mäkilä & Moisanen, 2007), 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, refer to, for example, Frenzel (1983), Charman (2002c), Wieder & Vitt (2006), Mitsch et al. (2009) or Rydin & Jeglum (2013b). For spatial distribution of peatlands see, for example, Joosten et al. (2017), Tanneberger et al. (2017) or IMCG (2021).

2.3 | Legacy data in peatland research

Meta-analyses of composite datasets often provide new supra-regional insights and may point to knowledge gaps that need to be addressed by future research. For instance, in an extensive study by Tolonen & Turunen (1996) on carbon accumulation in Finnish mires, over 1,000 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; Hijma & Cohen, 2019; Meijles et al., 2018) or to increase insights into 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 1,400 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.

2.4 | 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 (Figure 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 oxidises to $^{14}CO_2$, which is incorporated into 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 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 this is problematic because of the complications mentioned above. These are solved by the Radiocarbon Convention, which defines the ^{14}C timescale (Stuiver & Polach, 1977; Van der Plicht & 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 $\delta^{13}C = -25‰$, 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 $\delta^{13}C$ 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 updated regularly (Figure 1).

In radiocarbon practice, the $\delta^{13}C$ and %C values are indicators for sample integrity (Mook & 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, thus its concentration is time independent. It can therefore be used as a measure of fractionation of the photosynthesis process. Since $\delta^{14}C = 2\delta^{13}C$, 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 $\delta^{13}C$ is defined as $\delta^{13}C = [^{13}R_{sample} - {}^{13}R_{reference}]/[^{13}R_{reference}]$ ($\times$1000‰), 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 1950s, i.e., before the Convention), $\delta^{13}C$ was not measured, and fractionation correction was not applied. The significance of $\delta^{13}C$ is dependent on the type of photosynthesis used by plants, known as the C_3 and C_4 pathways. For C_3 plants, the $\delta^{13}C$ 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 $\delta^{13}C$ value is around $-10‰$, which leads to large fractionation corrections; here the difference from the reference value ($\delta^{13}C = -25‰$) is around 15‰, which corresponds to an effect of

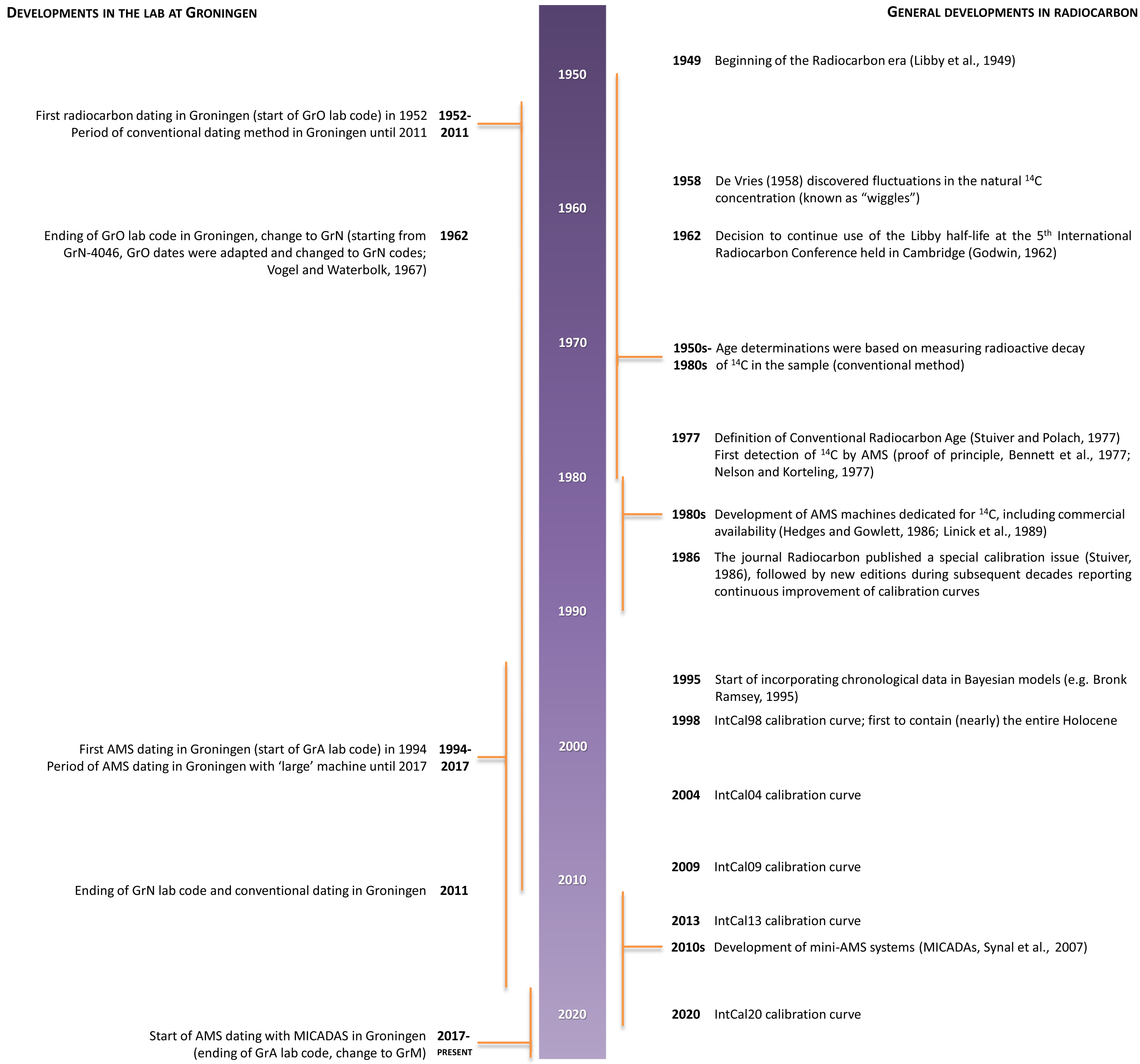

FIGURE 1 Timeline of developments in radiocarbon dating (right). Changes at the radiocarbon laboratory in Groningen (left) are relevant for the case study

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 that measured by 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 & Woods, 2013). The lower the carbon content of the ^{14}C sample, the larger the effect of contamination (i.e., all the carbon that was not related to the sample when it was alive) will be (Lanting & van der Plicht, 1994).

Initially, radiocarbon concentrations were measured by radiometry. This method requires large quantities (typically 1 g) of carbon (Cook & 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 mg (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 on where the date was measured and often also on the measurement method (conventional or AMS).

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

2.5 | Case study selection and aims

Palaeogeographic maps are often built though integration of (legacy) data from various sources (e.g. Pierik & Cohen, 2020). Current palaeogeographic reconstructions of the Netherlands (Vos, 2015; Westerhoff et al., 2003; Zagwijn, 1986) were created with a strong focus on the development of river deltas (e.g. Berendsen & 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 for these areas (Spek, 2004; Van Beek, 2009; Vos, 2015). Increased understanding of their spatiotemporal dynamics is needed to refine representation of these landscapes on the palaeogeographic map series, for the 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. Erkens et al., 2016; Yu et al., 2011). 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 (Figure 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?

2.6 | Case study area

The (northern) coversand landscape (Figure 2) is characterised by diverse landforms, enabling peat growth in various geomorphological settings, and is representative of 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 (Figure 2b, c). 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; Rappol et al., 1989; TNO-GSN, 2021a; Van den Berg & Beets, 1987). The central part of the study area is known as the Drenthe Plateau or till plateau (Bosch, 1990; Ter Wee, 1972). Meltwater scoured deep valleys east and south of the Drenthe Plateau, the Hunze valley (Bosch, 1990) and palaeo-Vecht valley (Bosch, 1990; Kuijer & Rosing, 1994; Ter Wee, 1966) 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-GSN, 2021b). This deposit is present at the surface in the north-eastern, eastern and south-eastern parts of the Netherlands (Figure 2c) and the larger European Sand Belt (Koster, 1988, 2005).

Peat deposits in the study area formed on both 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 & Sohl, 1981). Based on historical data peat thickness on the plains appears to have reached at least 7 m at some sites (Fochteloërveen, Douwes & 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 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 (Figure 2d and 2e).

3 | APPROACH AND METHODS

We propose a workflow for data rescue in geochronological peatland research (Figure 3, Section 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 3.1.2);
iii. To assign a penalty score to each date based on case-specific weights for quality aspects (Section 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 2.5.1). To answer these questions, we tailor the proposed workflow as explained in Section 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.

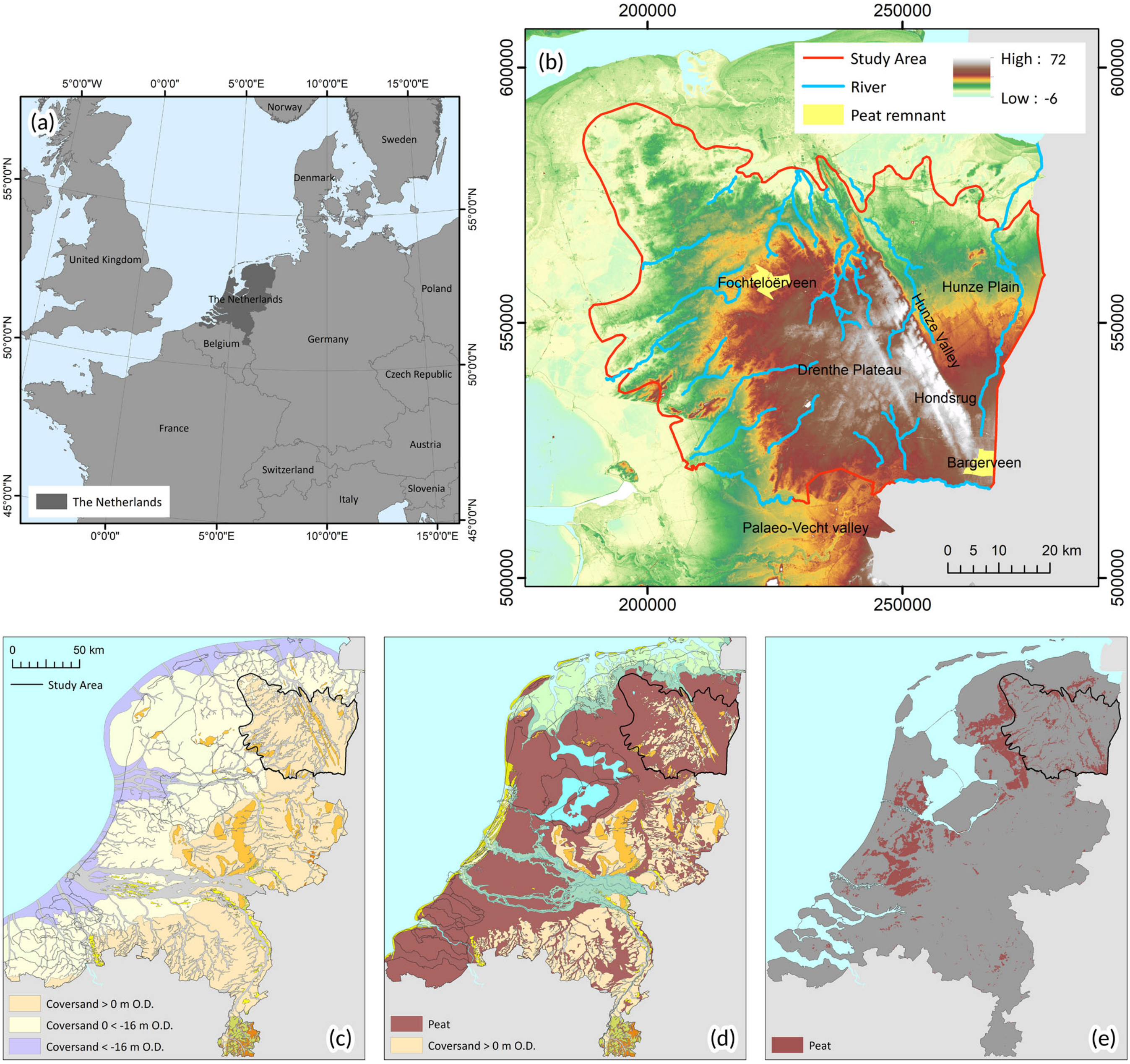

FIGURE 2 Location and (palaeo)environmental characteristics of the case study region. (a) Location of the Netherlands in Europe. (b) Ditigal Elevation Model (DEM) of the northern coversand landscape. Elevation is in metres relative to Dutch Ordnance Datum (O.D., roughly mean sea level). Within the study 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 years 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 & De Vries (2013) and Vos et al. (2020). (e) Current distribution of peat soils (i.e. containing >20% organic matter). Sources: DEM of the Netherlands (AHN2; horizontal resolution 5 m, vertical resolution 0.2 m) from van Heerd et al. (2000) and AHN (2018); coversand extent and Dutch palaeogeography from Vos & De Vries (2013) and Vos et al. (2020); rivers in the study area from Ministerie van Verkeer en Waterstaat (2007); Dutch soil map from Alterra (2014); two largest peat remnants (Natura 2000 areas) from Ministerie van Economische Zaken (2018)

3.1 | Workflow, database set-up and quality assessment

3.1.1 | Overview of the workflow

The workflow for data rescue and reuse (Figure 3) consists of:

i. A database set-up that can be tailored as required by the study scope (Table 1);
ii. A complementary set of quality criteria with flexible weights to suit specific research questions (Table 2; see Section 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 2.4, we propose quality criteria that consider technical aspects of radiocarbon dating and

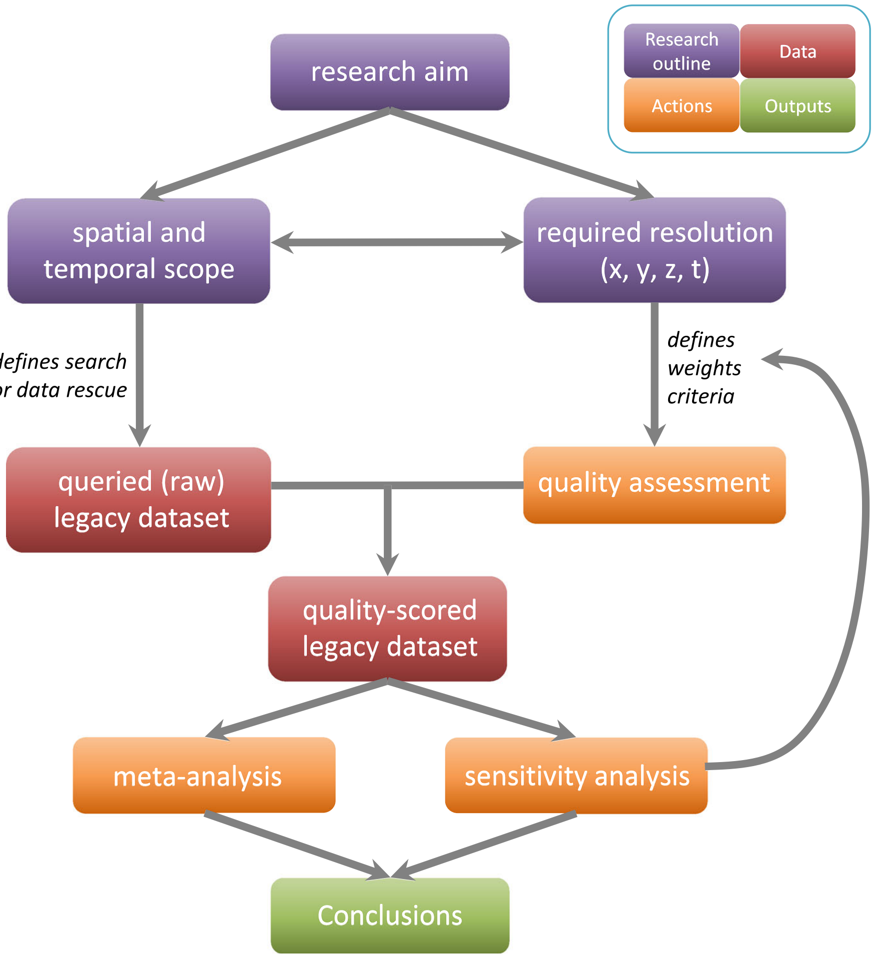

FIGURE 3 Proposed workflow for data rescue, quality assessment and meta-analysis in geochronological (peatland) research. See legend in upper right for explanation of colours

sample selection, while other criteria are concerned with the landscape position and taphonomy of the dated material (Section 3.1.2). A penalty is assigned for traits that are considered negative (Table 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.

3.1.2 | Quality criteria

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 laboratory. *Taphonomy*, a term originating from palaeontology, is the science of 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. Figure 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 Figure 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. the degree to which replicate measurements lead to the same result) is not indicated in Figure 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

TABLE 1 Proposed database structure. For all categories, 'NR' indicates not retrieved/reported

GENERAL	LabCode	Laboratory code as assigned by the laboratory that conducted the analysis.
	Add LabCode	Any additional laboratory 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 (Figure 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	Licence under which the data was published (if applicable).
	ConsultedLab [1]	Either 'yes' or 'no' to indicate whether the laboratory 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 before common era (BCE)/common era (CE).
	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.
	Delta13source	Either 'measured' or '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'.

(Continues)

TABLE 1 (Continued)

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 O.D., approximately mean sea level).
	DepthFromNAP	Reported depth of the upper boundary of the sample in m NAP (Dutch O.D., approximately mean sea level).
	DepthToNAP	Reported depth of the lower boundary of the sample in m NAP (Dutch O.D., approximately mean sea level).
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.

[1]In case laboratory data differed from data provided by publications, the laboratory 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'.

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 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 the 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 sites with uncertain location as well). This allows a purposeful assignment of dates to various analyses.

Design of the quality criteria

Age. This category contains criteria for three properties: *Mean and SD*, *Delta13* and *Carbon content* (Table 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 & van der Plicht, 1994). The sample size is included in the quality assessment as a property under *Sample Information* 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 an 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 a specific Ordnance Datum (O.D.), relative to the (former) land surface or not retrieved.

Landform and Stratigraphy. This category contains *Landform* and *Stratigraphy* as two properties, each distinguishing whether these properties are 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, for example 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 the retrieved coordinates).

Sample information. For this category, five properties were included: *Sample Thickness*, *Sample Type*, *Species Type*, *Aboveground* and *Pre-treatment*. *Sample Thickness* 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. Piotrowska et al., 2011; Törnqvist et al., 1992), we formulated the criteria for *Sample Type*, *Species Type* and *Aboveground*. *Sample Type* differentiates macrofossil samples (dated with AMS) from bulk samples (mostly conventional dating) and implicitly contains information about sample size (mentioned above under *Age*). *Species Type* is concerned with the habitat of the organism(s) that were sampled, either terrestrial species, aquatic species, both or undefined (i.e. in the 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 a 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 robust pre-treatment. However, when the amount of sample material is limited, gentle (or no) pre-treatment may be applied to ensure preservation of sufficient material for dating.

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. 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 normalisation, 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 3.2) the weights listed in Table 2 are used, resulting in maximum values of Q_T and Q_d of 0.464 and 0.536, respectively. The normalised Q_T, Q_d and *Q* values may be used as such, or may be converted into 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 3).

TABLE 2 Criteria used in the quality assessment, based on the categories listed in Table 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: 0	Criteria: +1	Criteria: +2	Criteria: Disqualified	Subscore dating penalty (Q_d)	Subscore taphonomic penalty (Q_T)	Total penalty score (Q)
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 (six-number RD coordinates; degrees, minutes and seconds for geographic coordinates).	Reported at field level (three-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	Sample Thickness	2	Sample thickness was reported.		Sample thickness was not retrieved.			Q_{T5}	
	Sample Type	5	Macrofossil (AMS dating).	Bulk sample (AMS or conventional dating).	Not retrieved.		Q_{d4}		
	Species Type	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							$Q_d = \sum_{i=1}^{7} Q_{di}$	$Q_T = \sum_{i=1}^{5} Q_{Ti}$	$Q = Q_d + Q_T$

3.2 | Application of the workflow to a case study

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 (Figure 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 1 and recorded dates from peat layers (i.e. excluding dated archaeological artefacts originating from peat layers).

The majority of retrieved dates was performed by the radiocarbon facility of Groningen University (Centre for Isotope Research and its predecessors). The history of this laboratory is shown in Figure 1. Developments are also reflected in laboratory codes, 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 & Streurman, 2018). Consequently, data retrieval required both digital querying and hardcopy searching.

3.2.2 | Case study: Meta-analysis

To answer the case study research questions (Section 2.5.1), 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. 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 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 from the (former) surface. To this end, we derived the surface elevation from the digital elevation model (DEM) and subtracted the sample depth. For basal dates, elevation is not affected by compaction. Dates from within the peat or the top might be affected by compaction, 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 effects.

All ages were (re-)calibrated in OxCal (version 4.4; Bronk 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 (Bronk Ramsey, 2017). To test model outcome for sensitivity to previously assessed data quality, the data subsets from the four confidence levels (Figure 6) were added to the model in separate runs and outcomes compared.

To derive spatiotemporal insights on peat initiation, data were plotted in geographic information system (GIS) software (ESRI ArcMap, version 10.6) using the chronostratigraphy shown in Table 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 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 5).

4 | RESULTS

4.1 | Data rescue for case study region

We compiled a dataset consisting of 313 legacy radiocarbon dates. The majority (85%) of the retrieved dates indicates peat layers of Holocene age, but Late Glacial and Pleniglacial ages are also represented (Figure 5a, 5c). Ages from the Subboreal (37%) and Atlantic (29%) periods are by far the most frequent (Figure 5b), 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 under-represented in the dataset (Figure 5a). Precision regarding the locations where the dated samples were collected appeared to be mixed (Figure 5e), with most sites only known to 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).

4.2 | Quality assessment

Based on the values for Q_d and Q_T, each date was subsequently assigned to one of four confidence levels (Table 3, Figure 6). For green dates, both Q_d and Q_T were fairly low, meaning that sufficient information is available regarding dating aspects and taphonomic

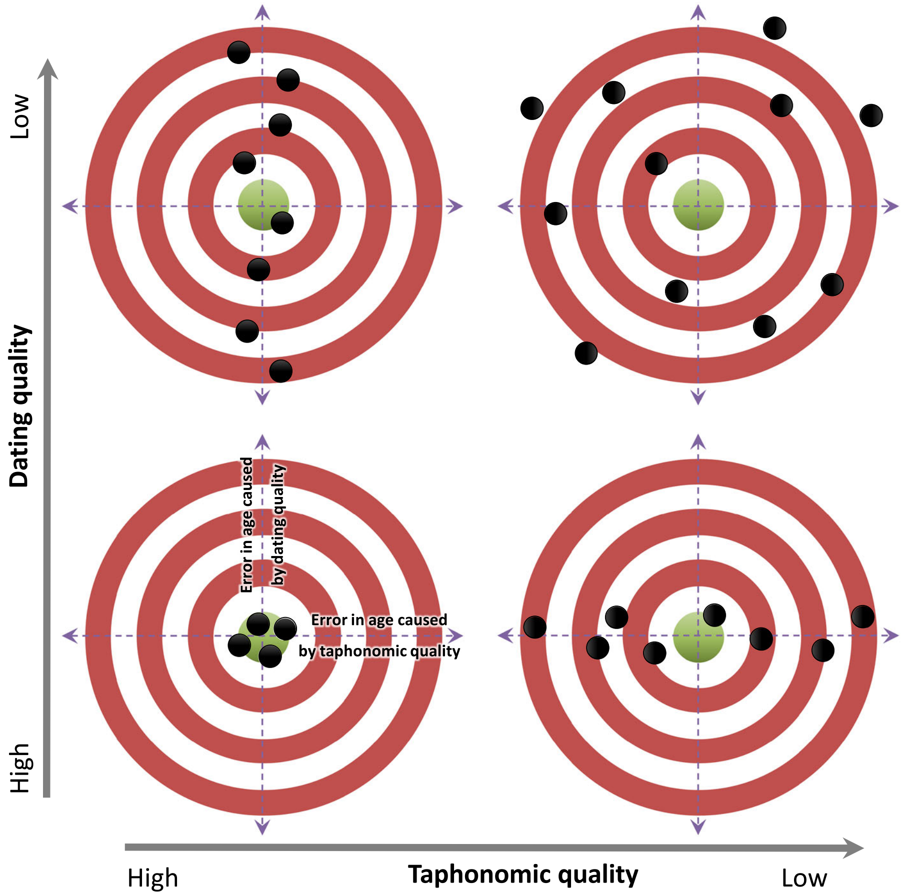

FIGURE 4 Effect of methodology (dating and taphonomic quality) on representation of the true age of the event of interest (bull). The distance to the bull indicates how robust a date is, i.e. the degree to which the date corresponds with the true age of the event of interest. Note that multiple black 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

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.

Figure 5b and Figure 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 (Figure 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 (Figure 5b), for example 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 was 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 (Figure 7b), indicating that year of dating is not necessarily indicative of quality. However, samples from the 2010s received on average the lowest penalty for taphonomic quality (Q_T).

4.3 | Meta-analysis

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 Figure 5d). The estimated distribution of these ages is shown in Figure 8a to 8c, based on green dates with applied filter for above-ground 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 Figure 8a shows a clear bimodal distribution, with peaks at about 14,000 cal years BP (Late Glacial) and 4,500 cal years BP (Subboreal). This trend is still visible in Figure 8b, while the largest dataset of Figure 8c reveals additional peaks at around 11,500 cal years BP (Preboreal) and 6,500 cal years BP (Atlantic). All models show a clear low at 9,500 cal years 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 from either primary mire formation or paludification (Table 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 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.

4.3.2 | Peat initiation trends for different landforms and elevations

We grouped landforms into four categories (Table 6). For both green confidence level dates and dates from all confidence levels combined, KDE models were constructed (Figure 9, showing only models from all confidence levels combined). Too little data were available to model

TABLE 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	$Q_{d,lim} \leq Q_d \leq Q_{d,max}$

only green confidence level dates that were filtered for aboveground terrestrial macrofossils. The distribution for 'Peatlands (unspecified)' in Figure 9c shows two peaks similar to the model outcomes in Figure 8. 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' (Figure 9d) appear to be of younger age, overlapping only with the second peak in the bimodal distributions of Figure 8. The model for 'Topographic depressions' (Figure 9e) results in a multi-peak distribution that does not show a clear age trend. Samples from 'Valleys' (Figure 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 (Figure 9g).

Age–elevation plots were constructed for basal peat samples (Figure 10c, $n = 73$) and for samples from all stratigraphical positions (Figure 10d, $n = 302$). Basal peat samples from topographic depressions mostly date from before 6,000 cal years BP. Valleys are located at both lower and higher positions and have ages across the Late Glacial and entire Holocene (Figure 9f), with high-lying locations being youngest (Figure 10c). Basal dates from plains all date from after 6,000 cal years BP. Basal dates from low-lying plains (≤0 m O.D.) fit the relative sea level (RSL) curve for the Wadden Sea (Figure 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 years BP. When plotting data from all stratigraphical positions (not only basal dates, Figure 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 and 0.57 mm/year. Because elevations from non-basal dates were not corrected for potential compaction issues, these lines indicate only the minimum accumulation speed.

TABLE 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

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.

5.1 | Case study

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 (Figure 5). The 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 (Figure 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, for example 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 (Figure 9). Onset of peat growth took place during the Late Glacial 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 above. Age–elevation plots show a general trend that peat growth started earliest at the lowest locations, and reached higher positions later in time (Figure 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 (Figure 10a and 10b). Comparison of Figure 8 with Figure 9 suggests that this peak primarily consisted of peat initiation in topographic depressions (Figure 9e) and onset of peat growth in river valleys (Figure 9f). The rise and maximum of the second peak in the bimodal distribution coincide with strong sea level rise

TABLE 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

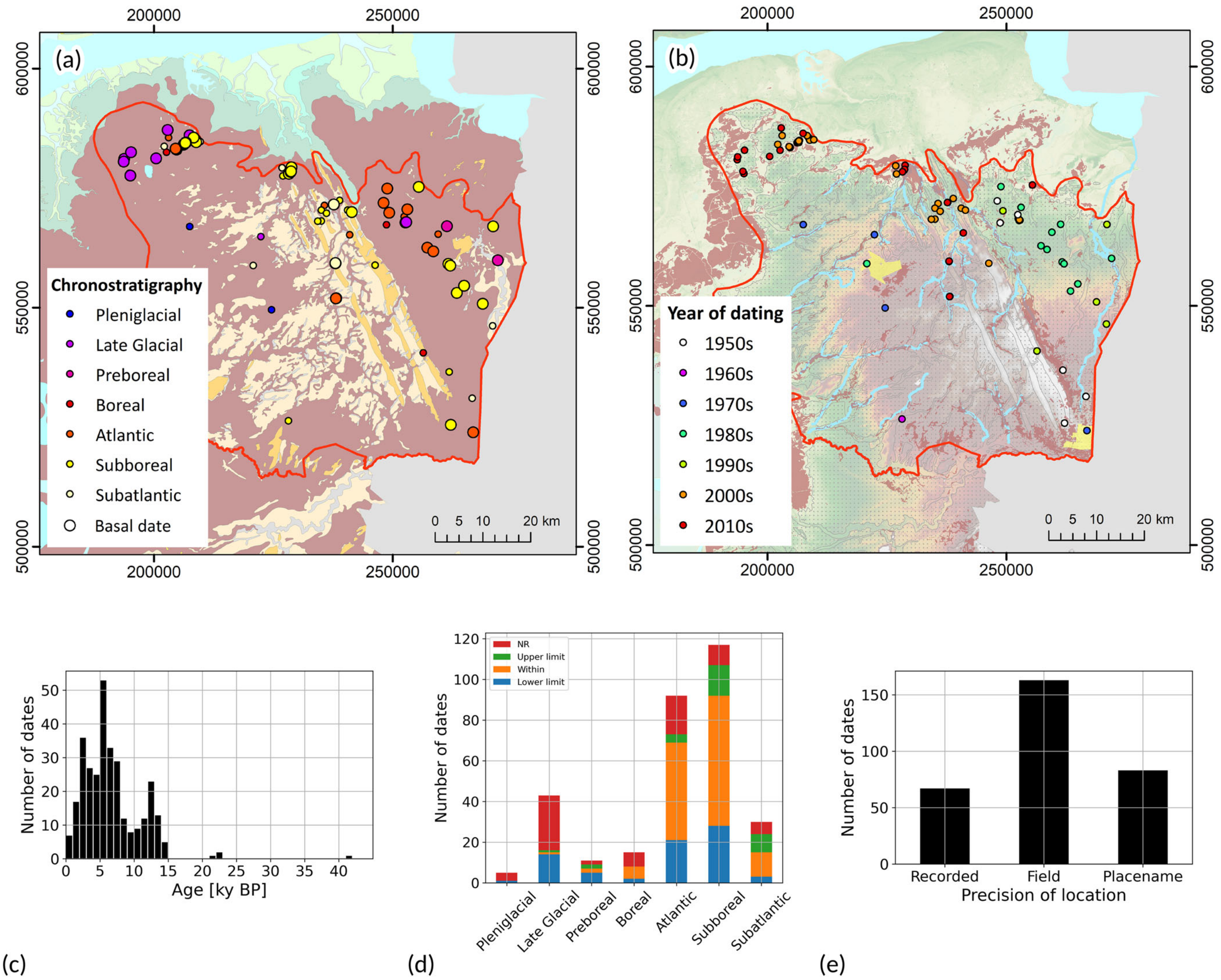

FIGURE 5 Overview of age and location of case study legacy data points ($n = 313$). (a) Locations of data points binned based on chronostratigraphy, using definitions listed in Table 4. Uncertainty of locations (see text) not shown for legibility. Note that several data points overlap (i.e. multiple 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 years BP (also see Figure 2c). (b) Location of data points binned per decade when the date was performed. See legend in Figure 2b for other map elements. (c) Histogram of calibrated radiocarbon dates. (d) Histogram of chronostratigraphy. (e) Histogram showing precision classes for retrieved locations

(Figure 10b and 10c, Meijles et al., 2018) and the hypsithermal (Holocene Thermal Maximum; 9,000 to about 5,000–6,000 years ago; Renssen et al., 2009; Wanner et al., 2008). 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 (Figure 9f and Figure 10c) and eventually formed on high-lying plains (Figure 9d and Figure 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 & 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 years BP, start of Atlantic) and around 5,000 BCE (~7,000 cal years BP, middle Atlantic). Both periods fall between the start of the second peak and the 'bump' prior to its maximum in Figure 8c, but the legacy dataset shows no indication of a drop of peat initiation between 8,500 and 7,000 cal years BP. Van Geel et al. (1998) advocate that the 2,800 cal years BP event is a cause for peat initiation. Locally, peat may have initiated at this timing, but 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 years BP is not supported by the bimodal distribution of the legacy data. Based on detailed palynological investigations in the Bargerveen peat remnant (indicated in Figure 2b), Dupont (1986) concludes that human influences can be traced in arboreal pollen data only from 5,500 cal years 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 7), peat initiation in the study area starts at the earliest around 7,500 cal years BP, slightly later than the rise of the second peak in the bimodal distribution in Figure 8. No peat deposits are present on the maps prior to 7,500 cal years 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, Figure 9e and Figure 9f). According to the map series, the maximum extent of peatlands was reached between 3,250 and 2,500 cal years BP (Table 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 years BP. However, some basal dates show younger ages (Figure 8), especially in valleys (Figure 9f), indicating that peat initiation (or lateral expansion) continued at least at some sites after 2,500 cal years BP. Non-basal dates show that vertical peat growth continued as well (Figure 10d), suggesting that the maximum extent and maximum thickness of peat deposits were probably not reached at the same time.

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). 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 unclear.

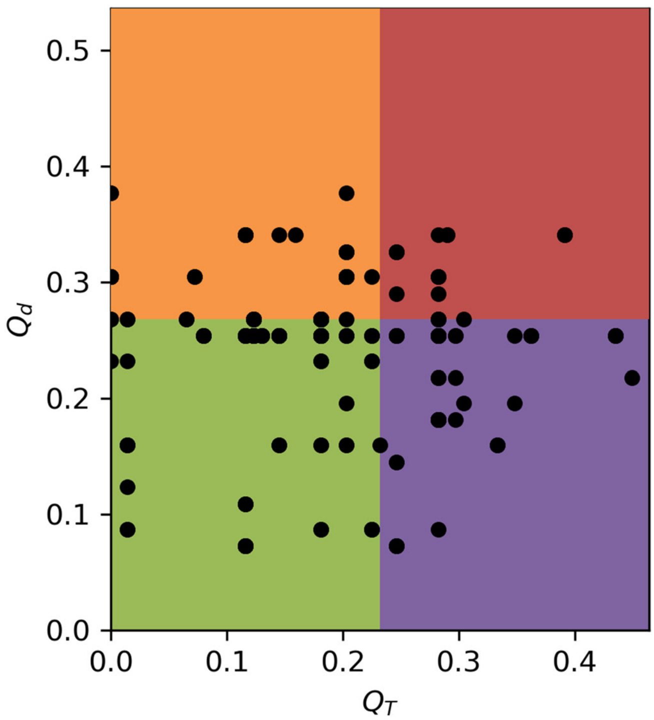

FIGURE 6 Overview of the quality assessment of the case study dataset ($n = 313$) showing resulting Q_d and Q_T values for each data point (note that some points overlap). Limits of the confidence levels are defined in Table 3, with $Q_{d,lim}$ and $Q_{T,lim}$ set at 50% of their respective maximum normalised values. The coloured quadrants indicate the four confidence levels that were used in subsequent data analyses

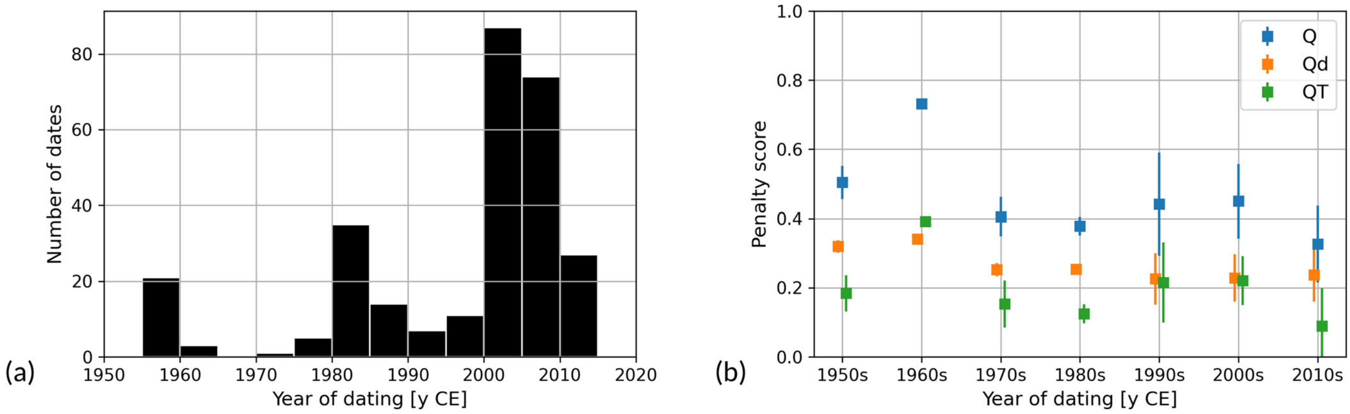

FIGURE 7 Overview of years when dates were performed (i.e. between 1950s and 2020). (a) Histogram of data points per 5-year period. (b) Assessed quality (Q, Q_d, Q_T) averaged per decade

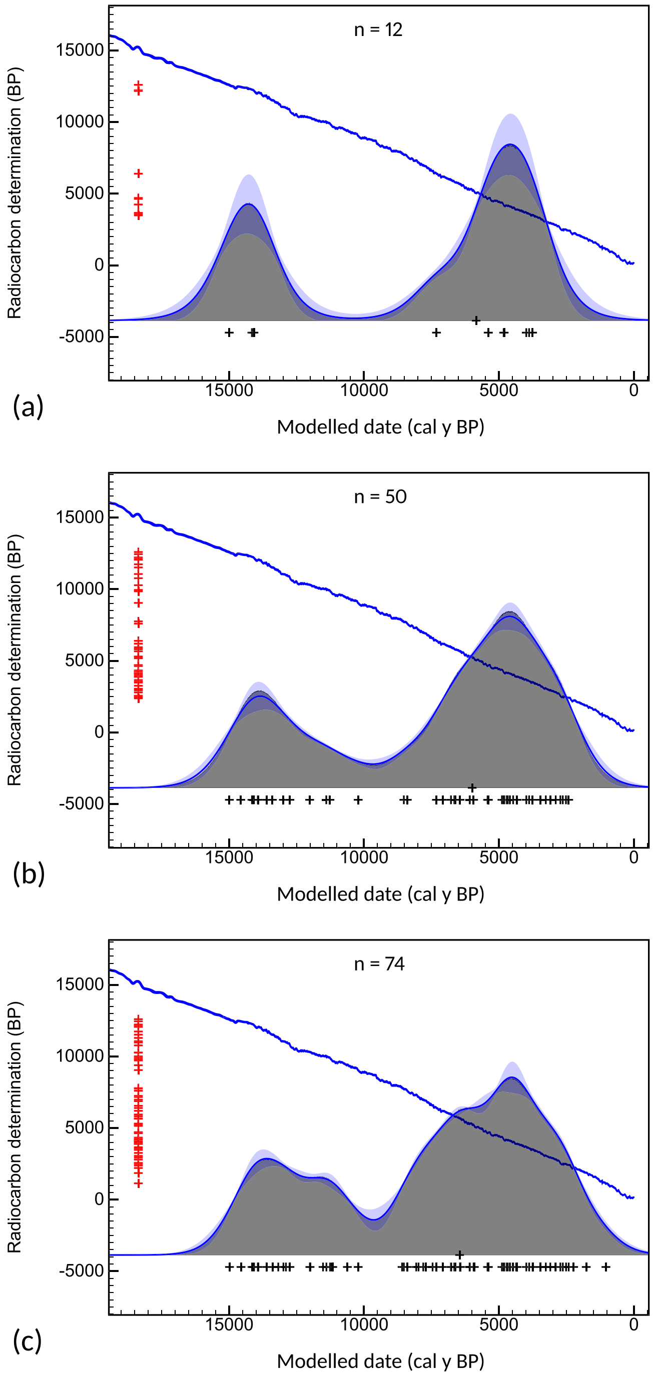

FIGURE 8 Outputs of KDE models for basal peat ages in the case study dataset. Results are based on model runs of basal ages with (a) green confidence level that were based on aboveground remains of terrestrial macrofossils ($n = 12$), (b) dates with green confidence level with no further filtering applied ($n = 50$) and (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)

5.1.2 | Experiences regarding data retrieval

Most scientific publications from which data were 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 laboratory code for all samples, thus providing insights into the uncalibrated dating results. In case of ambiguities, dates could be retrieved from the Groningen databases. The bulk *SampleType* was mainly deduced from laboratory codes. Details for macrofossil samples were retrieved from publications and laboratory archives. Overall, we found many more dates than anticipated.

Unfortunately, quite often location and sample elevation were not documented in great detail (Figure 5e). 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 unprecise location and surface levels changing over time, for example because of 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, for example 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.

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 number 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 Figure 5b and Figure 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, Figure 2b) is very rich in Mesolithic sites (Groenendijk, 2003). Such finds provide a terminus-post-quem for peat initiation, even though potential hiatuses must 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 provide a terminus-ante-

TABLE 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.

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.

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 (Figure 6). 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 (Figure 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, Figure 8a and Figure 8b) result in a clear bimodal distribution. When including all data (Figure 8c), this trend remains visible but becomes less clearly defined. The use of confidence levels provides insight into 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, for example, for the analysis of landform groups this subdivision was not fully possible.

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 included, 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 their 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 (Blaauw et al., 2004; Kilian et al., 1995), then 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 more strictly the boundaries of the confidence levels are defined, and the more subsequent filtering is applied, the smaller the resulting subset of data points will be. This may also result in over-representation 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.

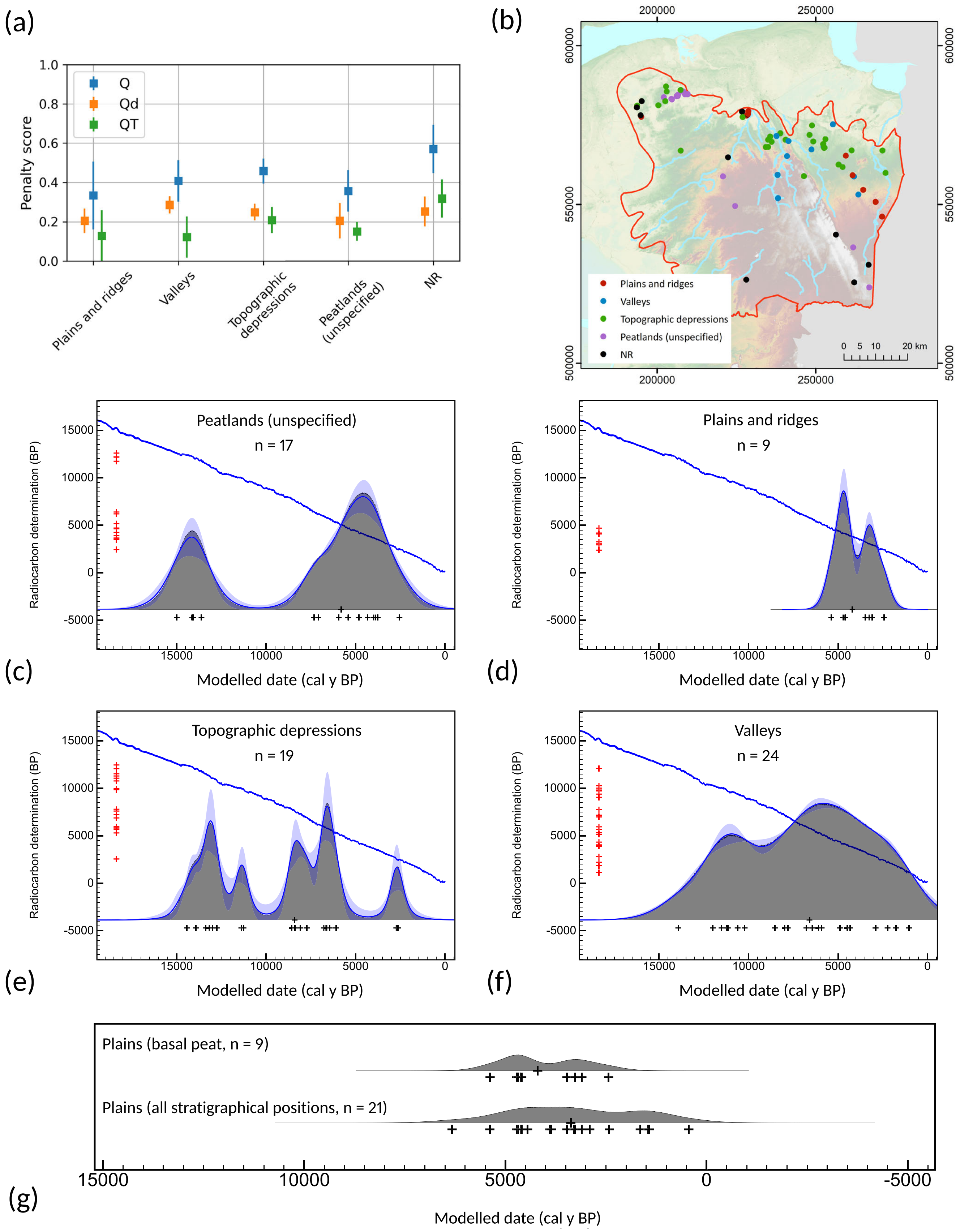

FIGURE 9 Overview of landform data. (a) Assessed quality (Q, Q_d, Q_T) averaged per landform. (b) Locations of data points binned based on landform grouping (Table 6). Note that several data points overlap (i.e. multiple samples collected at [nearly] the same location). (c–f) KDE models of peat initiation per landform grouping (detailed in Table 6, for interpretation of KDE plots see caption Figure 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

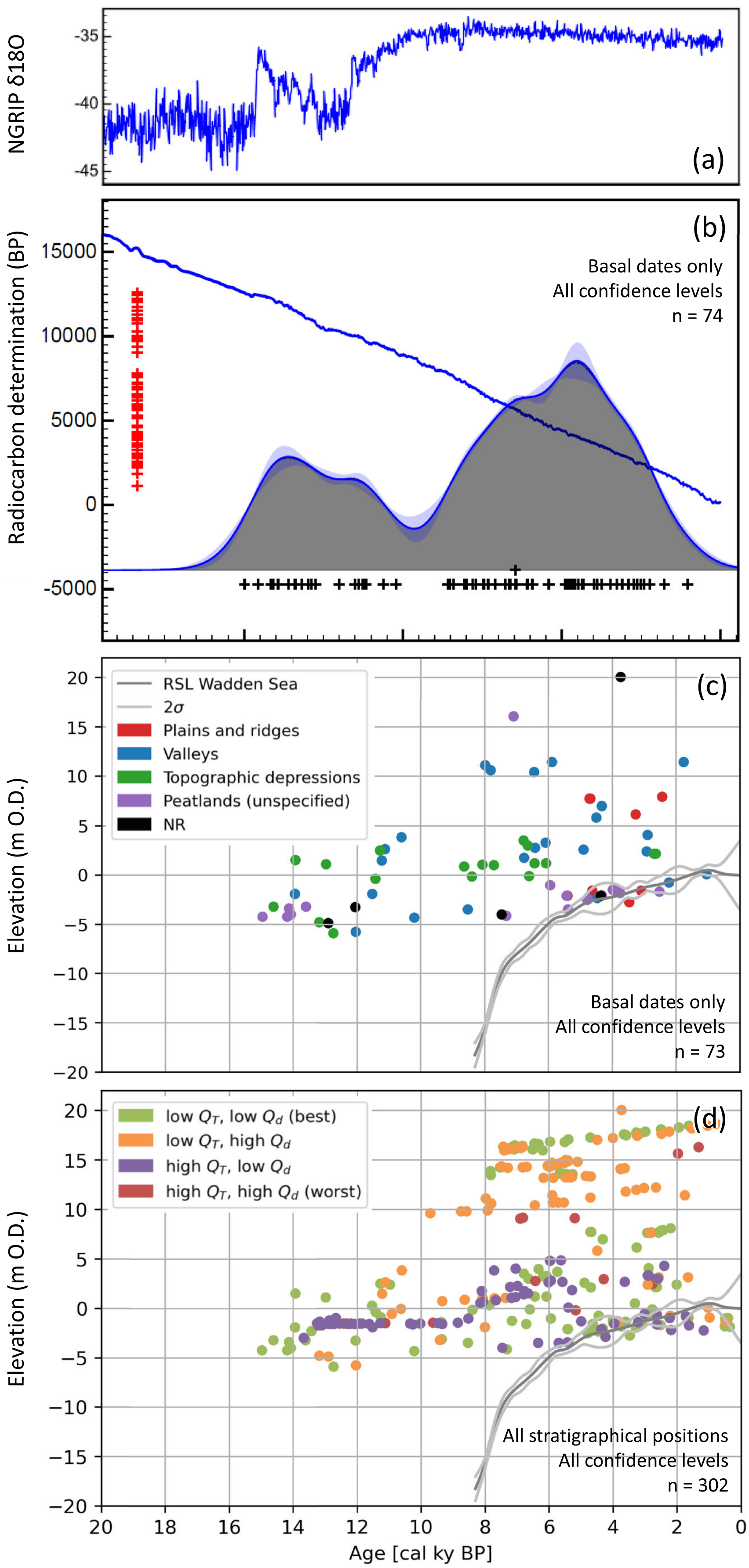

FIGURE 10 Comparison of peat initiation data with $\delta^{18}O$ and sea level rise curves. (a) $\delta^{18}O$ curve (GICC05 NGRIP δ18O data accessed through OxCal). The bimodal distribution of peat initiation dates (including all confidence levels) is shown in (b); see Figure 8c for details. In the age–elevation plot in (c) only basal peat dates are included ($n = 73$; note that in (b) $n = 74$ as for one date no elevation information 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

TABLE 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 (2015)
Nr. of maps/timeframes	10	6	13
Peat initiation [1]	~ 7,500 cal years BP	~ 6,500 cal years BP	~ 7,500 cal years BP
Maximum extent [1]	~ 3,250 cal years BP	~ 2,600 cal years BP	~ 2,500 cal years BP

[1]For our study area

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.

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. Ruppel et al., 2013; Tolonen & Turunen, 1996, 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 (Dupont, 1986; Van Geel et al., 1998). 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 emphasise 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 (findability, accessibility, interoperability and reusability) principles is key (Gil et al., 2016; Wilkinson et al., 2016), otherwise options for reuse decrease rapidly (Savage & Vickers, 2009).

6 | CONCLUSIONS

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 penalised 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 years BP), dropped during the Boreal (~9,500 cal years BP) and showed a second peak in the Subboreal (~4,500 cal years 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 bird's-eye view to be discovered. However, their success depends on data retrieval. We therefore emphasise the importance of FAIR sharing of 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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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data from this study are available under CC-BY 4.0 license at the 4TU.Centre for Research Data; see Quik et al. (2021). The automated quality assessment (Python script) and OxCal scripts are also included.

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