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Multicore Study of Upper Holocene Mire Development in West-Frisia, Northern Netherlands: Ecological and Archaeological Aspects

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Abstract: We studied twelve late Holocene organic deposits in West-Frisia, The Netherlands. Pollen, spores, non-pollen palynomorphs, mosses, other botanical macrofossils and insect remains were recorded for reconstructions of changing environmental conditions. Eastern West-Frisia was a cultivated landscape during the Bronze Age, but it became a freshwater wetland in the Late Bronze Age. In most of our sites, radiocarbon dates show that time transgressive inundation of soils preceded the climate shift at 850 cal BC for several centuries. We suggest that solar forcing of climate change may have delivered the final push to the inundation and depopulation of West-Frisia, which had already commenced several centuries before, due to sealevel rise. We did not find evidence for significant Bronze Age tree growth in West-Frisia before the inundations. Vegetation successions in the new wetlands developed from shallow mineral-rich freshwater to rich-fen vegetation. Subsequently poor fen vegetation with birch and pine developed, and the natural succession led to ombrotrophic raised bog vegetation. Complete successions from shallow, mineral-rich lakes to raised bog lasted between 1000 and 1500 calendar years. We hypothesize that medieval drainage and reclamation became possible only when the mires of West-Frisia had reached the raised bog stage. Reclamation of raised bogs by medieval farmers (drainage, eutrophication, peat digging) caused compaction, oxidation and loss of the upper part of the peat deposit. Seeds of salt-tolerant and salt-demanding plant species indicate that the medieval sites were inundated during storm surges with brackish or salt water, which triggered the farmers to build artificial mounds and, later, dikes. Under mounds and dikes, peat deposits remained protected against further decay. With our data we deliver a long-term perspective on contemporary ecosystem dynamics of freshwater wetlands, relevant for nature conservation and future climate change.

Keywords: West-Frisia; Bronze Age; microfossils; macrofossils; vegetation succession; freshwater wetlands; medieval reclamation

1. Introduction

Conservation and management of landscapes for people and nature is important for societal and ecosystem health [1]. Information on past environments, human impacts and ecosystems can provide valuable insights to inspire and guide conservation and management policies [2–4]. However, landscape scale information from palaeoecological systems is often lacking because the spatial density of suitable study sites is too low. The landscape in West-Frisia (Noord-Holland, The Netherlands) sits on top of a thick sequence of Holocene marine, fluvial and peat deposits [5] and has a long history of human habitation [6–8]. The similarity between West-Frisia and other wetland regions in North-West Europe means that findings are likely to provide insights into how climate and humans have changed landscapes and vegetation that are informative for developing management and conservation strategies. In this study we present extensive new landscape scale palaeoecological data from West-Frisia that shed new light on the nature of the past vegetation and the role of past climate change in shaping the landscape.

1.1. The Abundance of Trees in the West-Frisian Landscape during the Bronze Age

Eastern West-Frisia was inhabited by Bronze Age farmers (between ca. 1700 and 800 BC) and is now one of the best preserved and most intensively investigated Bronze Age landscapes in northwest Europe [6–8], however, the vegetation of the area during the Bronze Age is still a matter of discussion. The established paradigm for the vegetation suggests that the landscape of West-Frisia through the Bronze Age consisted mostly of grassland and arable fields on sandy ridges. In this model, upland trees are thought to have been virtually absent [9,10], with wetland trees like *Salix* and *Betula* only in depressions [11]. This 'treeless landscape' paradigm has been challenged, based on new interpretations of pollen records, wood finds and bones of mammals, to suggests that forests made up a significant part of the Bronze Age landscape in West-Frisia; with *Alnus* carr in wet depressions, *Fraxinus-Ulmus* forests at drier sites and grasslands in the relatively high and dry areas [6,12]. Furthermore, it has been suggested that, during the Bronze Age, lakes, marshy grasslands and dry arable fields alternated with patches of woodland, shrubs and even with riparian *Fraxinus* and *Quercus* forest [7]. In this study we try to find arguments pro or contra the established paradigm and the alternative ideas of van Amerongen [6,12] and van Zijverden [7]. See research question 1.

1.2. The Role of Climate Change in Driving Human and Vegetation Dynamics in West-Frisia

During the mid-Holocene (ca. 5000 BC to ca. 1500 BC) the region of West-Frisia formed part of the Bergen tidal basin. Behind an inlet near the present village of Bergen a multi-channel river system deposited sediment into tidal flats. Around 2100 BC the eastern part of the Bergen tidal basin area became disconnected from the western part [7]. The disconnection was due to a slow down in sea-level rise that allowed beach barriers and dunes to develop along the Dutch coast [5]. During the Bronze Age habitation (ca. 1700 to 800 BC) the inlet near Bergen closed around 1570 BC, increasing the area of land available to people.

Archaeological evidence indicates that towards the end of the Bronze Age (ca. 800 BC) houses were more frequently situated on creek ridges, and possibly on small artificial mounds, suggesting rising groundwater tables [8,13]. This interpretation is supported by a concomitant rise in the water table indicated by the formation of shallow freshwater lakes on top of soils that had been exposed during the Bronze Age, and the appearance of new wetlands [14,15]. This landscape change in West-Frisia is coincident with a climate event detected around the world that has become known as the 2.8 ka event [16]. A decline of solar activity around 850 cal BC (Subboreal/Subatlantic transition in raised bogs) has been suggested to have triggered an abrupt climate shift, to cooler and wetter conditions [14,15]. Around this time agricultural communities abandoned the area of West-Frisia likely due to a declining ability to produce food in an increasingly wet landscape. Evidence for this comes from the site of Enkhuizen-dijk, a shallow freshwater lake that terrestrialized and developed into a

peat-forming mire, and finally to an ombrotrophic raised bog [14,15,17]. In this study we examine landscape scale palaeoecological evidence to assess if a rapid rise in groundwater occurred at a large scale across West-Frisia (research question 2).

1.3. Late Medieval Degredation of the West-Frisian Landscape

Archaeological evidence from the Iron Age and early Medieval period (ca. 800 BC to ca. AD 1000) from the wetlands of West-Frisia is almost absent, apart from settlements along the borders of Lake Wervershoof, an early Iron Age settlement site near Opperdoes [6,7], and the early medieval trade centre Medemblik [18]. About 1000 years ago, people started large-scale reclamation of the wetland areas in the western Netherlands by digging drainage ditches in the peat deposits.

Today most of the peat deposits in West-Frisia dating from the Iron Age have disappeared due to oxidation and peat digging [19]. However, some peat deposits have been found to have been preserved under subsequent medieval accumulation layers, e.g., artificial mounds [20] and dikes [17]. Access to the Iron Age peats for palaeoecological investigation has been possible during the last ten years thanks to archaeological excavations targeting the medieval deposits. It is the palaeoecological analysis of these peats that is presented here. Specifically, organic deposits from the following twelve sites are presented (Figure 1 and Table 1): Beets (BTS), Berkhout (BKH), Bovenkarspel (BVK), Enkhuizen-LangeTuinstraat (ELT), Enkhuizen-Paktuinen (EPK), Enkhuizen-Raamstraat (ERS), Enkhuizen-Vijzeltuin (EVT), Enkhuizen-Westeinde (EWE), Grootebroek-Zesstedenweg (GBZ), Oostwoud (OWD), Venhuizen-Elbaweg (VEL) and Venhuizen-Spuiter (VSP). Furthermore, the new sites are compared with two previously published palaeoecological studies of West-Frisian peat deposits, at Klokkeweel [11] and Enkhuizen-dijk [17].

Figure 1. (**A**) Map of the Netherlands; and position of map (**B**) that shows the area where samples were taken. Sampling sites are indicated with red dots. Green: meadows; dark green: forested; yellow: arable; grey: villages and towns. (**C**) Detailed map of the Enkhuizen area showing position of sampling sites: 1: Vijzeltuin (EVT); 2: Raamstraat (ERS); 3: Paktuinen (EPK); 4: Lange Tuinstraat (ELT); 5: Enkhuizen-dijk [17]; 6: Westeinde (EWE); 7: Bovenkarspel (BVK); 8: Grootebroek-Zesstedenweg (GBZ).

Table 1. Archeological project numbers, site names, coordinates, levels of starting organic deposits in meters below Dutch Ordnance Datum (NAP), evidence for nearby Bronze Age archaeology, overlying deposits and archaeological references.

Project		Archaeological Site Names	Coordinates		Start of Organic Deposit (m-NAP)	Bronze Age Archaeology	Overlying Deposits	Reference
No.	Codes and Short Site Names		X	Y				
410	BKH: Berkhout	Berkhout, Westeinde 322	126,411	516,703	2.88	Absent	Anthropogenic. 12th or 13th C AD	[21]
414	BTS: Beets	Beets 47	127,375	511,361	No data	Absent	Anthropogenic. Mid 14th C AD	[22]
328	BVK: Bovenkarspel	Bovenkarspel, Hoofdstraat 17–19	144,798	523,401	1.98	Middle and Late Bronze Age occupation	Anthropogenic. 12th C AD	[23]
433	ELT: Lange Tuinstraat	Enkhuizen, Lange Tuinstraat 1 tm 35	147,971	523,588	2.39	Occupation 300 m from sampling site	Reclamation 12th C AD	[24]
372	EPK: Paktuinen	Enkhuizen, Paktuinen-Ridderstraat	148,277	523,777	3.74	Occupation 600 m from sampling site	Reclamation 12th C AD. Anthrop. from AD 1590	[25]
381	ERS: Raamstraat	Enkhuizen, Raamstraat	147,960	523,973	2.72	Absent	Anthropogenic.12th-13th C AD	[26]
341	EVT: Vijzeltuin	Enkhuizen, Vijzeltuin-West	148,345	524,256	2.59	Absent	Anthropogenic. 15th C AD	[27]
369	EWE: Westeinde	Enkhuizen, Westeinde 107	146,789	523,626	2.39	Middle Bronze Age ditches	Anthropogenic. 12th C AD	[28]
431	GBZ: Grootebroek	Grotebroek, Zesstedenweg 203	143,591	523,378	2.98	Absent	Anthropogenic. 12th-13th C AD	[29]
383	OWD: Oostwoud	Oostwoud, Oostwouderdorpsstraat 69	134,302	527,441	1.66	Bronze Age ard marks	Anthropogenic. 13th C AD	[30]
325	VEL: Elbaweg	Zuiderdijk, Venhuizen, Elbaweg	143,719	518,069	2.64	Middle Bronze Age ditches, pits	Anthropogenic. 14th C AD	[31]
325	VSP: Spuiter	Zuiderdijk, Venhuizen, Spuiter	142,838	517,515	2.41	Absent	Anthropogenic. 14th C AD	[31]

1.4. Research Questions

In this palaeoecological study we focused on four research questions and assess the suitability of the landscape scale palaeoecological data from West-Frisia for informing conservation and management practice today:

(1) Is there evidence for upland forest during the late Bronze Age habitation phase in West-Frisia as suggested by van Amerongen [6,12] and van Zijverden [7]?

(2) Is there evidence for abrupt groundwater rise (start of formation of shallow lakes and mires) in eastern West-Frisia around 850 cal BC [14]?

(3) Did medieval people only drain wetlands that had developed to ombrotrophic raised bogs, because successful drainage with man-made ditches was possible in raised areas only?

(4) Are the reconstructed vegetation successions relevant for present day and future management of wetland nature and landscapes [2–4]?

2. Materials and Methods

During archaeological excavations of medieval sites by the West-Frisian Archaeological Survey, fresh vertical cross sections were made, and metal boxes were used to sample the organic deposits (Figure 2). In most cases the samples include the transition from sandy clay (the former Bronze Age, soil surface layer), through the natural accumulation of organic material (gyttja and subsequently peat), into the layer representing the start of medieval, man-made accumulation.

Figure 2. Example of a sampling site: section of the site Vijzeltuin with sample boxes.

Sub-samples for microfossil analysis (ca. 0.5 cc each) were taken for all sites and prepared following Faegri and Iversen [32]. The microfossils were embedded in glycerol gelatin and sealed in with paraffin wax on microscopic slides. Pollen was identified with the keys and illustrations of Moore et al. [33], Beug [34] and the pollen reference collection of IBED, University of Amsterdam. In addition to pollen grains other microfossils with a characteristic morphology (non-pollen palynomorphs or NPP) were also recorded in the pollen slides. Identification and ecological interpretation of NPP followed van Geel [35], Pals et al. [11], van Geel and Aptroot [36], and van Geel et al. [37–39]. See also Appendix A for additional information on the ecological indicator value of NPP.

Pollen of herbaceous swamp and aquatic taxa, fern spores and NPP are normally excluded from the sum for percentage calculations, but in the present project we focused on the strictly local vegetation successions and therefore we included, in addition to the pollen total, the fern spores and

algae in the sum for percentage calculations. Diagrams were produced using the TILIA program [40]. The percentage curves in the diagrams are exaggerated ten times in light gray. Macrofossil data are shown as bars, representing counted numbers or volume-percentages as indicated below the *x*-axis.

Sub-samples for macrofossil analysis were taken from all sites in 1 cm thick slices from the same levels as the pollen samples. Each macrofossil sample had a volume of ca. 15 cc. The samples were treated according to Mauquoy and van Geel [41]. Fruits, seeds, other plant remains, and zoological remains were hand-picked from the residue using a stereomicroscope and the material was stored in glycerol. Most fruits and seeds were identified using the catalogue of Cappers et al. [42] and the reference collections of the University of Amsterdam and the Cultural Heritage Agency (RCE, Amersfoort). *Juncus* seeds and Poaceae fruits were identified with the keys and illustrations of Körber-Grohne [43,44]. In some cases, identifications of seeds or fruits were to "type-level". Table 2 shows the possible species for those types. For identification of vegetative plant remains the reference collection of the University of Amsterdam and illustrations by Mauquoy and van Geel [41] were used. Bryophytes were identified using BLWG verspreidingsatlas [45], Landwehr [46], Nyholm [47], Siebel and During [48], Smith [49] and Touw and Rubers [50]. An exceptional case was the identification of *Tomentypnum nitens*. Fossil material observed in the present study did not show rhizoids on stems and leaves. Such rhizoids are an important characteristic feature of the species. However, in rare occasions *T. nitens* plants occur with decreasing frequency of tomentum, and plants can even be almost without rhizoids [47,51]. Macrofossils like fruits and seeds were counted, but for vegetative remains, like mosses, volume percentages in the macrofossil samples were estimated. Some of the recorded seeds, other plant remains, and some zoological remains are illustrated in Figures 3 and 4.

Table 2. Species included in types as based on fruit and seed morphology.

Type	Species
Atriplex littoralis-type	*Atriplex littoralis/prostrata* var. *salina*
Carex acuta-type	*Carex acuta/elata/nigra/trinervis*
Carex paniculata-type	*Carex appropinquata/diandra/paniculata*
Juncus articulatus-type	*Juncus acutiflorus/articulatus/bulbosus*
Juncus effusus-type	*Juncus conglomeratus/effusus/inflexus*
Ranunculus repens-type	*Ranunculus acris/bulbosus/repens*
Sagina apetala-type	*Sagina apetala/micropetala/procumbens*
Veronica beccabunga-type	*Veronica anagallis-aquatica/beccabunga/catenata*

Insect remains were studied from just two sites (EVT and EWE) due to logistical and financial constraints. The Coleoptera were identified using reference specimens from the collection of the Naturalis Biodiversity Center in Leiden. The nomenclature follows Vorst [52]. The remains of other insect groups were also identified. Each "insect" sample had a volume of ca. 15 cc and the minimum number of individuals per taxon in any one sample was mostly one, sometimes two or three. The preservation of much of the insect material was excellent. Examples are the small Sphaerocerid fly in a late stage of adult development found inside its puparium (Figure 4H), a parasitoid wasp developing inside a fly puparium (Figure 4G) and a tiny parasitoid wasp *Anteris* (Figure 4I) found inside an arthropod egg in which it developed. We have to await further contemporary research on the parasite and its hosts before this and some other finds can be used in palaeoecological reconstructions.

Material for radiocarbon dating was sub-sampled from above-ground material (such as seeds, leaves and bud scales). The choice for the levels to be dated was mainly based on the wish to date at least the oldest and the youngest undisturbed organic levels. There were limitations in the choices because of the availability, or absence, of above-ground materials. Twenty-nine radiocarbon dates were obtained from eleven sites (Table 3). Radiocarbon dates were calibrated using OxCAL 2019–06-09 (IntCal13; [53,54]). Graphical illustrations of the calibration results are available online as Electronic Supplementary Material (ESM Document 1). For calculation of the duration of vegetation successions the choice of the age in calendar years was made based on the highest probability.
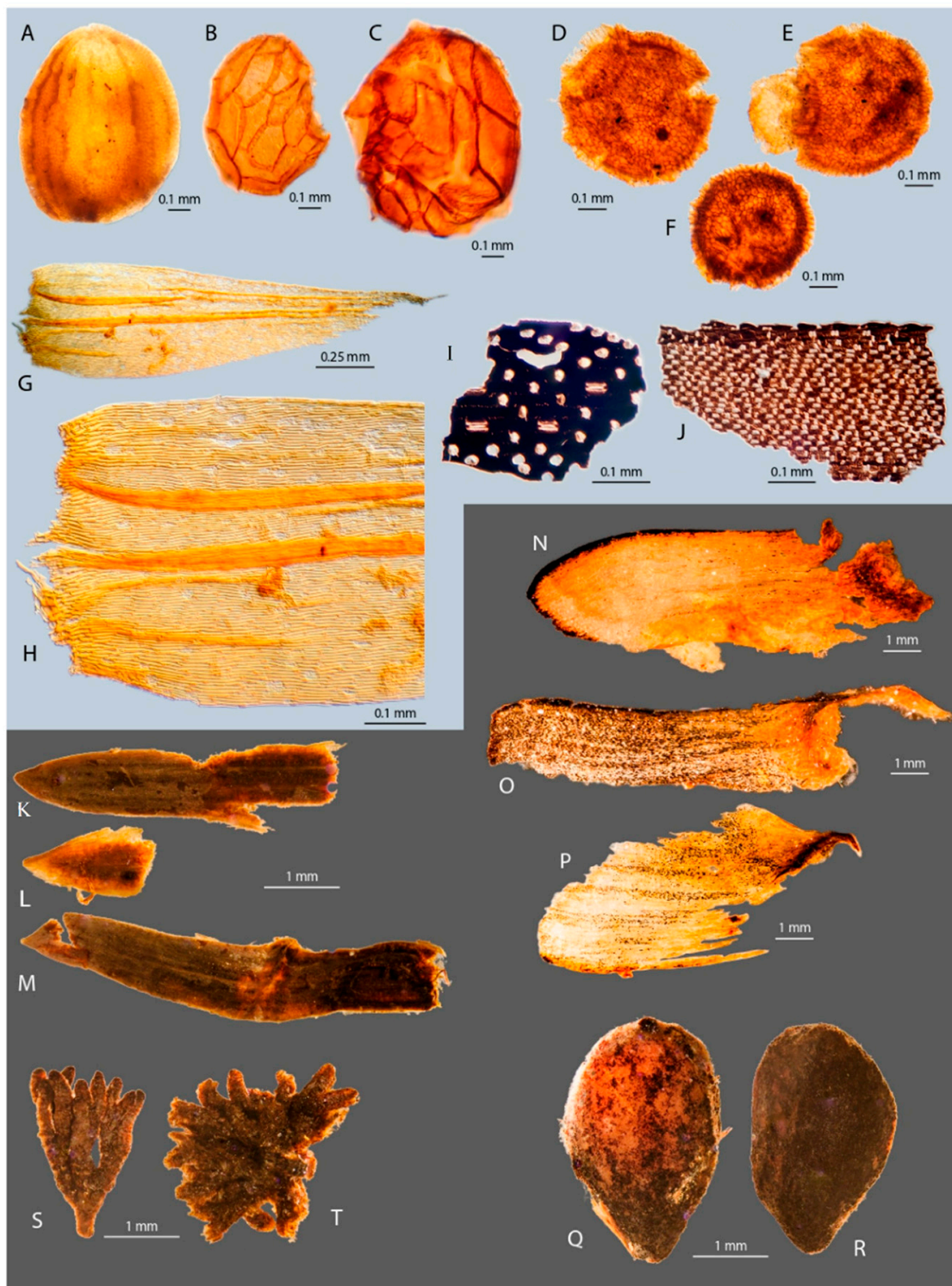
Figure 3. (**A**) *Lemna* spec., seed; (**B**) and (**C**) *Hottonia palustris*, seeds; (**D**–**F**) *Utricularia* spec., seeds; (**G**) and (**H**) *Tomentypnum nitens*, leaf; (**I**) and (**J**) charred epidermis fragments Poaceae; (**K**–**M**) *Pinus sylvestris*, needle fragments; (**N**–**P**) *Pinus sylvestris*, seed wing fragments; (**Q**) and (**R**) *Pinus sylvestris*, seeds; (**S**) and (**T**) *Pinus sylvestris*, mycorrhizal roots.
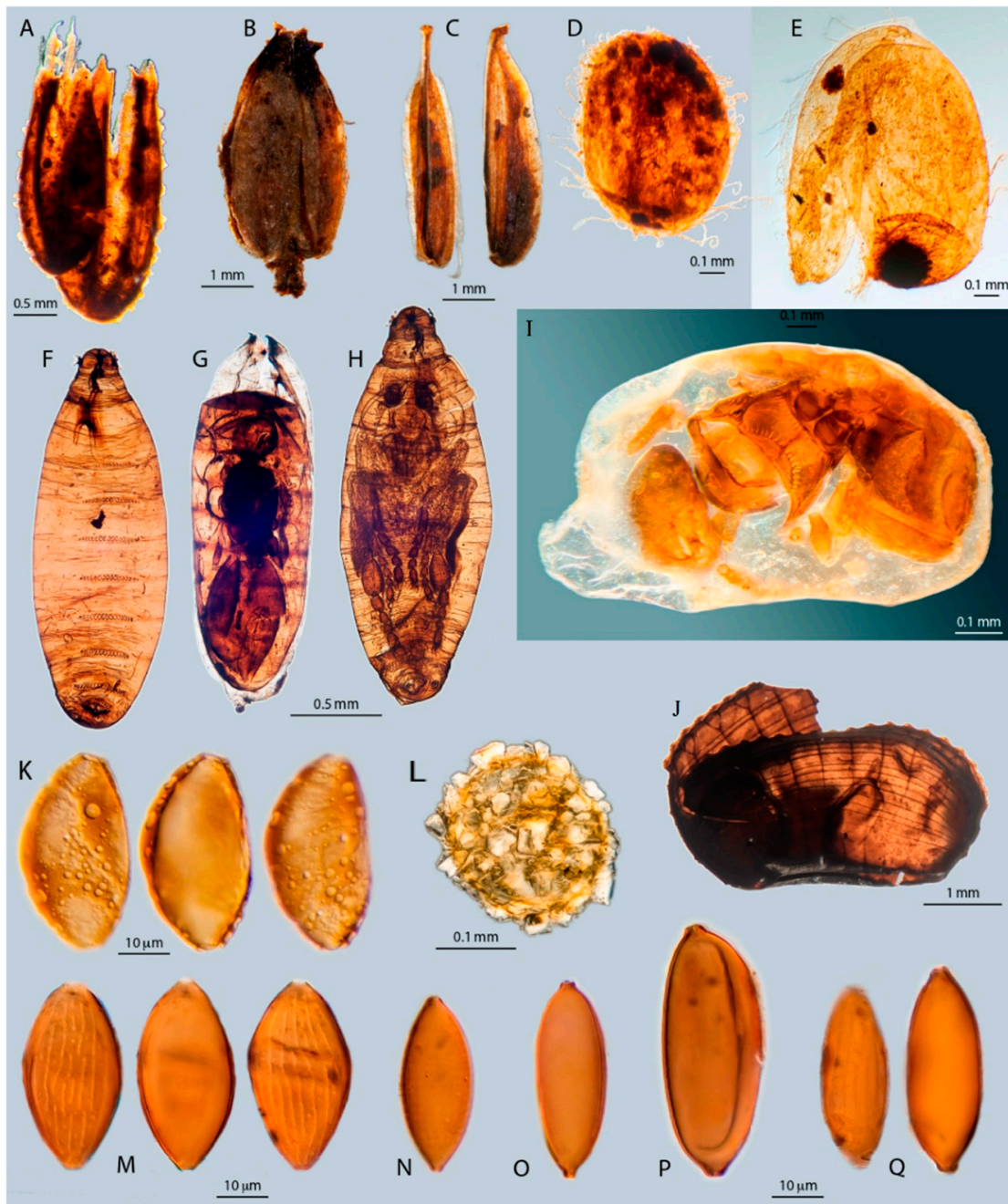
Figure 4. (**A**) *Anthriscus caucalis*, seed; (**B**) and (**C**) *Triglochin maritima*, fruit and seeds; (**D**) and (**E**) *Salicornia europaea*, seeds; (**F–H**) Sphaeroceridae, puparia, (**H**) with adult inside, (**G**) with a parasitoid Hymenopteron inside; (**I**) parasitoid wasp *Anteris* spec. inside an arthropod egg; (**J**) *Ectobius lapponicus/sylvestris*, ootheca; (**K**) HdV-598 spores; (**L**) HdV-597 macrofossil; (**M–Q**) ascospores of *Neurospora* (HdV-55B/C) with, and without longitudinal grooves.

Table 3. Radiocarbon dates and calibration results of samples from the studied West-Frisian sequences. GrM and GrA samples were dated by the Centre for Isotope Research, Groningen and Beta samples by the radiocarbon laboratory of Beta Analytic, London, UK.

Sites	Depth (cm)	Lab. Code	14C BP	Calibrations OxCAL 2019–06–09 (IntCal 13): 68.2% Probability	Material Used for Dating
BKH: Berkhout	7 + 8	GrM-17116	3090 ± 20	cal BC 1406–1381; 1343–1306	*Betula* leaf, seed, catkin scale, bud scale.
	32 + 33	GrM-17117	3685 ± 25	cal BC 2133–2082; 2060–2031	*Betula* leaf, bud scale; seeds *S. flos-cuculi*.
	42 + 43	GrM-17347	4009 ± 18	cal BC 2568–2519; 2498–2489	*Carex* seeds.
BTS: Beets	7 + 8	GrM-17115	1765 ± 20	cal AD 240–259; 281–324	*R. alba* seeds, stems; *Sphagnum* opercula.
ELT: Enkhuizen-Langetuinstr	29	GrM-17125	1815 ± 25	cal AD 140–160; 166–196; 208–238	*Betula* bud scales, leaves; Musci.
	65	GrM-17839	2825 ± 40	cal BC 1022–919	Seeds: *Alisma, Carex, Mentha, Lythrum*.
EPK: Enkhuizen-Paktuinen	18 + 19	GrM-17284	1950 ± 20	cal AD 25–75	*Menyanthes* seed, *Betula* leaf.
	62 + 63	GrM-17348	2835 ± 25	cal BC 1018–970; 961–935	*Carex* seeds, *Iris pseudacorus* seed.
ERS: Enkhuizen-Raamstraat	16 + 17	Beta-431213	1870 ± 30	cal AD 82–170; 194–210	leaves: *Betula, Oxycoccus palustris*, musci.
	37	Beta-431214	2270 ± 30	cal BC 395–357; 282–257; 244–236	*Betula* leaf, female catkin scale; fern leaf.
	68 + 69 + 70	Beta-431215	2840 ± 30	cal BC 1043–971; 960–936	Seeds: Cyperaceae, Apiaceae, *Iris, Lycopus*.
	84 + 85 + 86	Beta-431216	3030 ± 30	cal BC 1374–1354; 1302–1226	Seeds: Cyperaceae, Apiaceae, *Iris, Mentha*.
	90 + 91 + 92	GrA-64000	2920 ± 35	cal BC 1192–1172; 1166–1143; 1132–1051	Seeds: *Mentha, Glyceria*, Apiaceae, *Alisma, Solanum, Eleocharis*.
EVT: Enkhuizen-Vijzeltuin	18	GrA-56077	985 ± 35	cal AD 1014–1048; 1087–1123; 1138–1149	Seeds: Chenopodiaceae.
	21	GrA-56075	1970 ± 35	cal BC 19–13; cal AD 1–72	*Pinus*, female cone fragment.
	69 + 70	GrA-56073	2985 ± 40	cal BC 1267–1155; 1148–1128	Seeds: Cyperaceae, *Mentha*.
EWE: Enkhuizen-Westeinde	13	GrM-17285	2450 ± 20	cal BC 742–687; 665–645; 550–485	Seeds: *Carex, Menyanthes*, Apiaceae.
	25 + 26	GrM-17287	2705 ± 20	cal BC 894–871; 851–818	Seeds: *Menyanthes, Iris*, Apiaceae, *Solanum*, Ranunculaceae, Caryophyllaceae.
	37	GrM-17124	2760 ± 25	cal BC 927–891; 879–846	*Iris pseudacorus* seed.
GBZ: Grootebroek-Zesstedenweg	48 + 49	GrM-17206	1996 ± 19	cal BC 37–29; 22–10; cal BC 2–cal AD 25	*Pinus* needles, *Betula* leaf, seed *Menyanthes*.
	69 + 70	GrM-17207	2504 ± 19	cal BC 767–748; 684–667 cal BC 641–588; 580–559	Seeds: *Carex, Menyanthes*; musci, fern leaf.
	96 + 97	GrM-17209	2855 ± 20	cal BC 1051–979	*Carex* seeds.
OWD: Oostwoud	29	GrM-17210	2498 ± 19	cal BC 762–748; 685–666 cal BC 642–587; 581–556	Seeds: *Menyanthes, Carex, S. flos-cuculi*. *Betula*, Caryophyll., *Sphagnum, Polytrichum*.
	61	GrM-17211	3250 ± 17	cal BC 1595–1589; 1532–1499	Seeds: *Carex, Ranunc., Menyanthes, Lycopus*, Apiaceae, Caryophyllaceae.
	68	GrM-17879	3350 ± 35	cal BC 1690–1611; 1572–1566	Seeds: *Urtica, Hypericum, Mentha, Solanum, Carex, Juncus*.
VEL: Venhuizen-Elbaweg	53–54	GrA-53539	1645 ± 30	cal AD 353–367; 380–426	Alkaline fraction of bulk peat.
	68–70	GrA-53538	2465 ± 30	cal BC 751–683; 669–636 cal BC 626–614; 592–516	
VSP: Venhuizen-Spuiter	30	GrA-53540	2450 ± 35	cal BC 747–686; 666–643; cal BC 554–452; 446–430	Alkaline fraction of bulk peat.
	Ditch	GrA-53541	1555 ± 30	cal AD 430–494; 510–518; cal AD 528–545	Leaf fragments, bud scales, seeds.

3. Results and Interpretation

For practical reasons we only illustrate here the diagram of the site Enkhuizen-Vijzeltuin (Figure 5). For all sites the complete diagrams are available online as ESM Documents 2 and 3. Zone boundaries for each site were determined based on our ecological knowledge of the recorded taxa and on major vegetation changes. Here we present the vegetation successions at the twelve West-Frisian sites in alphabetical order. In addition to the ecological reconstructions, attention is given to chronological aspects based on radiocarbon dates, and to the duration of pre-Medieval hiatuses.

3.1. Beets (BTS, Diagram in ESM2)

During the excavation only undisturbed peat (50–9 cm depth) and the transition to the start of a human impacted peat layer were sampled. Deeper peat was not cored and therefore was not available for this study. Based on a radiocarbon date at 7 + 8 cm depth (ca. AD 300; Table 3) and the rise of *Carpinus* pollen we conclude that peat growth stopped in late Roman time (ca. AD 300), but it may well be that younger peat disappeared because of digging for fuel and/or by oxidation.

3.1.1. Zone BTS-1 (50–9 cm Depth)

The sampled and studied upper part of the peat deposit at Beets was formed by a raised bog with Ericales (*Calluna vulgaris*, *Erica tetralix*, *Andromeda polifolia*), *Sphagnum* sp. and specific raised bog fungi [35]: *Tilletia sphagni* (HdV-27), *Anthostomella fuegiana* (HdV-4), HdV-10, HdV-12, cf. *Entophlyctis lobata* (HdV-13), *Meliola ellisii* (HdV-14), *Helicoon pluriseptatum* (HdV-30), HdV-92 and HdV-9 (HdV-9 spores were illustrated by van Geel et al. [16]).

The lower 25 cm of the studied peat core was formed in relatively dry conditions (*Sphagnum* sect. Acutifolia, *Aulacomnium palustre*, *Calluna vulgaris* and its parasitic fungus *Meliola ellisii*, and HdV-10), while the upper part represents more wet local conditions (*Sphagnum cuspidatum*, *Rhynchospora alba*).

3.1.2. Zone BTS-2 (9–1 cm Depth)

The substrate is *Sphagnum* peat, but it is mixed with indicators for brackish or saline conditions: *Armeria maritima*, *Juncus gerardii*, *Salicornia europaea*, *Suaeda maritima*, *Zannichellia palustris* ssp. *pedicellata*, *Triglochin maritima* and Foraminifera, indicating marine inundations with brackish or salt water. Recorded freshwater taxa are *Botryococcus*, *Pediastrum*, *Spirogyra* and HdV-128A. Human impact is evident from the presence of *Secale*, Asteraceae liguliflorae, Brassicaceae, *Plantago major/media*, *Rumex acetosella*, *Poa annua*, *Polygonum aviculare*, Ranunculaceae, *Anthoceros punctatus* and spores of coprophilous fungi: *Podospora, Sordaria* and *Sporormiella*.

3.2. Berkhout (BKH, Diagram in ESM2)

The vegetation succession is not essentially different from the sites in, and near Enkhuizen, but the three radiocarbon dates (Table 3) point to relatively early starting peat growth (ca. 2550 cal BC) at the Berkhout site. The succession from the start of zone BKH-1/2 (mineral-rich shallow freshwater) to the ombrotrophic zone BKH-4 took about 1100–1300 years.

3.2.1. Zone BKH-1 (49–44 cm Depth)

Freshwater taxa are present, but to a limited extent: algal spores HdV-128A and HdV-128B, *Pediastrum* and *Spirogyra*. *Neurospora* ascospores (HdV-55B/C, as illustrated in Figure 4M–Q) are linked to local fire (charcoal). Cysts of marine Dinoflagellata, HdV-115 and Chenopodiaceae may be reworked from the clayey subsoil. No human impact indicators were recorded at the base of the sequence.
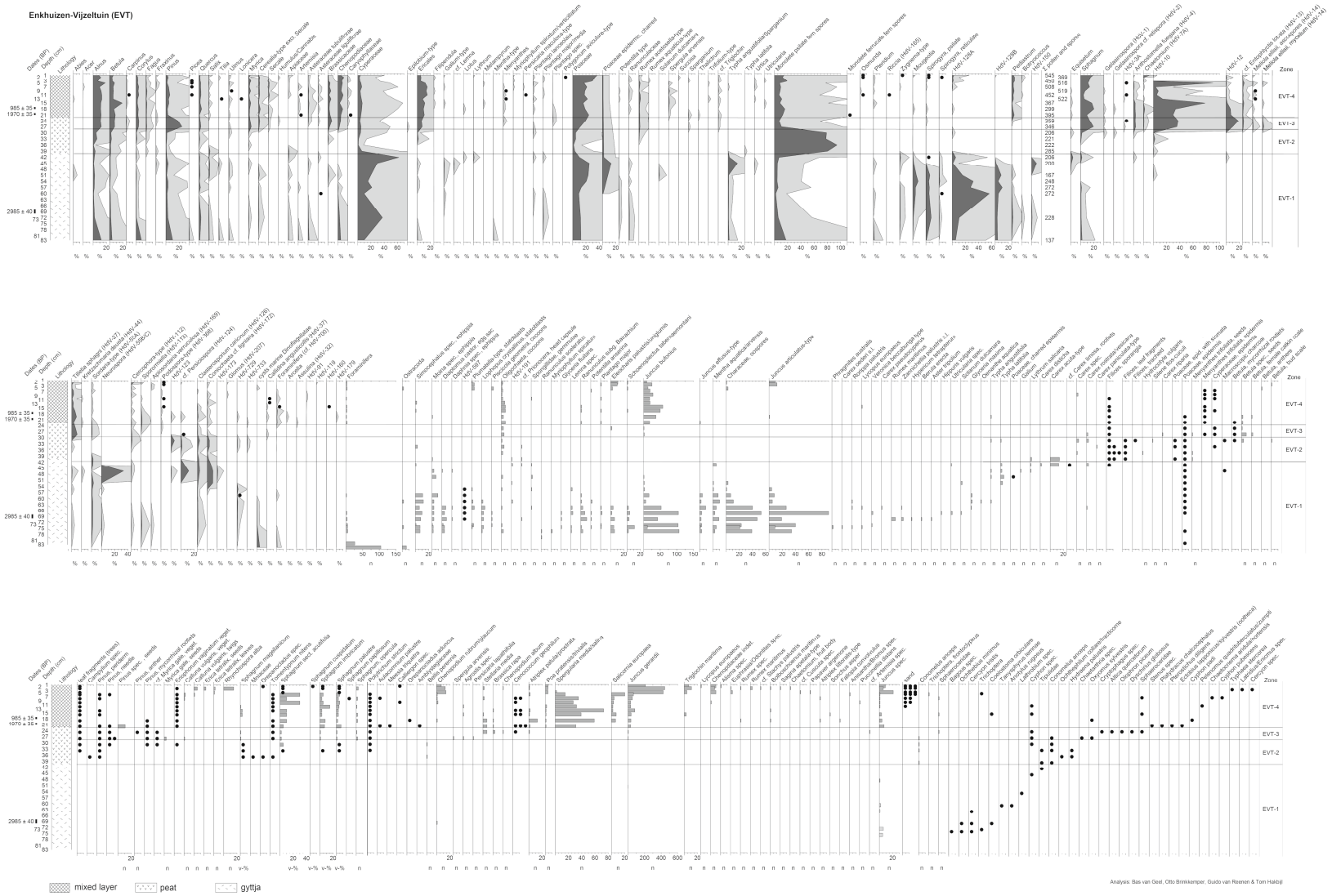
Figure 5. Diagram of Enkhuizen-Vijzeltuin.

3.2.2. Zone BKH-2 (44–40 cm Depth)

Ranunculus subg. *Batrachium, Lythrum salicaria, Ranunculus flammula, Carex rostrata, C. riparia, C. pseudocyperus, Stellaria palustris, Solanum dulcamara* and *Thalictrum flavum* play a role in the succession from eutrophic wet-growing species towards the mesotrophic and mineral-rich fen conditions of the *Thelypteris palustris* phase of BKH-3.

3.2.3. Zone BKH-3 (40–4 cm Depth)

BKH-3 is a *Thelypteris palustris* phase of relatively long duration. Other taxa are *Betula, Carex rostrata, C. acuta*-type, *Eriophorum vaginatum, Galium*-type, *Melampyrum, Menyanthes trifoliata, Pedicularis, Silene flos-cuculi, Sphagnum* sp., *Tomentypnum nitens, Paludella squarrosa* and *Calliergon giganteum*. This assemblage is characteristic for mineral-rich fens with seepage of calcium and iron-rich groundwater [55].

Within zone BKH-3 we distinguish five sub-zones, based on the alternation of the bryophyte species *Calliergon giganteum* and *Tomentypnum nitens/Paludella squarrosa*:

BKH-3A (40–37 cm Depth)	Mineral-rich fen with *C. giganteum*.
BKH-3B (37–31 cm Depth)	Mineral-rich fen with *T. nitens*, although the raised bog fungi cf. *Entophlyctis lobata* (HdV-13) and HdV-65 already indicate development towards mineral-poor conditions.
BKH-3C (31–21 cm Depth)	Mineral-rich fen with *C. giganteum* and a maximum of HdV-123.
BKH-3D (21–10 cm Depth)	Mineral-rich fen with *Tomentypnum nitens*. HdV-13, HdV-65, *Amphitrema flavum* and the presence of *Paludella squarrosa* already point to local acidification. *Paludella squarrrosa* occurs in areas with a relatively high input of groundwater [56] but is especially common in mineral-poor fens.
BKH-3E (10–4 cm Depth)	Mineral-rich fen with HdV-123 and *C. giganteum*. Some temporary disturbance (flooding with water, enriched in minerals) is evidenced by the presence of *Mougeotia, Spirogyra, Zygnema*-type and HdV-128A in the sample at 5 cm depth.

3.2.4. Zone BKH-4 (4–1 cm Depth)

The transition to local ombrotrophic conditions is shown by *Sphagnum* sp., the *Sphagnum*-parasite *Tilletia sphagni*, Ericales pollen, *Andromeda polifolia, Eriophorum vaginatum* and some typical raised bog microfossil taxa (*Anthostomella fuegiana*, HdV-12, cf. *Entophlyctis lobata, Amphitrema flavum* and *Assulina*). No human impact indicators were recorded.

3.3. Bovenkarspel (BVK, Diagram in ESM2)

No radiocarbon dates are available for the Bovenkarspel core, but based on the *Fagus* pollen curve we conclude that the organic sequence was formed after 800 cal BC [35].

3.3.1. Zone BVK-1 (48–41 cm Depth)

Spores of Zygnemataceae (*Mougeotia, Spirogyra, Zygnema*-type) indicate shallow, stagnant freshwater, with some terrestrialization. Other aquatic and semi-aquatic taxa in this zone are *Botryococcus*, HdV-128A, HdV-128B, *Eleocharis palustris, Euphorbia palustris, Galium palustre, Lythrum salicaria, Mentha aquatica, Oenanthe aquatica* and *Utricularia*. Possible human impact indicators are Asteraceae liguliflorae, Brassicaceae, *Juncus articulatus*-type and spores of *Riccia* (sporulation pointing to moist arable land [17]). Cysts of marine Dinoflagellata are probably reworked from the mineral subsoil.

3.3.2. Zone BVK-2 (41–35 cm Depth)

Equisetum temporarily becomes important in the vegetation succession. HdV-128A, *Alisma plantago-aquatica, Cicuta virosa, Galium palustre, Lemna* spec., *Valeriana* and *Simocephalus* show that wet, mineral-rich conditions still prevailed.

3.3.3. Zone BVK-3 (35–25 cm Depth)

A maximum of monolete psilate spores indicates the dominance of *Thelypteris palustris* in the rich-fen stage.

3.3.4. Zone BVK-4 (25–1 cm Depth)

Based on the occurrence of *Sphagnum*, *Tilletia sphagni* (parasite on *Sphagnum*), the raised bog fungi *Anthostomella fuegiana*, HdV-10, HdV-12, cf. *Entophlyctis lobata* (HdV-13), *Meliola ellisii* (parasite on *Calluna vulgaris*) and *Eriophorum vaginatum,* the local vegetation develops to a raised bog. The raised bog peat is mixed with human impact indicators and taxa that need a relatively high level of nutrients (Cerealia, Asteraceae, Brassicaceae, *Atriplex patula/prostrata*, *Chenopodium glaucum/rubrum*, *Galium aparine*, *Polygonum aviculare*-type, *Persicaria maculosa*-type, Ranunculaceae and *Spergula arvensis*). Ascospores of *Podospora*, *Sordaria* and spore cells of *Sporormiella*, point to the nearby availability of feces. The presence of *Juncus gerardii* and *Triglochin maritima* indicates marine inundations with brackish or salt water. *Lemna* spec. and *Pediastrum* point to freshwater conditions.

3.4. Enkhuizen-Lange Tuinstraat (ELT, Diagram in ESM2)

A radiocarbon date at 65 cm depth (Table 3) indicates the local start of aquatic organic accumulation around 1000 cal BC. The radiocarbon date at 29 cm depth shows the age of the top of undisturbed mineral-poor *Betula*-peat (second to third century AD). The duration of the recorded vegetation succession was ca. 1250 years.

3.4.1. Zone ELT-1 (85–63 cm Depth)

Spores of Zygnemataceae (*Mougeotia*, *Spirogyra*, *Zygnema*-type) indicate shallow, stagnant freshwater and HdV-128A, HdV-128B, *Botryococcus*, *Pediastrum* also point to the presence of a local aquatic habitat. Fruits and seeds of *Alisma* spec., *Eleocharis palustris/uniglumis*, *Juncus articulatus*-type, *Lemna* spec., *Lythrum salicaria*, *Mentha aquatica*, *Oenanthe aquatica* and *Ranunculus* subg. *Batrachium* reflect local aquatic to semi-aquatic, and relatively mineral-rich conditions. Aquatic invertebrates *Lophopus crystallinus*, *Diaptomus castor*, *Moina* and *Simocephalus* were recorded. Spores of coprophilous fungi (*Apiosordaria verruculosa*, *Sordaria*, *Bombardioidea*), Asteraceae, Brassicaceae and spores of *Riccia* may be linked to nearby farming. Ascospores of *Neurospora* (HdV-55B/C) are fire indicators. Dinoflagellata and Foraminifera are probably reworked from the subsoil that was deposited in marine conditions preceding the Bronze Age.

3.4.2. Zone ELT-2 (63–51 cm Depth)

This assemblage zone represents an *Equisetum* phase, with *Carex acutiformis*, *C. disticha*, *Conium maculatum*, *Lycopus europaeus*, *Pedicularis palustris*, *Sparganium* and *Utricularia* spec. The zone is further characterized by the appearance of *Carex rostrata* and *Menyanthes trifoliata*. This assemblage is indicative for mineral-rich fens. Spores of *Closterium* cf. *rostratum*, *Mougeotia* and *Zygnema*-type point to temporary presence of shallow stagnant freshwater.

3.4.3. Zone ELT-3 (51–27 cm Depth)

Thelypteris palustris (monolete psilate fern spores) is an important species, in combination with *Carex rostrata*, *Betula* spec., *Galium palustre*, *Potentilla palustris* and *Silene flos-cuculi*. The spectrum of taxa indicates that mineral-rich fen conditions still prevailed.

3.4.4. Zone ELT-4 (27–1 cm Depth)

This is a mixed assemblage zone of highly decomposed macrofossils. Indicators for originally ombrotrophic conditions are *Sphagnum* (spores), *Tilletia sphagni* (parasite on *Sphagnum*) and *Polytrichum. Tomentypnum nitens* at the base of the ELT-4 indicates contact with mineral-rich water. There are various

indicators for inundations. The presence of Dinoflagellata, Foraminifera, *Juncus gerardii*, *Sperularia media/salina*, *Triglochin maritima* and the snail *Hydrobia ulvae* point to inundations with brackish or salt water. The presence of *Botryococcus*, *Pediastrum*, *Spirogyra*, HdV-128A and HdV-128B, *Eleocharis palustris*, *Lemna* spec., *Ranunculus* subsp. *Batrachium* and *Moina* point to inundation with fresh water, possibly due to dissolution of brackish water with rain.

Human impact is evident from the occurrence of *Secale*, *Centaurea cyanus*, Asteraceae, Brassicaceae, Chenopodiaceae, *Chenopodium glaucum/rubrum*, *Juncus bufonius*, *Poa pratensis/trivialis*, *Polygonum aviculare*, *Potentilla anserina*, *Ranunculus repens*-type, *Ranunculus sceleratus* and spores of *Riccia*.

3.5. Enkhuizen-Paktuinen (EPK, Diagram in ESM2)

A radiocarbon date at 62 + 63 cm depth (Table 3) points to an age of ca. 1050–950 cal BC for the start of the aquatic phase (zone EPK-1). The date at 18 + 19 cm depth shows that mineral-poor *Betula*-peat was formed until the first century AD. The duration of the recorded vegetation succession was ca. 1100 years. Evidence for later peat growth (if any) is absent because of oxidation, decomposition and mixing with medieval plant remains (Zone EPK-5).

3.5.1. Zone EPK-1 (88–69 cm Depth)

Botryococcus, Characeae, *Mougeotia*, *Pediastrum*, *Spirogyra*, *Zygnema*-type, HdV-128A and HdV-128B point to stagnant, shallow freshwater. Other (semi-)aquatic taxa are *Alisma* (pollen) and *Alisma* spec. (embryos), *Euphorbia palustris*, *Iris pseudacorus*, *Lemna* spec., *Lycopus europaeus*, *Mentha aquatica*, *Oenanthe aquatica*, *Ranunculus* subg. *Batrachium*, *Ranunculus sceleratus*, *Sium latifolium* and *Veronica beccabunga*-type. Recorded invertebrates are *Lophopus crystallinus*, and *Moina*. Recorded human impact indicator taxa are Asteraceae, Brassicaceae, *Polygonum aviculare*-type, spores of *Riccia* and eggs of the parasitic intestinal nematod *Ascaris*. Chenopodiaceae, Dinoflagellata and Foraminifera point to marine material reworked from the mineral subsoil.

3.5.2. Zone EPK-2 (69–59 cm Depth)

Equisetum is temporarily dominant. Algae are still present. Semi-aquatic taxa are *Carex disticha*, *C. elongata*, *C. pseudocyperus*, *C. riparia*, *C. rostrata*, *Lycopus europaeus*, *Lythrum salicaria*, *Oenanthe aquatica* and *Ranunculus sceleratus*. The cladocera *Daphnia* and *Simocephalus* were recorded. A peak of *Neurospora* ascospores indicates local fire.

3.5.3. Zone EPK-3 (59–30 cm Depth)

Thelypteris palustris (monolete psilate fern spores) is the dominant species, initially with *Utricularia* spec., *Solanum dulcamara* and *Symphytum*, and later with *Betula* spec., *Menyanthes trifoliata*, *Pedicularis*, *Ranunculus lingua*, *Rumex acetosa*, *Silene flos-cuculi*, *Carex flacca/panicea* and *C. pseudocyperus*. This points to mineral-rich fen conditions.

3.5.4. Zone EPK-4 (30–23 cm Depth)

Thelypteris shows relatively low percentages, while *Betula* spec. and *Menyanthes trifoliata* continue to be important taxa. *Calliergon giganteum* indicates relatively mineral-rich conditions, and point to seepage of calcium and iron-rich groundwater.

3.5.5. Zone EPK-5 (23–1 cm Depth)

The original vegetation was ombrotrophic peat with Ericales (including *Calluna vulgaris*), *Sphagnum* with its parasite *Tilletia sphagni*, *Betula* spec. and *Polytrichum*. Human impact and mixing of peat with younger material is evident from the increase of Cerealia pollen, the presence of *Fagopyrum* pollen, and *Alopecurus geniculatus*, Asteraceae, *Atriplex patula/prostrata*, Brassicaceae, *Chenopodium glaucum/rubrum*, *Juncus bufonius*, *Knautia arvensis*, *Lycopus europaeus*, *Poa pratensis/trivialis*, *Polygonum aviculare*-type,

Plantago major, *Rhinanthus*, *Rumex acetosella*, *Rumex maritimus*, *Schoenoplectus lacustris*, *Stellaria palustris*, *Urtica dioica*, *Riccia*, spores of coprophilous fungi *Podospora* and *Sordaria*, and an egg of the intestinal parasite *Ascaris.* Inundation with brackish or salt water is indicated by taxa such as Chenopodiaceae, *Juncus gerardii*, *Samolus valerandi/Centunculus minimus*, *Spergularia media/salina*, *Triglochin maritima*, Dinoflagellata and Foraminifera. Freshwater indicators are the algae *Botryococcus*, *Pediastrum*, *Spirogyra*, HdV-128A and fruits and seeds of *Eleocharis palustris/uniglumis*, *Hippuris vulgaris*, *Ranunculus* subg. *Batrachium*, and the invertebrates *Moina*, *Simocephalus*, *Lophopus crystallinus* and *Plumatella*-type.

3.6. Enkhuizen-Raamstraat (ERS, Diagram in ESM2)

Five sampled levels in the lower part of the sequence (zones ERS-1 and ERS-2) were too poor in microfossils to show percentages. Black dots in the diagram only indicate presence of taxa. Three radiocarbon dates (90–92, 84–86 and 68–70 cm levels; Table 3) indicate that inundation with shallow freshwater started around 1300 cal BC and lasted until about 1000 cal BC. Subsequent undisturbed peat growth occurred during ca. 1200 years, until the second century AD (radiocarbon date 16–17 cm; ombrotrophic raised bog peat). Any later peat formation is not traceable because of human disturbance (drainage, oxidation and possibly peat digging).

3.6.1. Zone ERS-1 (100–73 cm Depth)

The deepest spectrum includes marine microfossils reworked from the sandy clay below the organic deposit: cysts of marine Dinoflagellata and *Micrhystridium* (HdV-115). The organic sequence starts with an aquatic phase. *Mougeotia*, *Spirogyra* and *Zygnema*-type indicate shallow stagnant freshwater. Other recorded algae are *Botryococcus*, *Pediastrum*, Characeae, HdV-128A and HdV-128B. Aquatic and semi-aquatic macrophytes in this assemblage zone are *Alisma* spec., *Iris pseudacorus, Juncus articulatus*-type, *Lemna* spec., *Ranunculus* subg. *Batrachium, Sparganium* and *Veronica beccabunga*-type. Invertebrate taxa of this aquatic phase are *Daphnia*, *Diaptomus castor, Lophopus crystallinus*, *Plumatella*-type and *Simocephalus*. Nearby human impact is evidenced by *Persicaria maculosa*, *Polygonum aviculare*, *Riccia* and by the spores of the coprophilous fungi *Apiosordaria verruculosa*, *Podospora* and *Sordaria*.

3.6.2. Zone ERS-2 (73–61 cm Depth)

A short phase with *Equisetum*, *Carex acuta*-type, *C. disticha*, *C. rostrata*, *Lycopus europaeus*, *Lythrum salicaria*, *Mentha aquatica*, *Oenante fistulosa*, *Phalaris arundinacea*, *Ranunculus flammula* and *Utricularia* spec. characterizes the terrestrialization towards mineral-rich fen dominated by *Thelypteris* of zone ERS-3. Ascospores of *Neurospora* indicate nearby fire.

3.6.3. Zone ERS-3 (61–29 cm Depth)

Thelypteris palustris dominates the rich-fen vegetation, initially with *Carex rostrata*, *C. acuta*-type, *Lythrum salicaria*, *Potentilla palustris*, and *Utricularia*. *Betula* spec., *Menyanthes trifoliata*, and *Silene flos-cuculi* form part of the local vegetation, indicating increasing ombrotrophy and temporary relatively dry conditions, necessary for the germination of *Betula* seeds.

3.6.4. Zone ERS-4 (29–7 cm Depth)

The vegetation changes to ombrotrophic conditions with *Sphagnum* (mainly *S. palustre*), Ericaceae, *Eriophorum vaginatum*, *Pinus sylvestris*, *Aulacomnium palustre* and raised bog fungi HdV-10, cf. *Entophlyctis lobata* (HdV-13) and *Tilletia sphagni*. The presence of *Tomentypnum nitens* indicates contact with mineral-rich groundwater.

3.6.5. Zone ERS-5 (7–1 cm Depth)

In the upper two samples various taxa were recorded that indicate eutrophication by inundation and human impact: *Pediastrum*, Foraminifera, *Cerastium*, Cerealia, *Hydrocotyle vulgare*, *Juncus effusus*-type, *Nasturtium* spec., *Ranunculus sceleratus* and *Solanum dulcamara*.

3.7. Enkhuizen-Vijzeltuin (EVT)

The radiocarbon date at 70 + 69 cm level (Table 3) indicates a rising water table (start of gyttja) around 1200 cal BC, while the dates at 21 cm (pine cone fragment) and 18 cm depth (seeds Chenopodiaceae) point to a hiatus between ca. cal AD 50 and cal AD 1050. The recorded vegetation succession from shallow open water to ombrotrophic raised bog vegetation took about 1250 years.

3.7.1. Zone EVT-1 (83–40 cm Depth)

Zygnemataceae (*Mougeotia*, *Spirogyra*, *Zygnema*-type) indicate shallow, stagnant freshwater. Other recorded algae are *Botryococcus,* Characeae, *Pediastrum*, HdV-128A and HdV-128B. In addition, we found (semi-)aquatic taxa: *Berula erecta*, *Carex oederi*, *Carex pseudocyperus*, *Eleocharis palustris/uniglumis*, *Glyceria fluitans*, *Glyceria maxima*, *Hippuris vulgaris*, *Hypericum tetrapterum*, *J. articulatus*-type, *Lemna* spec. (with its phytofage weevil *Tanysphyrus lemnae*), *Lycopus europaeus*, *Lythrum salicaria, Mentha aquatic/arvensis*, *Myriophyllum spicatum*, *Oenanthe aquatica*, *Potentilla anserina*, *Phragmites australis*, *Ranunculus* subg. *Batrachium*, *Ranunculus sceleratus*, *Rorippa palustris*, *Rumex maritimus*, *Schoenoplectus tabernaemontani*, *Solanum dulcamara*, *Typha angustifolia*, *Typha latifolia*, *Utricularia* spec., *Veronica beccabunga*-type and *Zannichellia palustris*. *Bagous* feeds on water and marsh plants. The beetles *Cercyon tristis*, *Ochthebius minimus*, *Coelostoma orbiculare* and larval Trichoptera live in shallow water, together with the other invertebrates: *Simocephalus*, *Moina*, *Diaptomus castor*, *Plumatella*-type, *Lophopus crystallinus* and *Piscicola geometra*. *Equisetum*, *Lythrum salicaria* and *Carex acuta*-type occur at the transition to EVT-2. HdV-597 (Figure 4L) is a newly recorded globose "macrofossil". Its wall is covered with small mineral particles. It was also observed (but not counted) in the gyttja phase of other West-Frisian sites.

Human impact indicators (in a broad sense) recorded in zone EVT-1 are *Plantago major*, *Juncus bufonius*, *Sordaria*, *Sporormiella*, *Apiosordaria verruculosa* and *Podospora*. Dinoflagellata and Foraminifera probably represent reworked marine subsoil.

In the lower half of this zone the macroscopic parts of aquatic invertebrates are common, but in the upper half of EVT-1 these organisms diminish or disappear, indicating terrestrialization that is also reflected by a decline of *Ranunculus* subg. *Batrachium* and Characeae, the appearance of *Typha latifolia* and *T. angustifolia* and the occurrence of charcoal and fungal spores of the fire indicator *Neurospora*.

3.7.2. Zone EVT-2 (40–28 cm Depth)

Thelypteris palustris (monolete psilate fern spores) plays a role in the vegetation succession with *Carex rostrata*, *Hydrocotyle vulgaris*, *Menyanthes trifoliata*, *Silene flos-cuculi*, *Sphagnum* sp., *Polytrichum strictum*, *Campylium*, *Drepanocladus* and *Tomentypnum nitens*. This species assemblage points to mineral-rich fen. *Betula* and Pinus start to occur on the fen surface.

3.7.3. Zone EVT-3 (28–22 cm Depth)

Pinus pollen shows a maximum and various pine macrofossil (Figure 3K–T) indicate local occurrence at the sampling site. *Betula* spec., *Myrica gale, Tomentypnum nitens*, *Meesia triquetra* and *Eriophorum vaginatum* occur and Ericales and Sphagna show an increase, which points to development of mineral-poor fen. Raised bog fungi HdV-10, HdV-12, cf. *Entophlyctis lobata* (HdV-13), and *Meliola ellisii* (HdV-14) are present. The rotifer *Callidina angusticollis* (HdV-37) is also an indicator of mineral-poor conditions. In EVT-3 there is the first appearance of *Secale* and other human impact indicators show a rise: Asteraceae, Brassicaceae, Chenopodiaceae, Caryophyllaceae, *Rumex acetosella*-type and spores of

the coprophilous fungi *Podospora* and *Sordaria*. The beetle *Altica quercetorum* may indicate the nearby presence of *Quercus*, possibly in its juvenile state.

3.7.4. Zone EVT-4 (22–1 cm Depth)

In addition to the raised bog taxa mentioned for EVT-3, we recorded *Pediastrum, Myriophyllum spicatum/verticillatum, Utricularia, Piscicola geometra, Tomentypnum nitens* and *Meesia triquetra,* which point to more mineral-rich conditions. In addition, *Bolboschoenus maritimus*, Foraminifera, *Juncus gerardii, Puccinellia distans, Spergularia media/salina, Salicornia europaea, Triglochin maritima, Atriplex littoralis*-type and Dinoflagellata indicate inundation with brackish or salt water. The beetles *Pelenomus quadrituberculatus/zumpti* are halotolerant. Various human impact indicators (*sensu lato*) appear: *Agrostis*, Asteraceae, *Atriplex patula/rostrata*, Brassicaceae (pollen), *Brassica rapa*, Caryophyllaceae, Chenopodiaceae (pollen), *Chenopodium album, Chenopodium rubrum/glaucum, Euphrasia/Odontites* spec., *Fallopia convolvulus, Juncus bufonius, Papaver argemone, Plantago major, Poa pratensis/trivialis, Riccia, Sagina apetala/procumbens, Sonchus asper, Spergula arvensis* and *Stellaria media*. Puparia of Sphaeroceridae (Figure 4F–H) were observed. They commonly occur in organic refuse such as feces [57]. In the top of EVT-4 the beetle *Typhaea stercorea* was recorded. Nowadays it is often found in barns with stored products, together with *Latridus/Enicmus*.

The find of a subfossil egg capsule of the cockroach *Ectobius* (Figure 4J) in the sample at 21 cm depth is noteworthy. These only accidentally house-dwelling cockroaches currently do not occur in the lower parts of the Netherlands. The recent distribution of *Ectobius* spp. in the Netherlands is restricted to the Pleistocene and coastal sand dune landscapes, now the only areas with low nutrition levels and open vegetation types. At the site Vijzeltuin (EVT) *Ectobius* lived on the raised bog, in the open pine forest, which it prefers (pine seeds and other pine macrofossils present in the same sample).

3.8. Enkhuizen-Westeinde (EWE, Diagram in ESM3)

The radiocarbon dates at 37 and 25 + 26 cm depth (Table 3) point to inundation of the site around 900–850 cal BC. The date at 13 cm depth corresponds to the Hallstatt plateau in the calibration curve [58] and therefore it represents a very long period (ca. 350 years of uncertainty between ca. 740 and 410 cal BC) on the calendar time axis. The period of the last ca. 2500 years is not represented as undisturbed peat.

3.8.1. Zone EWE-1 (46–26 cm Depth)

Zygnema-type, *Spirogyra*, and *Mougeotia* point to shallow, stagnant freshwater. Apart from those filamentous algae *Pediastrum, Rivularia*-type (HdV-184; cyanobacteria) HdV-128A and HdV-128B also occur. *Alisma lanceolatum/plantago-aquatica, Callitriche* spec., *Glyceria fluitans, Hottonia palustris* (Figure 3B,C), *Iris pseudacorus, Lythrum salicaria, Mentha aquatica, Ranunculus sceleratus, Rorippa palustris, Ranunculus* subgenus *Batrachium, Sparganium, Stachys palustris, Oenanthe aquatica, Utricularia* spec. and *Veronica beccabunga*-type all point to a local aquatic to a semi-aquatic nutrient and mineral-rich environment. In the upper part of EWE-1 seeds of *Sium latifolium* and *Stellaria palustris* were recorded.

Local zoological aquatic taxa in zone EWE-1 are Cladocera (*Daphnia, Moina, Simocephalus*), Bryozoa (*Lophopus crystallinus, Plumatella*-type), *Diaptomus castor* and Porifera.

The insects *Ochthebius* spec, *Coelostoma orbiculare, Tanysphyrus lemnae, Hydroporus* and Trichoptera larvae also point to shallow water and *Donacia semicuprea* lives on *Glyceria* and *Sparganium*. Several ascospore types of coprophilous fungi in EWE-1 indicate a nearby presence of feces as a substrate: *Apiosordaria verruculosa, Bombardioidea*-type, *Cercophora, Podospora, Sordaria* and *Sporormiella*. *Neurospora* spores (HdV-55B/C) indicate nearby fires, and *Riccia* spores indicate moist arable land [17]. During the excavation parcellation ditches were observed below the peat deposit. The cysts of Dinoflagellata may be reworked (bioturbation) from the clayey, silty subsoil that was deposited before the Bronze Age habitation.

3.8.2. Zone EWE-2 (26–20 cm Depth)

The taxa at the start of this zone (*Cicuta virosa*, *Epilobium palustre*, *Lycopus europaeus*, *Lythrum salicaria*, *Ranunculus flammula*, *Salix* and *Solanum dulcamara*) still point to nutrient and mineral-rich local moist conditions. The beetles *Hydraena*, *Noterus crassicornis* and *Hydroporus* point to the presence of water, *Gyrinus aeratus* to sufficient surface water, *Limnobaris dolorosa* to the presence of Cyperaceae and *Plateumaris bracata* to *Phragmites australis*.

An important role in the terrestrialization of the site is played by *Equisetum* (most probably *E. fluviatile*). A declining nutrient level is indicated by *Menyanthes trifoliata*, and the occurrence of *Carex pseudocyperus*, *C. riparia*, *Pedicularis palustris* and *Potentilla palustris*, which point to mesotrophic mineral-rich fens. HdV-598 is a newly recorded microfossil that occurs in this zone. It is still unidentified and has a characteristic form and wall sculpture (Figure 4K).

3.8.3. Zone EWE-3 (20–13 cm Depth)

The vegetation succession is taken over by *Thelyptris palustris* (monolete psilate fern spores and sporangia). *Galium*-type (probably *G. palustris*), *Menyanthes*, *Rumex acetosa*-type, *Silene flos-cuculi* and finally *Betula* spec. seeds, coinciding with a maximum in *Betula* pollen, all fit in the picture of a further decline of mineral richness. *Betulapion simile* feeds on *Betula*, while *Sialis, Cyphon* and *Laccobius* indicate the nearby presence of open water.

3.8.4. Zone EWE-4 (13–3 cm Depth)

The transition from EWE-3 to EWE-4 shows a decline of fern spores, and a sudden increase of *Sphagnum,* its parasite *Tilletia sphagni*, and Ericales, together reflecting ombrotrophic bog conditions. However, there is no undisturbed bog deposit present at the site, because the samples show a mix of ombrotrophic taxa, *Pediastrum* and HdV-128A (both occur in relatively nutrient-rich freshwater) and Foraminifera, the marine mollusk *Littorina* and *Triglochin* (salt or brackish conditions; probably as a consequence of marine inundations). *Secale* and some other taxa (e.g., Asteraceae, Brassicaceae, Chenopodiaceae) reflect nearby human impact on former raised bog deposits. Some ascospores of the dung-inhabiting *Sordaria* and *Podospora* were recorded.

3.9. Grootebroek-Zesstedenweg (GBZ, Diagram in ESM3)

The radiocarbon date at 96 + 97 cm (Table 3) points to a rising water table and inundation around 1000 cal BC. The dated level at 48 + 49 cm depth shows that the vegetation succession until the ombrotrophic stage took about 1000 years. There is no undisturbed peat deposit at the GBZ-site for the last ca. 2000 years.

3.9.1. Zone GBZ-1 (113–95 cm Depth)

Zygnemataceae (*Mougeotia*, *Spirogyra*, *Zygnema*-type) indicate shallow, stagnant freshwater. Other algae of the aquatic phase are *Botryococcus* and HdV-128A and HdV-128B. The zone is further characterized by various (semi-)aquatic taxa of mineral-rich conditions: *Alisma* spec., *Bidens tripartita*, *Carex riparia*, Characeae, *Eleocharis palustris/uniglumis*, *Glyceria fluitans*, *Hottonia palustris*, *Lemna* spec., *Lycopus europaeus*, *Mentha aquatica*, *Oenanthe aquatica*, *Ranunculus* subg. *Batrachium*, *Solanum dulcamara*, *Sparganium, Stachys palustris*, *Typha, Utricularia* spec., *Valeriana* and *Veronica beccabunga*-type. *Daphnia*, *Diaptomus castor*, *Lophopus crystallinus*, *Moina* and *Simocephalus*, are the recorded faunal taxa, while Dinoflagellata and Foraminifera were probably reworked from the underlying marine sediments that were deposited before the Bronze Age habitation. The ascospores of the coprophilous fungi *Podospora*, *Cercophora*, *Sporormiella* and *Apiosordaria verruculosa* indicate feces as a substrate.

3.9.2. Zone GBZ-2 (95–75 cm Depth)

GBZ-2 is a rich-fen phase with a dominance of *Thelypteris palustris*; initially with *Carex* cf. *aquatilis*. Other taxa occurring in this zone are *Conium maculatum*, *Lythrum salicaria* and *Euphorbia* (probably *E. palustris*).

3.9.3. Zone GBZ-3 (75–49 cm Depth; the Interval between 65 and 49 cm Depth Was not Sampled)

Temporarily the filamentous algae return (*Mougeotia*, *Spirogyra*, *Zygnema*-type) in combination with HdV-128A. Seeds of *Carex rostrata/vesicaria, C. pseudocyperus*, *Epilobium palustre* and *Menyanthes trifoliata* were recorded. Macro-remains of *Betula* spec. point to the local occurrence of birches on the mire surface. *Meesia triquetra* and *Calliergon giganteum* still point to mineral-rich conditions.

3.9.4. Zone GBZ-4 (49–39 cm Depth)

Apart from birch, *Pinus sylvestris* becomes locally present, indicating oligotrophication and relatively dry conditions of the mire surface at the sampling site. *Sphagnum palustre, S.* sect. *Acutifolia, S. imbricatum, Assulina* and *Callidina angusticollis* appear, pointing to a transition to ombrotrophic raised bog conditions. Ericales pollen starts to increase, but samples 45 and 41 already show some admixture with several taxa that do not grow in an undisturbed raised bog: *Atriplex patula/prostrata, J. bufonius, J. gerardii, Potentilla anserina, Ranunculus sceleratus* and *Spergularia media/salina*. Spores of *Sordaria, Podospora* and *Sporormiella* are present; these coprophilous fungi would not appear in undisturbed raised bog deposits.

3.9.5. Zone GBZ-5 (39–1 cm Depth)

Many recorded taxa, such as Sphagna, *Aulacomnium palustre, Polytrichum strictum, Pohlia nutans, Calluna vulgaris, Eriophorum vaginatum* and *Oxycoccus palustris* indicate raised bog conditions. Various fungal taxa are well known from raised bog deposits [35]: *Anthostomella fuegiana*, HdV-10, HdV-12, cf. *Entophlyctis lobata, Meliola ellisii* (parasitic on *Calluna vulgaris*), *Tilletia sphagni*, and *Helicoon pluriseptatum*. The invertebrate taxa *Amphitrema flavum, Assulina* and *Callidina angusticollis* also form part of the raised bog ecosystem.

The substrate of GBZ-5 is raised bog peat, but it appears to be disturbed, which is reflected by the recorded taxa of relatively nutrient-rich conditions: *Anthriscus caucalis, Atriplex patula/prostrata, Chenopodium glaucum/rubrum, Hydrocotyle vulgaris, Juncus bufonius, Persicaria lapathifolia, Polygonum aviculare, Ranunculus sceleratus, Rumex acetosella, Rumex hydrolapathum, Sonchus asper, Stellaria media* and *Urtica urens*. Salt-tolerant taxa were recorded: *Bolboschoenus maritimus, Juncus gerardii, Triglochin maritima* and Foraminifera, which point to inundation with brackish or salt water.

Nearby human impact is reflected by several pollen taxa: *Secale*, increased Brassicaceae, Caryophyllaceae, Chenopodiaceae, *Persicaria maculosa*-type and *Linum usitatissimum*. We cannot exclude that GBZ-5 already represents the basal layer (12th/13th century AD) of the man-made mound.

3.10. Oostwoud (OWD, Diagram in ESM3)

The radiocarbon dates at 68 and 61 cm level (Table 3) show that the start of the deposition of gyttja and subsequent peat growth at the Oostwoud site occurred around 1650 cal BC. The date at 29 cm shows that the peat deposit is undisturbed only until around 750 to 550 cal BC (Hallstatt plateau in the radiocarbon calibration curve [58]).

3.10.1. Zone OWD-1 (86–66 cm Depth)

From 86 to 66 cm depth some macrofossils were recorded in the sandy clay, but the concentration of microfossils was too low, and the preservation was too bad for reliable quantification. Seeds of *Juncus effusus*-type, *J. articulatus*-type, *J. bufonius*, *Carex riparia*, *Chenopodium polyspermum*, *Potentilla*

spec., *Rumex* spec. and *Solanum nigrum* were preserved in the sandy substrate. In the upper part of OWD-1 *Carex otrubae/vulpina*, *Hypericum tetrapterum*, *Mentha aquatica/arvensis* and *Urtica dioica* occur.

3.10.2. Zone OWD-2 (66–60 cm Depth)

This zone represents the transition from soil to peat-forming wetland vegetation with *Eupatorium cannabinum*, *Lycopus europaeus*, *Lythrum salicaria*, *Typha angustifolia*, *T. latifolia* and the algae *Spirogyra*, HdV-128A and HdV-128B.

In OWD-2 and at the transition to OWD-3, *Ranunculus lingua*, *Ranunculus* subg. *Batrachium*, *Carex rostrata*, *C. pseudocyperus*, *C. disticha*, *Menyanthes trifoliata*, *Pedicularis palustris*, *Sium latifolium*, *Stellaria aquatica*, *S. palustris* and the bryophytes cf. *Amblystegium* and cf. *Drepanocladus* occur, with aquatic invertebrates Trichoptera, *Lophopus crystallinus* and *Simocephalus*. Spores of *Riccia* may indicate damp arable land, while *Sporormiella* and *Sordaria* need feces as a substrate. *Neurospora* ascospores are stratigraphically and ecologically linked with macroscopic charcoal (diagram in ESM-3). Dinoflagellata and Foraminifera probably represent some bioturbation from the marine subsoil.

3.10.3. Zone OWD-3 (60–51 cm Depth)

Thelypteris palustris becomes a dominant species and it is growing together with *Lotus*, *Lythrum salicaria*, *Menyanthes trifoliata*, *Pedicularis*, *Potentilla*-type, *Carex rostrata* and *C. acuta*-type, which point to mineral-rich fen. The presence of *Mougeotia* spores shows that temporary shallow stagnant freshwater still prevailed, probably in springtime when the spores were formed.

3.10.4. Zone OWD-4 (51–27 cm Depth)

This zone shows high proportions of *Thelypteris palustris*, with *Betula*, *Carex rostrata*, *Epilobium palustre*, *Menyanthes trifoliata*, *Pedicularis* (probably *P. palustris*), *Rumex acetosella*-type (probably *R. acetosa*), *Silene flos-cuculi* and *Calliergon* cf. *giganteum*, which still point to mineral-rich fen. Spores of *Mougeotia* indicate temporary shallow, stagnant water. Spores of the desmids *Closterium idiosporum* and *C.* cf. *rostratum* mark the transition to the ombrotrophic conditions of OWD-5.

3.10.5. Zone OWD-5 (27–22 cm Depth)

Ericales (among which *Erica tetralix*), *Eriophorum vaginatum*, *Aulacomnium palustre*, *Polytrichum*, *Sphagnum imbricatum* and fungi known from ombrotrophic raised bogs (*Anthostomella fuegiana*, HdV-10, HdV-12, cf. *Entophlyctis lobata*, *Meliola ellisii*, *Tilletia sphagni*) form part of the original ombrotrophic vegetation.

The peaty substrate is mixed with indicators for nutrient and mineral-rich conditions and human impact indicators: Cerealia, *Atriplex patula/prostrata*, *Cerastium* spec., Chenopodiaceae, *Chenopodium glaucum/rubrum*, *Glyceria fluitans*, *Juncus bufonius*, *Persicaria maculosa*-type, *Poa pratensis/trivialis*, *Ranunculus sceleratus*, *Stellaria media* and *Sporormiella*, while *Pediastrum*, and *Plumatella*-type indicate relatively nutrient and mineral-rich freshwater. *Spergularia media/salina*, *Juncus gerardii* and Foraminifera point to inundations with brackish or salt water.

3.11. Venhuizen-Elbaweg (VEL) and Venhuizen-Spuiter (VSP)

During excavations at the sites Elbaweg and Spuiter, profiles of the "Westfriese Omringdijk" (Late Medieval dike for protection against the sea) were made and a compacted, ca. 15 thick peat layer, below the oldest, medieval layer of the dike was sampled at both sites, including the layers below and above the peat layer. The sampled sediments below the peat layer consisted of sandy clay, and therefore the microfossil contents have a predominantly allochthonous, marine origin, mixed with pollen of upland taxa. The peat layers (zones VEL-2 and VSP-2) were formed by local peat-forming plants. The sampled sediments deposited on top of the peat had been collected and transported to the sampling site as sods by late Medieval people when constructing the first dike. That dike-material was

also built up of sandy clay, but without an orderly stratigraphy. At the site Elbaweg a second, ca. 3 cm thick horizontal organic layer, situated about 35 cm above the peat layer, showed a stagnation phase in the history of dike building (see below, assemblage zone VEL-4).

3.12. Venhuizen-Elbaweg (VEL, Diagram in ESM3)

The two radiocarbon dates (Table 3) at the base (68–70 cm depth) and the top (53–54 cm depth) of the peat layer show that peat growth (zone VEL-2) started between ca. 750 and 450 cal BC and continued to accumulate until about 400 cal AD.

3.12.1. Zone VEL-1 (99–74 cm Depth)

The sediment (sandy clay) of this zone is characterized by microfossils indicating marine conditions (relatively high percentages of Chenopodiaceae and Dinoflagellata) and freshwater algae (*Pediastrum*, *Botryococcus*, *Mougeotia*, *Spirogyra*, other Zygnemataceae and HdV-128A).

3.12.2. Zone VEL-2 (74–52 cm Depth)

A peak of *Salix* pollen at the base of the peat deposit represents the first local carr vegetation, followed by high percentages of *Alnus* pollen. Willow and alder represent local wet, nutrient-rich conditions. *Oenanthe aquatica*, *Urtica dioica*, *Lemna* spec. (seeds and pollen) and the aquatic invertebrates *Lophopus crystallinus* and *Simocephalus* were also recorded in the peat layer. The upper few centimeters of the peat layer show a peak of *Betula* that indicates a decline of available nutrients, due to isolation from the mineral soil.

3.12.3. Zone VEL-3 (52–19 cm Depth)

The mineral sediments on top of the peat show some freshwater algae, Chenopodiaceae (*Chenopodium glaucum/rubrum*; *Atriplex patula/prostrata*), Foraminifera, *Juncus gerardii* and human impact indicators (*sensu lato*) like *J. bufonius*, *J. effusus*-type, *Ranunculus sceleratus* and *Stellaria media*.

3.12.4. Zone VEL-4 (19–16 cm Depth)

The thin organic layer of VEL-4 shows a peak in Poaceae (together with fruits of *Phragmites australis*), *Plantago major* and a considerable number of spores of coprophilous fungi: *Sordaria*, *Sporormiella*, *Cercophora*, *Apiosordaria verruculosa* and *Podospora*. We suppose that VEL-4 represents a stagnation phase in dike accumulation, while the large number of spores of coprophilous fungi shows that the first, low dike was grazed by herbivores.

3.12.5. Zone VEL-5 (16–5 cm Depth)

The spectra of microfossils and macro-remains have much in common with zone VEL-3.

3.13. Venhuizen-Spuiter (VSP, Diagram in ESM3)

The radiocarbon date at the base of the peat layer (Table 3) shows that peat growth started, like at the site Elbaweg, between ca. 750 and 450 cal BC. Plant remains from a small filled up depression (ditch) that disturbed the peat layer of zone VSP-2, were dated around 500 cal AD.

3.13.1. Zone VSP-1 (43–30 cm Depth)

The sandy clay sediment of this zone is characterized by microfossils indicating marine conditions (relatively high percentages of Chenopodiaceae and Dinoflagellata) and freshwater algae (*Pediastrum*, HdV-128A and HdV-128B).

3.13.2. Zone VSP-2 (30–21 cm Depth)

This zone represents the peat layer. *Alnus* shows relatively high percentages, indicating that the peat was formed by an alder carr, with local Apiaceae, *Potamogeton/Triglochin* and ferns.

3.13.3. Zone VSP-3 (21–1 cm Depth)

The sediments on top of the peat show freshwater algae (*Botryococcus*, Characeae, *Pediastrum*, *Spirogyra*, and HdV-128A and HdV-128B and *Hippuris vulgaris*), but also salt-tolerant and marine taxa (*Juncus gerardii*, Foraminifera, cysts of marine Dinoflagellata and Chenopodiaceae).

4. Discussion

4.1. Forest in West-Frisia during Late Bronze Age? (Research Question 1)

Van Amerongen [6,12] challenged the paradigm of an almost treeless landscape in West-Frisia during the Bronze Age. She suggested that there may have been a considerable forest cover: *Alnus* carrs in wetlands, *Fraxinus-Ulmus* forests at drier sites and grasslands in the relatively high and dry areas. In addition, van Zijverden [7] supposed that lakes, marshy grasslands and dry arable fields alternated with patches of woodland, shrubs and even with riparian *Fraxinus* and *Quercus* forest.

If forest would have been present during the late Bronze Age, then one could expect evidence for drowned forest at our sites. Local forest would have been reflected by high tree pollen percentages and we would expect clumps of tree pollen [59] that we did not observe. We also would expect arboreal fruits/seeds, and tree roots in the upper soil just below the shallow lake sediment that we found at most of the sites. We did not find such evidence. In other words: our samples representing the Late Bronze Age do not point towards a forested landscape, apart from willow and birch carr around the freshwater lake Klokkeweel [11].

We suppose that people with their domesticated herbivores will have hampered the immigration of tree species because of grazing pressure starting after the marine phase at the moment that the area became habitable for plants, for people and for domesticated and wild herbivores. We have no evidence for local tree growth on dry soils before the recorded rise of the groundwater and therefore we do not accept the hypothesis of van Amerongen [6,12] and van Zijverden [7] about forested areas in West-Frisia during the Bronze Age.

4.2. Rise of Groundwater and Climate Change (Research Question 2)

Van Amerongen [6] and van Zijverden [7] argued against the hypothesis that abrupt climate change and the consequent sudden rise of the groundwater table caused the depopulation at the end of the Bronze Age in eastern West-Frisia [14,15]. The hypothesis was mainly based on the radiocarbon dated site Enkhuizen-dijk and on the youngest archaeological Bronze Age dates of West-Frisia, and a link was made with the transition in raised bogs, elsewhere in The Netherlands, from "Older Sphagnum peat" to "Younger Sphagnum peat" at the start of a steep rise of Δ^{14}C around 850 cal BC (2.8 event). Martin-Puertas et al. [60] and van Geel et al. [16] found strong additional evidence for a link between a steep rise of Δ^{14}C starting around 850 cal BC and abrupt climate change to cooler and wetter conditions. The present study shows that inundation of most of our sites in eastern West-Frisia (ELT, EPK, ERS, EVT, GBZ; all in the Enkhuizen area) already started centuries before 850 cal BC, i.e., between 1300 and 1000 cal BC (Figure 6). A gradually rising sealevel apparently caused a rise in ground water [61], and the amount of shallow pools to increase. This hydrological change finally made eastern West-Frisia inhabitable around 800 cal BC. A short-term climate-related rise in ground water at 850 cal BC may have occurred; however, it seems that this was super imposed on a longer-term rise in ground water indicated by the process of paludification that had already been going on for several centuries. The hypothesis suggesting that solar forcing caused abrupt climate change around cal 850 BC is therefore not clearly tested with these data, because the impact of this event may, or may not, have been overridden by ongoing sealevel rise. However, we observe that by cal 850 BC all study sites

contain sediments indicative of shallow lake environments, suggesting that by this time the transition to wetlands across West-Frisia may have been given final impetus by the climatic shift. The first freshwater inundations of the sites Berkhout and Oostwoud are much earlier (respectively ca. 2550 cal BC and ca. 1650 cal BC) but those sites are relatively far away from the sites in and near Enkhuizen.
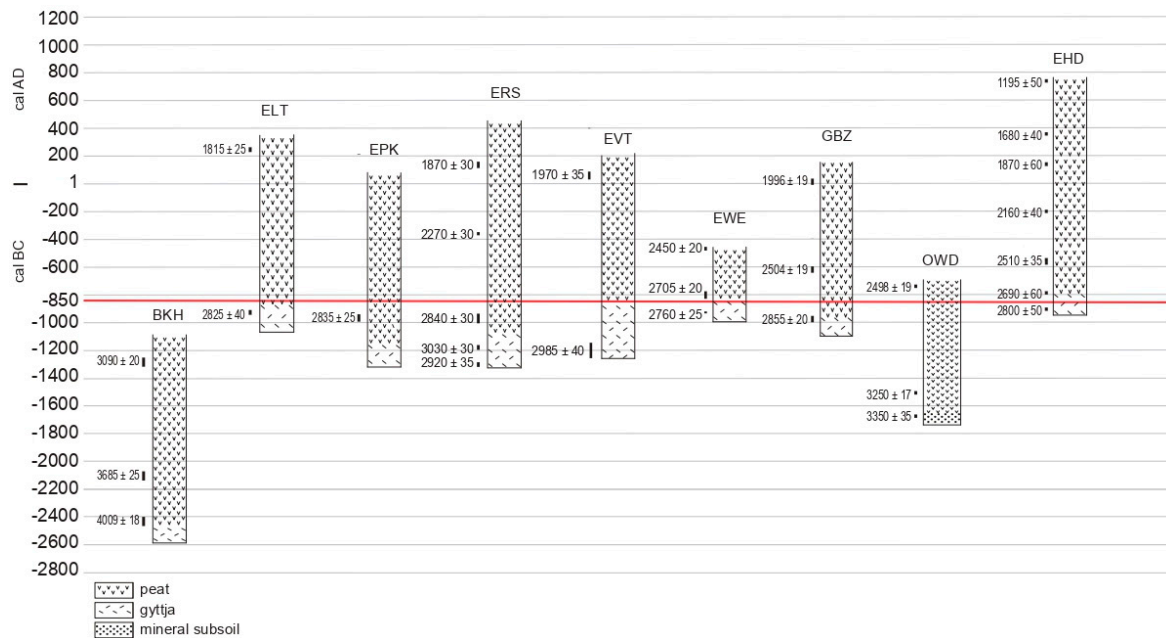

Figure 6. The base of the organic accumulation (gyttja and subsequently peat) at the sites Berkhout (BKH), ELT, EPK, ERS, Enkhuizen-Vijzeltuin (EVT), EWE, GBZ, Oostwoud (OWD) from this study and Enkhuizen-Dijk (EHD [17]) along a calendar time axis. The conventional radiocarbon ages (in BP) are indicated at the most probable calendar time position. The red line indicates 850 cal BC, and the illustration shows that at several sites inundation already started before 850 cal BC.

4.3. Medieval Start of Peat Land Reclamation and Settlements (Research Question 3)

Based on archaeological evidence in the Netherlands, Heidinga [62] supposed that the trigger for medieval reclamation of wetlands in the western Netherlands was a dry 10th century AD, and therefore population density pressure in the areas of sandy soils. Wetlands were available for reclamation, but we emphasize that not all wetlands on top of peat deposits could be sufficiently drained to allow reclamation. The suitability for artificial drainage and reclamation was determined by the water table position and the vegetation type. In wetland vegetation successions we often see a trend starting with plant species that require contact with the mineral subsoil that moves towards species that prefer mineral-poor conditions. During the vegetation succession the peat deposit increased in thickness and the roots lost contact with the mineral subsoil and the peat-forming vegetation became more and more dependent on rainwater.

There are strong indications that in most of our studied cores there is a hiatus between the medieval anthropogenic accumulation layer and the underlying natural peat deposit. At site EVT the age difference of ca. 1000 calendar years between the two upper radiocarbon dates illustrates this. Some upper peat will have disappeared because of oxidation, and even peat digging may have played a role. In spite of this complication, at ten of our sites we found that the recorded natural vegetation succession continued and probably ended with a stable phase with *Sphagnum*, *Betula* and three sites even with *Pinus* in the local vegetation. In acid raised bogs dominated by *Sphagnum*, the net organic production and therefore peat accumulation increased, and the mires became raised bogs where the Sphagna, with their extremely high-water storage capacity [63], caused groundwater tables to rise above the regional water tables in mineral soils. Therefore, the raised bogs were relatively easy

to drain by people, as after drainage initially their surface will have been still above mean sea level and also above water tables in adjacent mineral soils. We hypothesize that drainage and reclamation became possible only when the mires had reached the raised bog stage. Drainage of the preceding fen vegetation would have failed because after drainage the peaty soil surface would have been too wet to be turned into arable land or meadows. In other words: during a long period after the Bronze Age the local conditions were too wet for people to settle. The late Medieval farming communities could reclaim raised bogs (still without windmills and without dikes) with drainage ditches. An argument against our hypothesis (medieval settlement on raised bogs only) would be that oligotrophic conditions would hamper the growth of crop plants and also domesticated large herbivores would not thrive (grazing plants with low nutrient quality) in a newly reclaimed ombrotrophic bog and that would make life for farmers rather complicated. Natural drainage, compaction of peat and temporary inundations may have occurred and in that way mineral-poor peat deposits became fertilized with clay. In other words: we cannot exclude that water streams after storm surges triggered extra natural drainage (new gullies in the raised bogs), thus bringing minerals and nutrients for plants and therefore facilitating the start of human habitation. Natural drainage, erosion and oxidation (more available nutrients) may well have occurred before the arrival of the farmer communities. The hiatuses between undisturbed upper peat layers and the first anthropogenic accumulation layers make it difficult to find detailed answers to this question.

4.4. Human Impact and Increasing Marine Influence in West-Frisia

Indicators for salt marsh and marine conditions, such as *Juncus gerardii* and Foraminifera in the upper peat layers, just below the medieval accumulation layers were probably mixed by bioturbation and reworked by human action. The presence of salt marsh indicators together with freshwater indicators at our West-Frisian sites suggests that the raised bogs were temporarily flooded with brackish or salt water. This happened during storm surges [64,65] when many peat deposits in the northern Netherlands were eroded and the freshwater basin of Almere increased in size and gradually developed to the saltwater basin Zuiderzee [5]. Van Popta et al. [66,67] examined the dynamic cultural landscape of the north-eastern Zuiderzee region, ca. 23–50 km east of Enkhuizen, in the period AD 1100–1400. The cultivation of land and marine erosion of peatlands (floods and rising sea level) were considered as the main factors that caused the transformation of large parts of the landscape in the central Netherlands, from peatlands with freshwater basins into the tidal lagoon Zuiderzee. The southwestern part of the present province of Frisia (Friesland) became disconnected from West-Frisia. Reclamation and related compaction and oxidation of peat turned against the farmers, as it caused rapid erosion during storm surges. In a few centuries, large peatlands in the north-eastern Zuiderzee region [66] and in the area between West-Frisia and Frisia disappeared as a consequence of the eroding power of the Zuiderzee [5]. Residents of the coastal zones were struck by the many floods, as cultivated land was washed away, complete settlements were inundated and eroded, and thousands of people drowned [66].

Van Smeerdijk et al. [68] studied the botanical composition of samples from three chronologically successive medieval artificial mounds (terp) at Diemen, near Amsterdam, and reconstructed the increasing role of salt water in late medieval time. The authors recorded freshwater conditions for the oldest terp, followed by brackish conditions for a terp that had been built in the last part of the 12th century AD, while a 14th century terp even consisted of marine clay sods. Our West-Frisian sites show evidence for inundations from the sea before the terps were built. The Diemen sites, however, were located much more to the south (less and later marine influence) and the palaeoecological registration of the gradual salinization of the landscape at Diemen was possible due to different successive ages of the three terp sites.

4.5. Forest and Toponyms

At present, there is no natural forest in West-Frisia, but there is toponymic evidence for late medieval presence of forest and brook forest when villages were founded on the peat deposits. Names of several existing villages point to forest (-hout or -woud), or carr woodland (-broek): Berkhout, Schellinkhout, Aartswoud, Hoogwoud, Nibbixwoud, Oostwoud, Midwoud, Westwoud, Oudeboxwoude, Scharwoude, Hensbroek, Spanbroek, Benningbroek, Broek op Langedijk, Grootebroek. We suppose that artificial drainage of the raised bogs will even have facilitated germination and expanded growth of birch and pine, and the founders of villages will have experienced the West-Frisian landscape, or parts of the landscape, as forest.

4.6. Relevance for Management of Wetlands (Research Question 4)

Palaeoecological data can provide a valuable long-term perspective on contemporary ecosystem dynamics [2,3,69] but are not fully utilized in conservation management [70]. The present study is of interest for nature management of wetlands. Knowledge about the duration of the successive vegetation phases from shallow, mineral-rich freshwater to ombrotrophic *Sphagnum* bogs is useful, although duration depends on the local hydrological situation and climate [71]. In most of our West-Frisian cores, development of the vegetation followed the normal succession patterns in fresh water. Vegetation development started with shallow open water and aquatic species such as *Lemna*, followed by a rich-fen stage with semi-terrestrial species such as *Equisetum*, *Menyanthes trifoliata*, *Carex* spp., *Mentha aquatica* and *Thelypteris palustris*. In general, these vegetation patterns are also found today [4]. However, bryophytes such as *Tomentypnum nitens*, *Meesia triquetra* and *Paludella squarrosa*, which were present in several of our sequences, do not occur in the Netherlands anymore [45]. They are still common in fens in Scandinavia, but have strongly decreased in other European countries. At some of our sites, the seepage of calcium and iron-rich groundwater probably played a role in the rich-fen stage, especially the ones with mosses such as *C. giganteum, T. nitens* and *P. squarrosa* [55,56]. When the peat layer became thicker, this mineral-rich groundwater did not reach the surface layer anymore.

At most of our sites the rich-fen stage was followed by *Sphagnum*-dominated poor fen, bog forest with *Betula* and *Pinus* and raised bog with *Calluna vulgaris* and *Erica tetralix*, following present day analogs [4]. More minerotrophic carr with *Alnus glutinosa* were only present at the VEL and VSP sites. Development of *Sphagnum*-dominated bogs means that peat growth could keep pace with rising mean sea water tables, and the raised bog vegetation even continued to grow above the regional groundwater tables outside the bog area.

Terrestrialization stages of mire vegetation are important to northwest European nature conservancy because of high biodiversity, particularly of mineral-rich fens. Based on macrofossils and microfossil analysis Faber et al. [4] reconstructed vegetation successions in two former turbaries in the Netherlands. For both sites, the establishment of mineral-rich fens took about 60 years, and that vegetation type only remained for about 30 years before it was followed by Sphagna and other species of ombrotrophic conditions. On a landscape scale, succession from open water to raised bog may take more time [71]. Based on radiocarbon dates the duration of the West-Frisian vegetation successions from shallow freshwater to mineral-poor bogs was between 1000 and 1500 calendar years. This is comparable with succession rates in peatlands in northern Canada [71], but rather long compared with late Holocene *Sphagnum* peat found directly on podzolic soils in the eastern Netherlands and Germany [63]. Fen to bog transitions may be influenced by internal factors such as local hydrology, and external factors related to climate change. Although thickness of the fen peat differed between our sites from 23 to 74 cm, the succession patterns and periods were remarkably similar. This suggests that the general rise of the (sea) water level was more important than local hydrology. The relatively long duration of the wetland succession phases in West-Frisia compared to paludification of podzolic soils in the eastern part of the Netherlands is linked to the initial situation. Podzolic soils have formed in sandy parent material, which has low buffer capacity to acidification. The clayey soils of western Frisia

are however highly buffered and nutrient-rich, and even additionally enriched in nutrients by people and their domesticated animals during the Bronze Age.

Another example of knowledge obtained with palaeoecological methods is the answer to the question about extinction, or survival, of *Pinus sylvestris* in northwest Europe in the late Holocene [70,72]. See also Jamrichová et al. [73] for pine in Central Europe. We observed macro-remains of *Pinus sylvestris* (needles, seeds, periderm, roots, combined with relatively high pollen percentages; Figure 3K–T) in the early raised bog zones ERS-4, EVT-3 and GBZ-4. These pine records from West-Frisia date about 2000 years ago. Pals et al. [11] in their study of the nearby Klokkeweel site (Figure 1) dated a local wetland pine phase between ca. 900 and 800 cal BC and Brinkkemper [74] mentioned pine cones from roughly the same period in peat deposits in the southwestern part of the Netherlands. We conclude that pine was still present in the Netherlands during the late Holocene, like in northwest Germany [63], at least the presence of pine is established in mineral-poor bogs.

The succession patterns in the West-Frisian bogs are also important for the future, and potential effects of increased sea levels with global climate change. Inundation of the Bronze Age cultural landscape began around 1000 BC, when sea levels were approximately 2 m lower than today. After inundation, the wetlands of our study needed 1000–1500 years to develop from open ponds into raised bog, and the wetland surface continued to rise with the water table. However, with global climate change, sea level may rise to 3 m above the current level within the coming century. For the development of raised bogs, which may grow up with the water table, this is way too fast.

5. Conclusions

Van Amerongen [6,12] and van Zijverden [7] challenged the model of an almost treeless landscape in West-Frisia during the Bronze Age settlement period. If forest had been present during the late Bronze Age, then we would have found evidence for submerged forest at our sites. Our samples representing Late Bronze Age lack such evidence and therefore we do not accept the hypothesis of van Amerongen and van Zijverden about forested areas in West-Frisia during the Bronze Age. We suppose that people with their domesticated herbivores will have hampered the immigration of tree species because of grazing pressure when the area became accessible.

We reconstructed the start of freshwater inundation and successive peat growth in eastern West-Frisia and we found that, at the majority of our sites, inundations already started several hundred years before 850 cal BC. We suggest that solar forcing of climate change may have delivered the final push to the inundation and depopulation of West-Frisia which had already commenced several centuries before, due to sealevel rise.

We hypothesize that medieval drainage and reclamation became possible only when the mires of West-Frisia had reached the raised bog stage.

Our study is of interest for nature management of wetlands. The duration (between 1000 and 1500 calendar years) of the successive vegetation phases, from shallow, mineral-rich freshwater to ombrotrophic *Sphagnum* bogs may be used as a reference for newly created wetlands under eutrophic conditions.

Non-pollen palynomorphs, especially spores of fungi and Zygnemataceae were valuable indicators for the reconstruction of changing local environmental conditions.

vegetation successions. B.v.G. wrote most of the manuscript, and W.D.G. revised and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Appendix A. Some Remarks about the Ecological Indicator Value of Non-Pollen Palynomorphs (NPP) in the West-Frisian Cores

A.1. Fungi of Mesotrophic and Oligotrophic Conditions

Based on our data (fruits, seeds, pollen and fungi) it is evident that peat that was formed in mesotrophic conditions was characterized by specific fungal spore types: HdV-123, cf. *Persiciospora* (HdV-124) and *Coniochaeta* cf. *ligniaria* (HdV-172). *Clasterosporium caricinum* (HdV-126) was already linked in earlier studies to the local presence of *Carex* species [11,36,38] and in the present study this link is obvious again.

NPP-taxa that we know from ombrotrophic raised bog peat [35] appeared to be valuable indicators for ombrotrophic conditions in the present project, especially *Anthostomella fuegiana* (HdV-4), HdV-10, HdV-12, cf. *Entophlyctis lobata* (HdV-13), *Meliola ellisii* (HdV-14; a parasite on *Calluna vulgaris*) and *Tilletia sphagni* (HdV-27; a parasite on *Sphagnum*). Shumilovskikh et al. [59] also used NPP for a detailed study of changing environmental conditions in a Holocene succession from fen to raised bog.

A.1.1. *Neurospora* the Fire Indicator

Based on observations of longitudinal grooves in some HdV-55B ascospores in our West-Frisia study (Figure 4M–Q), those spores were identified in the present study as *Neurospora* spec. (compare HdV-55C in [35]. The spores appeared to be linked with local fires (carbonicolous; co-occurrence with charcoal, see Berkhout diagram, ESM2 and Oostwoud diagram in ESM-3). Based on the spore morphology and the ecology, the HdV-55B spores and HdV-55C spores [35] were merged in the present study as "*Neurospora* (HdV-55B/C)". The presence of these spores can be used as an indicator of local fire [35,75].

A.1.2. Coprophilous Fungi

Spores of coprophilous fungi, especially *Sporormiella*, *Podospora*, *Sordaria* and *Apiosordaria verruculosa* are valuable paleo-environmental indicators for the nearby presence of feces [36]. Such spores were frequently recorded in our samples representing the Late Bronze Age, when settlements of farming communities were present in West-Frisia. They also occurred in the upper samples of the cores, representing local medieval habitation on top of the peat deposits.

Based on the presence of palynological human impact indicators (spores of coprophilous fungi included), the sites BVK, ELT, EPK, ERS, EVT, EWE, GBZ and OWD showed evidence for nearby human impact during the Bronze Age with the exception of the BKH site. When we compare this with the archaeological information (Table 1; evidence for local human presence at BVK, EWE and OWD only) it seems that the microfossils show human impact, or at least the presence of large herbivores and their feces, maybe in a better way than the strictly archaeological excavation results at our sites.

A.1.3. Zygnemataceae

Ecological knowledge about individual zygnemataceous species is limited [76]. In general, Zygnemataceae occur in stagnant, shallow water. Based on our paleo-data we can obtain some

additional information. When we compare the curves of *Mougeotia* spores with the spore curves of *Spirogyra* in the diagrams of BVK, ELT, EWE and OWD, it seems that, in the process of a declining nutrient availability (declining influence of mineral-rich groundwater) *Mougeotia* species are able to stay longer (in more nutrient-poor environments) than the *Spirogyra* species.

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