Peatland restoration based on a landscape (palaeo)ecological system analysis (LESA): the case of Aamsveen, eastern Netherlands

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SUMMARY

The Dutch Aamsveen lies in a glacial basin in the Dutch-German border area. It consists of remnants of a cross-border raised bog and a lagg with degrading species-rich basiphilous plant communities. Farther west, the Glanerbeek drains the footslope at the edge of the basin and adjacent lagg. For the Netherlands, this is a rare wetland ecosystem and an important Natura 2000 area, but it is threatened by ongoing degradation. A spatiotemporal landscape ecological system analysis (LESA), including extensive palaeoecological research, showed the fundamental role of the interplay between infiltrating acid bog water that gradually acquires basic cations from the underlying base rich sediments as it flows laterally towards the lagg, where it seeps up, and the (lesser) influx of base rich surficial groundwater from the ice-pushed ridge in the west. Anthropogenic disturbance of this interplay has led to serious system degradation. The results of this LESA served to develop an integrated management plan at landscape level, instead of habitat level plans as is usual in the context of Natura 2000. This study illustrates the relevance of a spatiotemporal LESA for the recovery and sustainable management of such complex, dynamic systems.

KEY WORDS: lagg, nature management, palaeoecology, raised bog

INTRODUCTION

In The Netherlands, peat extraction was a major cause for the gradual reduction of the raised bog areas that once covered large tracts of the country. A second cause was their reclamation for agricultural purposes, notably the cultivation of buckwheat and grazing. Ultimately, only a few raised bogs systems with their specific flora and fauna remained, mostly in remote and less populated areas (Joosten *et al.* 2017). Today they are valued as wetlands with a very specific flora and fauna, protected by national and international conventions and networks such as Ramsar and Natura 2000. In addition, they are increasingly valued as natural carbon sinks and protected because of their large carbon stocks, as compared to other ecosystems.

The Dutch Aamsveen and adjacent German Amtsvenn - Hündfelder Moor together form the still impressive remnant of a major raised bog system in the western part of a large N–S oriented glacial basin (Figure 1), in between the Dutch town Enschede and the German town Gronau. The Dutch part consists of two main units: a raised bog remnant, to the east; and its former lagg with originally basic mire types, to the west. They are separated by the Middenpad, an old dirt road that runs along a low cover sand ridge (Figures 1 and 2). Farther west, the Glanerbeek runs along the foot of the ice-pushed ridge bordering the basin, draining the footslope and adjacent lagg. In The Netherlands, such bog landscapes with basic mires are particularly rare. The Korenburgerveen and the Wooldse Veen, also in the east of The Netherlands and situated in glacial basins, are the only other comparable systems (Jansen *et al.* 2019a).

The Aamsveen - Amtsvenn - Hündfelder Moor reached its largest dimensions in the 17th century. Significant exploitation of the peat and reclamation for agriculture (buckwheat cultivation) started in the early 19th century, but negative effects remained limited and the area was still noted for its highly varied lagg vegetation. This changed in the early 20th century, which brought the industrial exploitation of peat and larger scale reclamation. The first conservation and restoration attempts dated from the early 1990s and until recently were focused on individual species or habitats in their present state (e.g., Natura 2000, Habitats Directive). Thus, within Natura 2000, the ombrotrophic raised bog, the groundwater-fed zone next to it (the lagg), along with the Glanerbeek and rare plant and animal species therein, were considered virtually independent of each other, with the bog being held responsible for acidification of the groundwater-fed edge. Hence, for the various landscape units and their endangered flora and fauna, individual regimes of conservation measures were defined. These were neither integrated into a coherent vision of the potential future functioning of this complex landscape, nor based on a thorough understanding of its complex

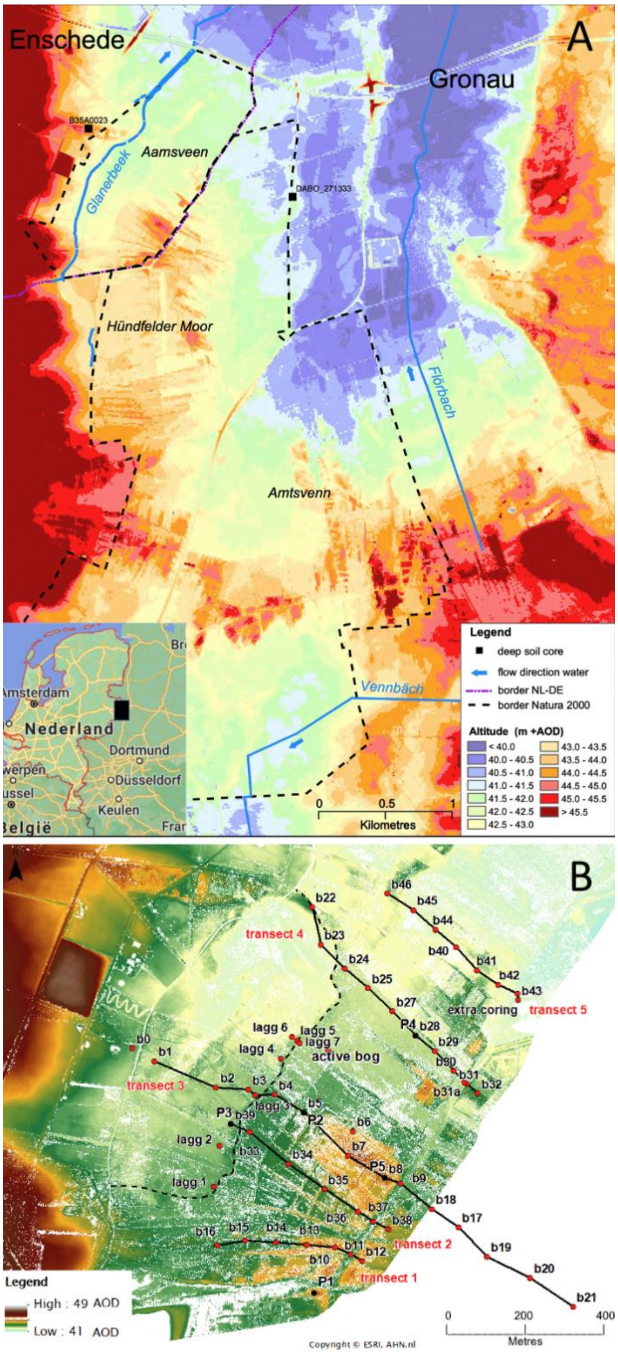


Figure 1. (A) Location and altitudinal map of the Aamsveen and Amtsvenn-Hündfelder Moor in the Dutch-German border area; (B) topography of the Aamsveen (from the Dutch AHN elevation map) with locations of transects and corings. The Middenpad is indicated by ------.

origin and functioning. A typical example was the recent plan for 'brook restoration' of the Glanerbeek (Waterschap Vechtstromen), which erroneously considered the brook to be natural and in fact negated its influence on the supply of base rich groundwater from the ice-pushed ridge into the lagg.

In recent years it was increasingly realised that fundamental insight into this past and current functioning would be required to establish what integrated measures and management could result in the sustainable conservation and restoration of a peat-forming bog and its associated lagg (Jansen & Grootjans 2019). This was the main goal of the Natura 2000 management plan. It led to the ultimate conclusion that a restoration plan was required for the whole of the Aamsveen area, based on a thorough spatiotemporal ecosystem analysis (see, e.g., Turner 1990), which identifies the conditions required and measures to be taken to restore this system. In The Netherlands it is often described as an ecohydrological analysis (Wassen & Grootjans 1996) or landscape ecological system analysis (LESA; Van der Molen *et al.* 2011).

The functioning of the current degraded system had already been described by Bell *et al.* (2016). However, this study did not touch upon the conditions under which peat formation started and continued over time, nor paid attention to the associated changes in ecohydrological functioning of the system and the potential for its restoration based on a thorough understanding of the system at landscape level.

This article incorporates the results of a later study that addressed these gaps via systematic observations on soils and sediments along transects through the area and the palaeoecological study of several sediment cores, supported by a series of ^{14}C datings (see Bell *et al.* 2018). It translates the information collected in that study into a full spatiotemporal LESA, critically addresses the approach of earlier studies in support of the Natura 2000 management programme, and discusses the relevance of LESA. The current vegetation and hydrology have already been dealt with extensively by Van Mullekom *et al.* (2016), Bell *et al.* (2016, 2018) and Jansen *et al.* (2019b) and are, therefore, only briefly summarised in the description of the study area.

The first concern of this article is the spatiotemporal dynamics of the Aamsveen system. We focus on the phases in development of the system and on the functional relationships between its various components over time. Basic data from the palaeoecological study and systematic corings which were used to identify these phases and relationships are presented and extensively discussed in the

Supplement (available for separate download). We then consider the implications of the spatiotemporal LESA for the future management of the area. At a more general level, our study serves to illustrate the added value of such analysis for the conservation and restoration of complex peatland ecosystems.

STUDY AREA

Geology

Van Huissteden (1990) provided a detailed overview of the geology of the area (for his geological map, see Figure S1 in the Supplement). Additional information comes from the 1:50.000 geological map, sheet East/Glanerbrug (34O/35) (Van den Berg *et al*. 2000). In the west, the former cross-border raised bog landscape of the Aamsveen and Amtsvenn-Hündfelder Moor is bound by the ice-pushed ridge of Oldenzaal-Enschede-Alstätte. The basin extends far into Germany, where its eastern and southern borders are formed by a series of low ice-pushed hills. Overall, the deeper subsoil consists of fine textured, calcareous, and impermeable Cretaceous and Tertiary rocks. Over most of the basin, these are covered by a layer of Saalian till that consists of a mixture of local bedrock (mostly clayey Tertiary rock) and glacial erratics, enabling its identification as till. The thickness of the till layer varies, and transitions between in-situ bedrock and till are gradual. Younger Pleistocene sediments covering the till are found on the slopes of the ice-pushed ridge and hills, and in the basin. They consist of Saalian fluvioglacial and Weichselian fluvial and sandy aeolian deposits. Holocene deposits dominantly consist of *Sphagnum* peat and some fluvial deposits along the small brooks Glanerbeek and Flörbach.

The thickness of the post-Saalian mostly sandy and permeable clastic sediments covering the impermeable till and older rocks increases to the east. The cross sections (Figures 2 and 3) illustrate this trend and additionally show the seasonal variation in the groundwater levels in the peat and sandy subsoil, respectively. This peat groundwater can be described as perched water with a poorly permeable gyttja layer at its base. The thick layer of boulder clay and Tertiary clay forms the practically impermeable hydrological base of the system, while the intermediate sand layer forms a thin aquifer.

Condition and management history

Unlike many bogs in The Netherlands, the cross-border raised bog landscape of the Aamsveen remained relatively untouched until the early 20th century, when it was rapidly transformed into a fragmented landscape of bog remnants intersected by deeply excavated areas. The original small brooks, the Glanerbeek in the west and the Florbach in the east, both running towards the Dinkel river in the north, were extended and deepened to improve the drainage of the whole area, and an intricate system of small canals and ditches was constructed to drain the lagg and raised bog. In the west, parts of the lagg were conserved (although strongly desiccated), but most of the lagg was turned into agricultural land. Because of the improved drainage, the influx of base

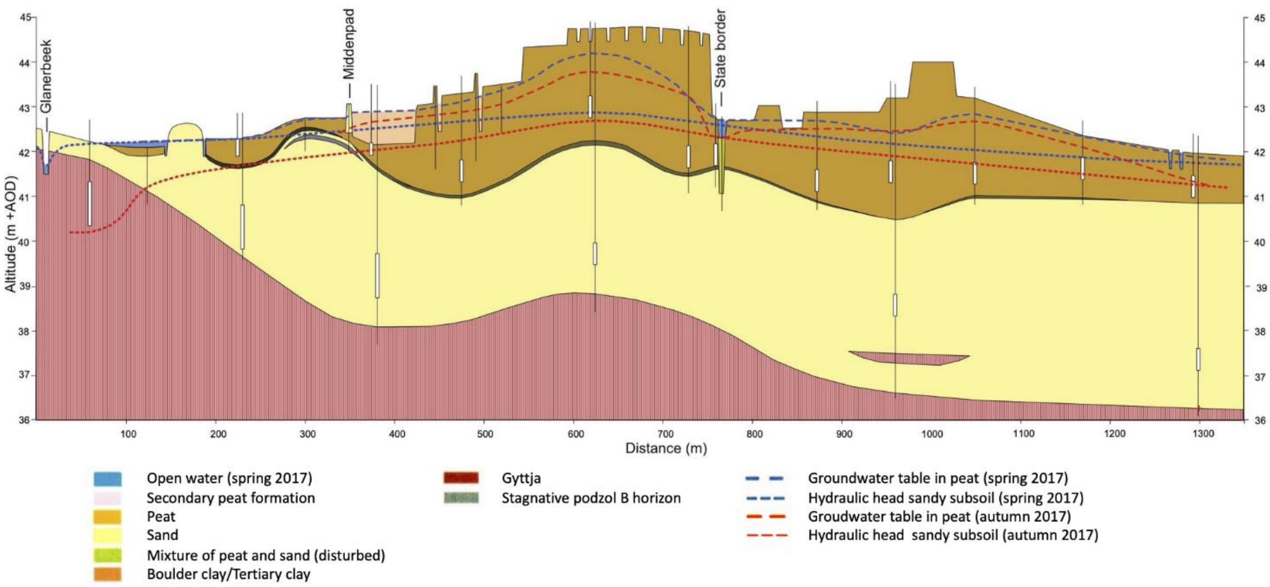


Figure 2. Geohydrological cross section of Transect 3 (after Bell *et al*. 2018). Locations and depths of groundwater piezometers are indicated by symbols.

rich groundwater decreased and the resulting acidification of soils was enhanced by atmospheric deposition of nitrogen. This led to further degradation of the original flora and fauna of the lagg.

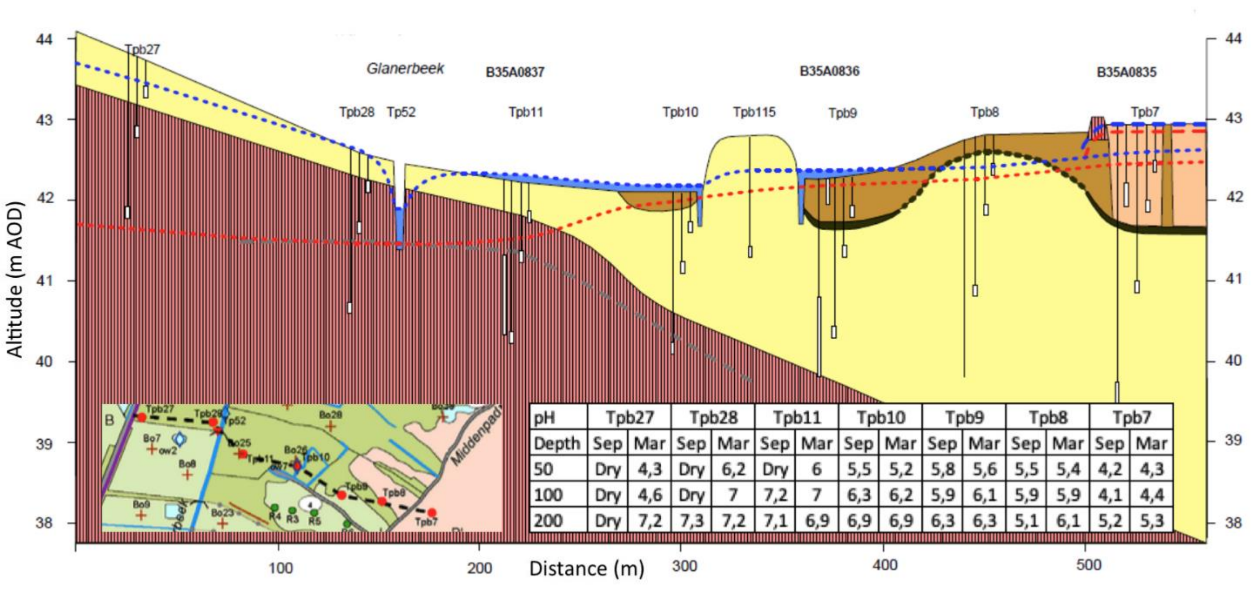
The first measures to counteract this development date from the early 1990s, when a system of small dams was constructed to reduce drainage losses and raise the groundwater level in the compartments thus created. This led to enhanced growth of *Sphagnum* in the bog area, notably in former deep excavation pits, but did not counteract the progressive acidification of the lagg. The further decline in abundance and occurrence of endangered basiphilous species was attributed to the increased *Sphagnum* growth and the associated larger influx of acidic bog water that suppressed the ingress of basic groundwater to the lagg.

Thus, in the early 21st century the area consists of a former raised bog of which large areas have been excavated, leaving behind only a thin layer of old moss peat, while towards the border with Germany larger areas of bog peat remain (see Figure 1). The scattered ‘blocks’ of peat stand out above the excavated areas, are clearly identifiable as such, and consist of both young and old moss peat with a total thickness of up to ~4 m. In the lagg, the originally thin peat layer has largely disappeared, and the vegetation differs strongly from that of the raised bog remnants, but the original basiphilous species have largely disappeared. Finally, the Glanerbeek forms a deep brook-like canal which is dry for a major part of the year.

Vegetation

Van der Veen & Attema (2012) produced a detailed vegetation map (Figure S5 in the Supplement). The vegetation of the bog area consisted of a mosaic of plant communities characteristic for well-drained raised bogs. Plant species forming the dominant plant community included the grass *Molinia caerulea*, the fern *Pteridium aquilinum*, the shrub *Salix aurita*, and the tree *Betula pubescens*. *Sphagnum*-dominated plant communities of hollows occurred locally, mainly in former turf pits. Their main plant species were *Sphagnum cuspidat*um and *S. fallax*, together with *Eriophorum angustifolium* and/or *E. vaginatum*, *Drosera rotundifolia* and *Rhynchospora alba*. Plant communities of hummocks with *Sphagnum magellanic*um and *S. papillosum* were very rare and were almost entirely limited to the transition with the lagg.

In the lagg, plant communities of acid conditions prevailed, such as wet heathland (*Ericion tetralic*is), small sedge communities (*Caricion nigrae*), shrubs of *Myrica gale*, and birch carrs (*Betulion pubescentis*). However, historic vegetation data from the beginning of the 20th century (Lako undated) and the 1950s and 1960s (Roding *et al*. 1959, NJN-afdeling Enschede 1964) show widespread occurrence in the lagg of well-developed species-rich plant communities of (moderately) base rich conditions, i.e. communities of alkaline fens (*Caricion davallianae*; *Campylio-Caricetum dioicae*), fen meadows (*Cirsio dissecti-Mollinietum*), species-rich *Nardus* grasslands (*Gentiano pneumonanthes*-



pH	Tpb27		Tpb28		Tpb11		Tpb10		Tpb9		Tpb8		Tpb7	
Depth	Sep	Mar	Sep	Mar	Sep	Mar	Sep	Mar	Sep	Mar	Sep	Mar	Sep	Mar
50	Dry	4,3	Dry	6,2	Dry	6	5,5	5,2	5,8	5,6	5,5	5,4	4,2	4,3
100	Dry	4,6	Dry	7	7,2	7	6,3	6,2	5,9	6,1	5,9	5,9	4,1	4,4
200	Dry	7,2	7,3	7,2	7,1	6,9	6,9	6,9	6,3	6,3	5,1	6,1	5,2	5,3

Figure 3. Geohydrological cross section near Transect 3 with pH values of groundwater, sampled in wells at different depths (in cm), after Van Mullekom *et al*. 2016). Locations, numbers and depths of the monitoring wells are indicated by symbols. For the legend, see Figure 2.

Nardetum) and species-rich acidic small sedge communities (*Carici curtae -Agrostietum caninae*). In 2012, only small, localised and poorly developed areas of these plant communities remained. Today, many characteristic species have disappeared, while communities of alkaline fens are extinct. Only few species of (moderately) base rich conditions can still be found, e.g., *Hottonia palustris*, *Phragmites australis*, *Equisetum fluviatile* and *Carex acutiformis*.

Climate and hydrology

The area has a temperate maritime (Cfb) climate with cool summers (17.1–17.4 ºC) and moderate winters (3.0–3.3 ºC). The mean annual precipitation and precipitation surplus are 825–850 mm and 240–280 mm, respectively. Values refer to the period 1991–2020 (https://www.knmi.nl/klimaat).

Van Mullekom *et al.* (2016) and Bell *et al.* (2016, 2018) extensively studied the current soil and water chemistry, and the hydrology of the Aamsveen, respectively. In the south, the groundwater in the raised bog remnant flows in a north-westerly direction. Infiltration into the sandy subsoil occurs but is rather limited owing to the considerable resistance of the gyttja layer and basal black peat, and the stable and high groundwater table in the sandy subsoil below. Therefore, fluctuations of groundwater level in the peat are relatively small. Thanks to the earlier hydrological restoration measures, the groundwater table in the lowest and often most deeply excavated parts is once again above the top of the residual peat layer with the result that peatmoss (*Sphagnum*) is growing abundantly in these parts (see Figure 2). In the higher bog peat remnants, the peat groundwater level remains too low for renewed peatmoss growth. In the northern part of the Aamsveen, the summer groundwater level in the sandy subsoil is too low for good peatmoss development. Here, to regenerate bog formation, the groundwater table would have to rise to an altitude of approximately 41.5 m + AOD (Amsterdam Ordnance Datum; the Dutch national datum) as evidenced by the altitude of the peat base (see Figure 4 later).

The lagg zone is fed with groundwater from the slope of the ice-pushed ridge and from the raised bog. The flux from the latter dominates because of the greater thickness of the local sandy aquifer underneath, as evident from the cross section in Figure 3. This Figure also shows that, upon infiltration, the acid bog water encounters the calcareous boulder clay and Tertiary clay and becomes more base rich, like the groundwater that comes from the slope of the ice-pushed ridge. Thus, in the lagg zone, base rich conditions are created by the combination of (1) stagnation of the water originating from the ice-pushed ridge because of the lesser slope and associated decrease in flow velocity, and (2) the input of groundwater from the bog induced by the thinning of the sandy aquifer forcing the groundwater to seep up. This specific spatial configuration of groundwater flows determined the former distribution of basiphilous plant communities in the lagg. Evidently the actual quality of the superficial groundwater in the lagg zone also depends on the balance between the flux of infiltrating precipitation and the fluxes mentioned above. The latter have been seriously reduced by the artificial drainage described above.

METHODS

Site selection and coring

Soils/sediments were cored with a gouge corer along transects and close to the wells used for the hydrological study described above. Additional gouge corings were performed along the Middenpad (for their locations, see Figure 1). Mineral soil materials encountered in the corings were described using the FAO system for soil description. Emphasis was on the nature and characteristics of the mineral substratum to the peat layer and eventually occurring stagnative layers and humilluvic materials. Soils were classified according to the WRB (2015). For terms used to describe the organic materials, reference is made to Van Delft *et al.* (2006), Bos *et al.* (2012) and Sevink (2019). These organic materials were qualitatively described for degree of decomposition (system of von Post 1922) and floristic composition.

Results from the gouge corings were used to identify sites that were optimal for palaeoecological research and would allow for a detailed palaeogeographical reconstruction. In total, five sites were selected (Figure 1) and sampled using a Russian corer (7.5 cm diameter). Core P1 was taken near the central part of the (former) bog, where the thickest peat layer was found. Locations P2 and P3 were near the western border of the bog, with P2 situated near a higher sand ridge and P3 in the former lagg zone. Location P4 was situated in a former depression in the north-eastern part of the bog. At this location most of the peat had been extracted for fuel, leaving only the lower part of the formerly thick layer. Location P5 was situated between P4 and P1 on the flank of a sand ridge. Coordinates (see Table 1) were established with a Trimble DGPS (combination of R10 (5452489398) and TSC3, RS3UC83405). For ground level and depths of soil/sediment boundaries related to ground level, altitudes are given to cm accuracy relative to AOD (Amsterdam Ordnance Datum, equivalent to mean sea level). For samples taken from cores, the accuracy of measurement is higher and depths are given with 0.5 cm accuracy.

Macrofossil and pollen analysis

All cores (see Table 1) were subsampled for macrofossil analysis by cutting them into 1 cm thick slices. These were rinsed over a set of sieves with mesh sizes 0.08, 0.25 and 0.5 mm to obtain the macrofossils, which were analysed using a Leica binocular incident light microscope at magnifications of 6× to 50×. The master core P1 was subsampled for pollen analysis by taking 1 cm thick slices at rather regular intervals, taking account of changes in macroscopically observable peat and sediment characteristics (for details see Table S1 in the Supplement). Pollen slides were produced following the standard method for pollen preparation (Erdtman 1960). To calculate pollen concentrations, a known quantity of *Lycopodium clavatum* spores was added to each sample (Stockmarr 1971). The pollen analysis was performed at BIAX Consult using compound light microscopy with a maximum magnification of 1000×. The numbers of pollen grains, moss, horsetail, and fern spores, and other microfossils (non-pollen palynomorphs such as fungal spores and algal remains) were quantified.

Pollen counts and percentage calculations were based on an arboreal pollen sum of at least 300 grains. To show the changes in openness of the landscape, the percentages of the ecological groups were also calculated based on a total pollen sum (total of all pollen and spores of terrestrial plants at least 600 grains). The results are presented in pollen and macrofossil diagrams produced using the software TILIA, version 2.0.14. The identification of the pollen and macrofossils is based on standard literature and reference collections, while the interpretation of the results is based on standard literature concerning the Dutch flora, bog development, and the Dutch abiotic indicator values of plant species. References can be found in the Supplement. The pollen data reflect local and regional vegetation development, while non-pollen palynomorphs (such as fungal spores and green algae) mainly reflect local environmental conditions, like the results of the macrofossil analysis, which reflect the local vegetation.

Radiocarbon analysis

Analyses were performed on hand-picked plant macro remains. Samples were analysed by AMS at the Tandem laboratory of the University of Uppsala. The ^{14}C dates given in yr BC are based on the standardised calculations, including correction for isotopic fractionation (Mook & Van der Plicht 1999, Van der Plicht & Hogg 2006). The dates were calibrated using the software OxCal 4.4 (Bronk Ramsey 2020) against the IntCal20 (Reimer *et al.* 2020). All date ranges are given to 95.4 % probability.

RESULTS

Results from the corings are summarised with focus on the spatial and temporal trends in soil development and sedimentary environment observed in the transects. This is followed by a more extensive description of the results from the palaeoecological studies in which focus is on the phases in development of the system and their dating. For a detailed description and analysis of the results, the reader is referred to the Supplement and to the publications cited in the Introduction.

Corings

Most corings were along more or less W–E oriented cross sections that ran from the lagg into the central part of the glacial basin. Additional corings were performed in the transition zone from the lagg into the bog, near the Middenpad. The cross sections are presented in Figure 4. Types of peat observed are

Table 1. Data on the palaeoecological cores studied. Po = number of pollen samples; Ma = number of plant macro remains samples; PAR = Peat accumulation rates. RD = Rijks-Driehoek (Dutch coordinate system).

Ref	Description	RD coordinates (m)		Peat surface (m AOD)	Peat thickness (cm)	n		PAR (mm yr^{-1})
		East	North			Po	Ma	
P1	Central/South	261,984.26	466,975.40	44.24	385	33	36	0.49
P2	Western flank	261,851.99	467,394.38	43.76	258		17	0.96
P3	Western flank, lagg zone	261,667.59	467,356.75	42.49	30 (–35)		8	
P4	North-east, excavated	262,138.63	467,587.06	42.15	50 (–170)		16	
P5	East, flank of sandy swell	262,061.64	467,222.92	44.69	339		41	0.66

only briefly mentioned and are further dealt with in the section on the palaeoecological study. The reader is also referred to Part 1 of the Supplement for details and for schematic cross sections in which the nature of the topsoil and pH values are indicated.

Overall trends in soil formation and sedimentary environment are described below.

- A prevalence of humic or eutric gleysols in the lower parts of the basin, covered by sediment, largely composed of stratified fine organic matter but often also holding thin layers of fine, clayey to loamy clastic material. The sediment was originally deposited in a eutrophic, very wet environment, or even open water, as indicated by its very fine stratification and composition, and is identified as gyttja. This is also evidenced by the macro plant remains found in this sediment, which comprise fine roots of Cyperaceae and seeds of *Typha*, *Sparganium*, and *Alisma*, indicative for marshy to open shallow water. *Juncus* seeds are almost absent.
- Variable soils in the lagg zone, ranging from podzolic soils to mostly eutric gleysols. Stagnative podzol B horizons are quite rare as are humilluvic layers (described in The Netherlands as 'gliede'; Van Heuveln *et al.* 1960, Sevink 2019) and these are limited to slightly higher positions with a thicker cover of Weichselian aeolian sands over till, where soils seemingly were and still are not under the influence of the lateral groundwater flow that characterises the lagg zone (see, e.g., cross section 3, Middenpad).

- The relief of the surface of the mineral subsoil is complex, with a gradual slope in the lagg zone which descends from the ice-pushed ridge to the east, a low swell near the Middenpad and a second swell near the Dutch-German border. Moreover, as shown by Transect 5, in the north the basin slopes somewhat upward (to 41–41.5 m), illustrating that the central part of the basin (at 40–40.5 m) must initially have been very poorly drained and a shallow lake probably existed at the onset of peat formation. This is in line with the occurrence of

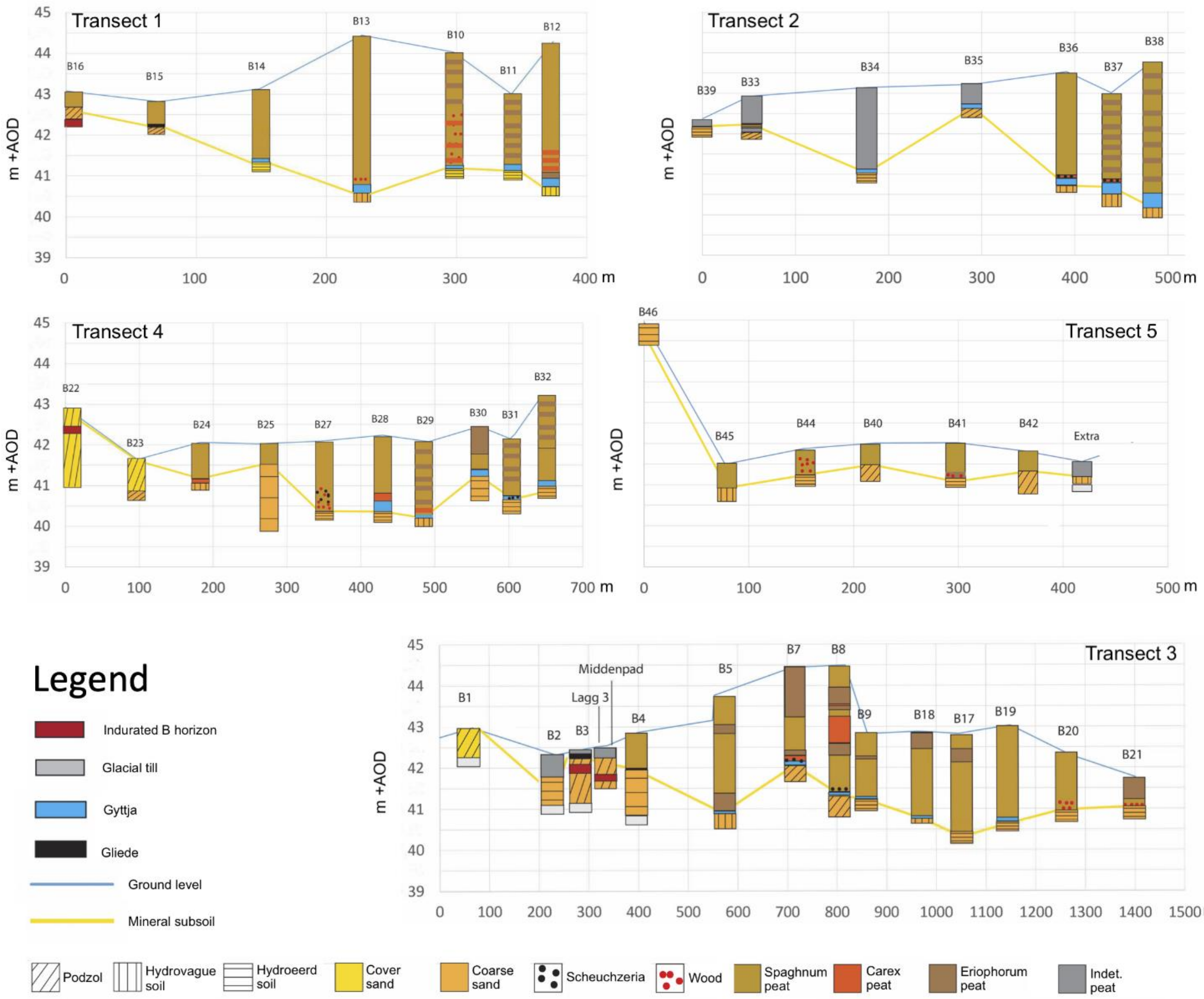


Figure 4. Transects with materials and soil types encountered. After Sevink & Jansen (2017).

stratified sediment (gyttja) immediately above the mineral soil in the lowest parts of the area.- Transect 4 illustrates that the current course of the Glanerbeek is artificial, having been dug through an impressive cover sand dune with very well-drained podzols and groundwater at more than two metres below ground level. The former natural drainage was to the east, towards the location of coring b24.

- As to the nature of the peat encountered, the cross sections demonstrate the originally more eutrophic to mesotrophic conditions that existed in the basin. Upward (i.e., later) these changed into ombrotrophic, rainwater-fed systems with *Sphagnum* peat, which expanded over the original lagg zone. This trend is described in more detail in connection with the palaeoecological results.

Palaeoecological sections

The simplified macrofossil diagram for Core P1 is presented in Figure 5, while its pollen diagram is presented in Figure 6. The pollen diagram reflects the regional (rather than local) vegetation history, which is due to the fact that medium and long distance transport of pollen by wind is an important process, while the local history is far better reflected in the macrofossil diagram, being based on the presence of plant remains that are not subject to such transport, but derived from plants growing locally nearby. This difference in the provenance of pollen versus plant macro remains explains the observed differences in species composition of the assemblages encountered. Based on the various diagrams and corings, general trends in the development of the Aamsveen could be readily identified, facilitated by the full conformance of our results with those for other, already extensively studied Dutch bog systems (e.g., Van Geel 1978, Casparie & Streefkerk 1992): Peat formation started in depressions, while later a raised bog developed because of the gradual rise of the groundwater table and acidification of the local environment. Over time, the bog expanded horizontally and vertically, leading to a very wet lagg zone in the western part of the bog. The various phases have been radiocarbon dated (see Table 2) and form the basis for the recognition of the main stages in the development of the area, which are schematically presented in Figure 7 and are described below. Details on the various diagrams, core records and stages are given in Part 2 of the Supplement.

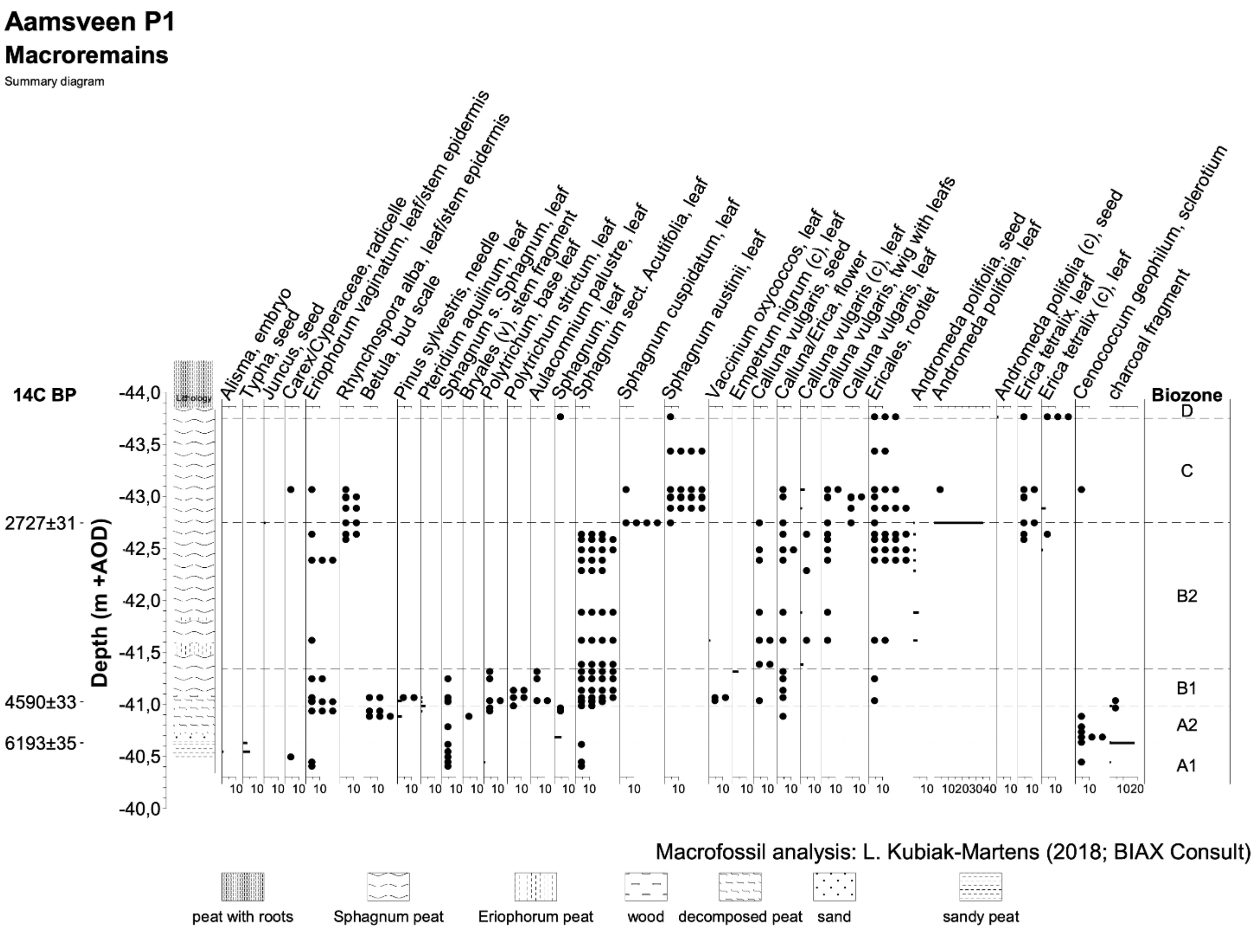


Figure 5. Simplified macrofossil diagram for Core P1.

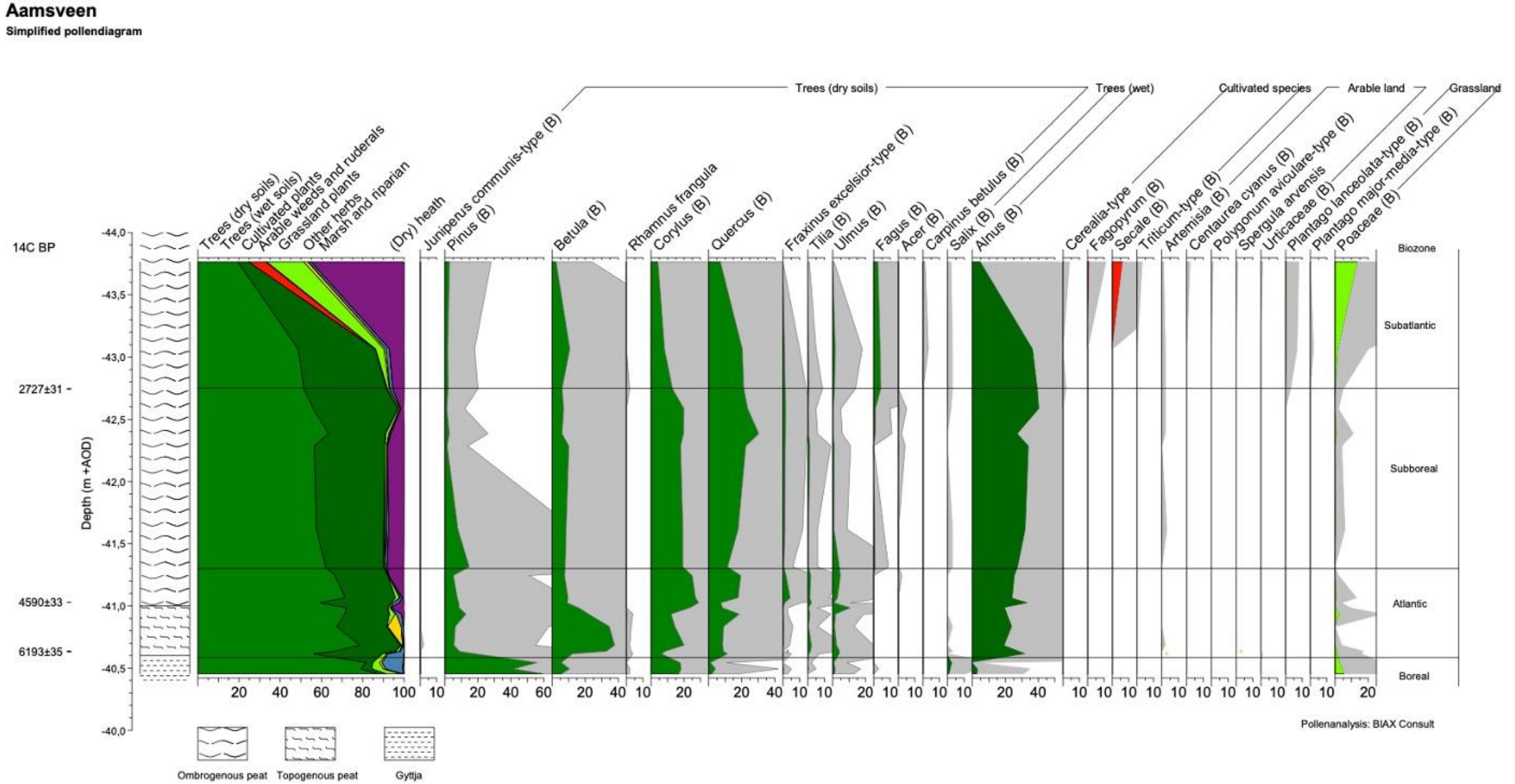


Figure 6. Simplified pollen diagram for Core P1.

Table 2. Radiocarbon dates for strata from the Aamsveen.

Labcode	Location	Depth below surface (cm)	Altitude (m AOD)	Description	Dated material	Weight (mg)	Age (BP)	Calibrated age (years BC)
UA-57996	P1	149–150	42.745	Transition from *Sphagnum* sect. *Acutifolia* to *S. austinii* (separated by a layer of *S. cuspidatum*)	Uncharred: *Andromeda polifolia* leaves, *Rhynchospora alba* seed	10	2727 ± 31	927–809
UA-60279	P1	321–322	41.025	Dominance of *Sphagnum* sect. *Acutifolia* peat (above wood)	*Sphagnum*	12	4590 ± 33	3504–3108
UA-57596	P1	361–361.5	40.628	Base of decomposed peat	*Pinus*: possible trunk wood, one fragment	12	6193 ± 35	5295–5220
UA-57997	P2	224–225	41.515	Transition to *Sphagnum*/*Aulacomnium*, termination	Uncharred: *Scheuchzeria palustris* (leaves), *Vaccinium oxycoccos* (leaves)	8	4716 ± 31	3628–3374
UA-57998	P2	232–233	41.445	Start of *Eriophorum* growth at base of layer	Uncharred: *Pinus sylvestris* (needles), *Betula pubescens* (fruits, catkin scales, bud)	8	4866 ± 34	3711–3531
UA-60280	P2	249–250	41.265	Start of formation of *Carex* peat	*Carex acutiformis* seeds (13×)	4	5184 ± 42	4220–3811
UA-58921	P3	29–30	42.195	Start of peat formation	Uncharred *Eriophorum vaginatum*, epidermis	2	4237 ± 38	2916–2675
UA-58001	P4	151–152	40.635	Termination of *Thelypteris*, *Juncus effusus* present	Charred *Pinus sylvestris* (cone scales)	10	5975 ± 35	4985–4729
UA-58002	P5	124–125	43.445	Transition from *Sphagnum* sect. *Acutifolia* to *S. imbricatum* (separated by an *Eriophorum* layer)	Uncharred *Eriophorum vaginatum*	6	2815 ± 32	1055–846
UA-58003	P5	140–141	43.285	Termination of *Thelypteris* and *Scheuchzeria*	Uncharred *Eriophorum vaginatum*	4	3057 ± 32	1411–1225
UA-60281	P5	317–318	41.565	Start of transition to *Sphagnum* peat	*Sphagnum*	12	4933 ± 33	3776–3644
UA-57597	P5	334–335	41.345	Peat base	Several species of terrestrial plants (including charred and uncharred remains)	10	5325 ± 34	4315–4049

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At the most central location studied, P1, and at P4, accumulation of peat started during the Boreal to Early Atlantic. In the large central depression, swampy conditions existed in which plants like *Typha, Sparganium, Alisma* and *Cyperaceae* grew under eutrophic conditions. In adjacent slightly drier parts of this area, a *Salix* carr existed, later with *Alnus* (alder). In Figure 7, this slightly later situation is depicted as Phase 1 (Mid Atlantic). At that time, a *Betula* carr had developed at location P1, while on the higher sandy ridges mixed forest was present. In the Late Atlantic period *Eriophorum vaginatum* and *Sphagnum* mosses began to grow, reflecting the transition towards a raised bog and the transition to oligotrophic and finally ombrotrophic conditions. At P5, which is situated on the higher ridge, concurrent with the development of this raised bog and due to the rising groundwater level, environmental conditions

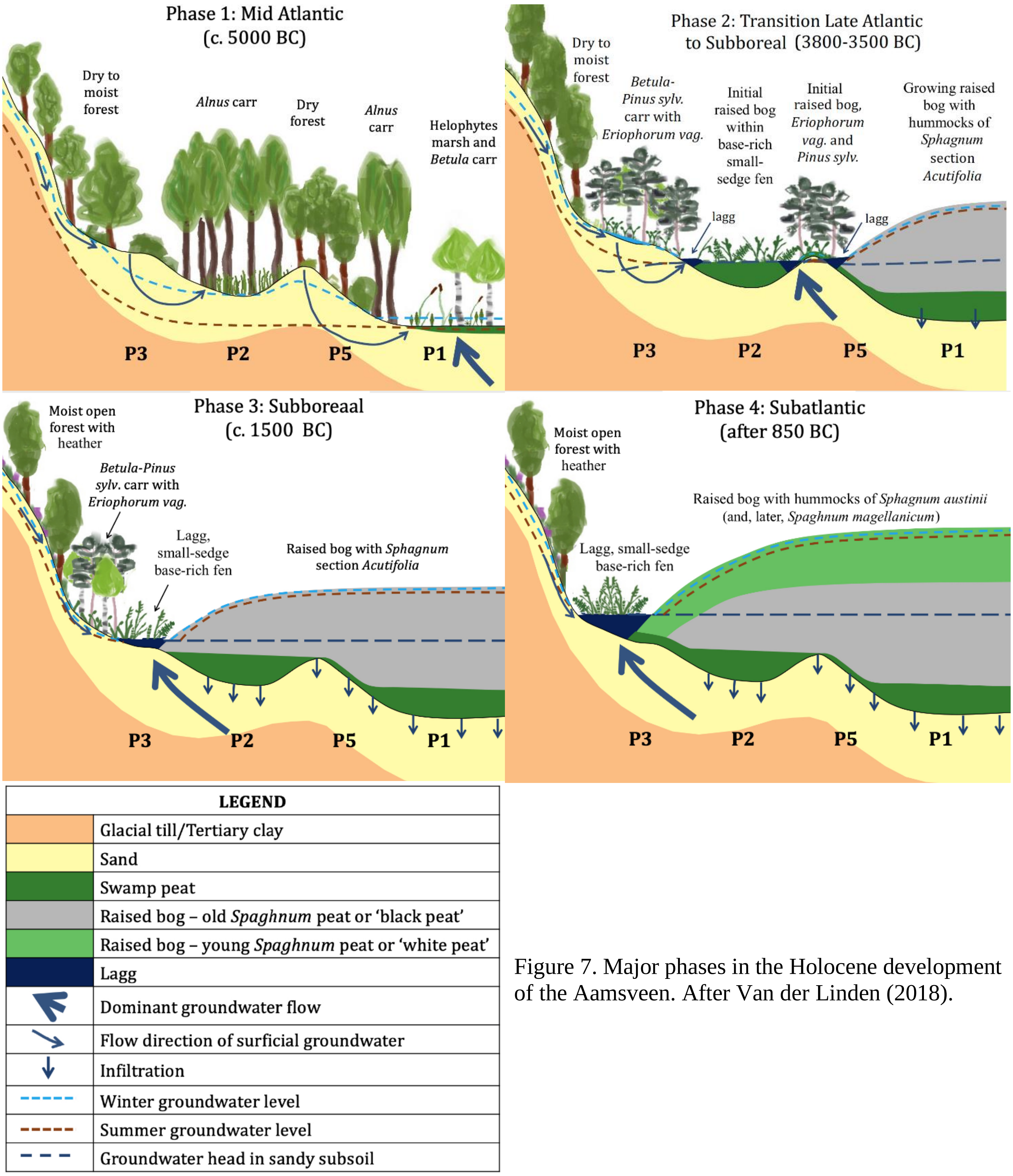

Figure 7. Major phases in the Holocene development of the Aamsveen. After Van der Linden (2018).

also became more nutrient-poor, wet and acidic. Thus, on this sandy ridge local bog peat formation started. First, groundwater fed *Thelyptris* peat was formed at ca. 4000 BC, but was soon replaced by *Eriophorum* and later *Sphagnum* peat. In Figure 7, the situation in this transitional period (3800–3500 BC) is depicted as Phase 2. During the Subboreal a raised bog vegetation dominated by *Sphagnum* sect. *acutifolia* and heather developed all over the central and north-eastern part of the depression (Phase 3 in Figure 7).

In the western border zone, at location P2, where the lagg zone was situated initially, peat accumulation started in a more base rich environment. It started with *Carex* peat, mainly consisting of *Carex acutiformis*, succeeded by vegetation with *Eriophorum vaginatum*, *Betula* and *Pinus sylvestris*. From ca. 3600 BC (Phase 2 in Figure 7) *Sphagnum* became dominant, starting with *Sphagnum cuspidatum* and followed by a short phase during which *Sphagnum riparium* dominated, indicating the transition between acid bog water and more base rich groundwater. From ca. 3500 BC, *Sphagnum magellanicum* and *Scheuchzeria palustris* dominated the bog vegetation in the western part of the mire, later being replaced by *Sphagnum* sect. *acutifolia* (mainly *Sphagnum rubellum*) as dominant species (indicating a transition to ombrotrophic conditions). In the west, the bog expanded towards the ice-pushed ridge of Enschede, pushing the lagg zone westward. This is clearly visible in the record from the most western location P3, where peat accumulated from ca. 3000 BC onward. The remaining peat at this location is very decomposed, but remains of *Eriophium vaginatum* and *Pinus sylvestris* testify to local nutrient-poor conditions in this lagg zone.

The transition from the Subboreal to the Subatlantic period is marked by a change in the dominant *Sphagnum* species. At locations P5 and P1 a wetter phase could be identified in which vegetation with *Scheuchzeria palustris* at P5 and *Sphagnum cuspidatum* at P1 occurred (around 950 BC at P5 and 860 BC at P1). Later during the Subatlantic period, the bog vegetation was dominated by *Sphagnum austinii* (hummocks) and *Rhynchospora alba* (hollows).

In Figure 7, Phase 4 reflects the maximum development of the bog and lagg system. Peat formation probably continued into the Late Middle Ages: in the top 50 cm of the peat, pollen of the cultivated species *Secale* and *Fagopyrum* was present (Core P1). *Ericaceae* also increased, evidencing an increase in heathlands in the surrounding areas and probably also on the peat surface itself. This indicates that the peat desiccated, enabling grazing on the drier parts of the bog. At the same time a dramatic decrease of tree species occurred, implying that originally forested areas outside the bog were exploited and probably used as meadows.

DISCUSSION

Palaeogeography and palaeohydrology

As elsewhere in NW Europe, peat accumulation in the Aamsveen started upon the gradual drowning of the lower parts of the basin during the Holocene, which was initiated by the rising sea level and associated rise of the groundwater level in the hinterland (Jansen & Grootjans 2019). Having once started, it followed the general temporal and spatial trends that are typical in development of such peats, undergoing the transition from a eutrophic groundwater-fed mire to an oligotrophic rainwater-fed raised bog depicted in Figure 7. This was brought about by a gradual rise of the peat surface and increased hydrological isolation from the groundwater that originated from the ridge and hills. Such gradual expansion of a raised bog and coeval rise of the groundwater level in adjacent, previously well-drained higher terrains has been widely described as paludification (Van Wirdum 1979, Succow & Jeschke 1990, Crawford *et al.* 2003, Joosten *et al.* 2017).

Most of the Dutch bog systems that formed by paludification are situated in areas with sandy soils that are apt to podzolisation (Jansen *et al.* 2019b). In the border zones of these bogs, these soils developed over time into hydromorphic podzols with a stagnative spodic B horizon, due to illuviation of humilluvic material and its accumulation on top of and in the podzol. It is particularly this illuviation that reduced the permeability of the ‘peat base’, enhancing the paludification process. This peat base plays an important role in plans for the conservation and regeneration of such raised bog systems, because of the evident concerns about its potential degradation under the influence of a lowered phreatic groundwater level (Sevink *et al.* 2014, Van den Akker *et al.* 2017).

In the Aamsveen basin, on the contrary, stagnative spodic B horizons and associated humilluvic layers played a very subordinate role at most, as evidenced by their virtual absence from the cores studied. In the border zone of the bog, the leaching and acidification required for podzolisation were counteracted by the supply of base rich groundwater, which originated by interaction of the infiltrating bog water with the calcareous sandy subsoil. Base rich groundwater from the very shallow aquifer in the ice-pushed ridge was supplied to the lagg zone only seasonally, and was of minor importance relative to the more permanent flux of infiltrated bog water. This is clearly illustrated by the spatial pattern in pH values registered in the transect of the lagg zone (Figure 3), the relatively high pH values for the sites Tpb28, Tp52 and Tpb11 in this lagg zone being indicative for more base rich conditions. Overall, this implies that relatively base rich conditions prevailed from the outset in the border zone from the bog towards the lagg and in the lagg itself, as is testified by the truly rare occurrence of humilluvic horizons (gliede) and by the palaeoecological data. In the current and former lagg, stagnative soil horizons were encountered in podzols that had developed in relatively thick cover sand deposits only when these soils had not been reached by the base rich groundwater flow and thus could acidify under the influence of infiltrating excess precipitation (see, e.g., B3 in Figure 7, Transect 3).

Figure 7 illustrates that the gradual built-up of the raised bog and associated body of acidic bog water led to a change in the balance between the groundwater fluxes originating from, respectively, the raised bog and the aquifer, and to a concurrently shifting boundary between the lagg and the bog. In other words, the gradual expansion of the bog and spatial shift in the boundary with the lagg are a function of this balance (Jansen *et al.* 2019b). In contrast to the situation in most Dutch bog systems, this did not depend on the development of a stagnative peat base during paludification. This also implies that management aiming at conservation and restoration does not have to reckon with an eventual degradation of such peat base, which is often considered to be a crucial factor in the conservation of these systems (Sevink *et al.* 2014).

The spatiotemporal landscape ecological system analysis (LESA) and its implications

The most striking aspect of the Aamsveen bog system is its invariable spatial configuration: over time the position of the bog and lagg changed, but functionally it remained invariable. This is due to its specific geohydrological context, being in a glacial basin with an impervious subsoil overlain by a thin sandy calcareous stratum which wedges out towards the margins of this basin. This insight evidently has great significance for the management plans and measures aiming at ecological recovery, as restoration of raised bog and basiphilous vegetation in the lagg go hand in hand. In fact, it was the earlier bog degradation and other interventions in the water regime, rather than the recent bog recovery, that were responsible for the current acidification of the lagg.

With our specific analysis as a background, the main effects of peat exploitation and reclamation on the geohydrological functioning of the area can readily be described. These human activities led to a reduction of groundwater flow from the bog to the lagg, and thus to serious diminishment of the supply of relatively base rich groundwater. This reduction can be ascribed to a combination of causes, namely the reduction of hydraulic head (lowering of the peat surface), the increased drainage of the bog (by ditches and canals), and the reduced storage capacity of the bog body (disappearance of the acrotelm). The early reclamation of wet heathland on the ice-pushed ridge led to increased peak flows and, thus, to attempts to reduce these by increasing the discharge capacity of the Glanerbeek and its associated system of trenches and ditches. The overall result was a reduction of the seasonal groundwater flow from the ridge towards the lagg. Additionally, the lagg itself has been drained, further diminishing the supply of base rich groundwater to the rooting zone of the vegetation. The overall effect was a major change in balance between the various fluxes and a shift towards a dominance of precipitation-controlled habitats affected by atmospheric deposition.

The palaeoecological analysis carried out as part of the LESA revealed that, from an early stage of development, the growing bog induced base rich groundwater to seep into the lagg and that this lagg shifted to the west as the bog expanded. This implies that a recovery strategy must aim to sharply raise water levels in the bog and sharply reduce drainage by the Glanerbeek and other watercourses, rather than to increase the discharge of rainwater via (new) watercourses. Thus, the focus should be on the restoration of an integrated bog and lagg system with its characteristic plant communities, as they existed in the past. Based on these principles, a restoration plan was developed comprising a range of measures that need to be taken. These have been shown to be effective in various earlier bog restoration projects and were extensively described by Schouwenaars (1995), Schouten (2002), Joosten *et al.* (2017) and Jansen & Grootjans (2019). The main measures are described below and form the core of the recent area development plan for the Aamsveen (Sietses 2020). Relevant examples of major Dutch restoration projects are provided in brackets.

- Design of a system of compartments aimed at higher water levels in the raised bog, which gradually decrease towards its edges (e.g., Bargerveen, Fochteloërveen, Haaksbergerveen, Wooldse veen).
- Filling in of ditches and canals in the bog and lagg system to reduce drainage losses (Bargerveen,

Korenburgerveen).

- Reduction of the drainage and discharge by the Glanerbeek by raising its stream bed (Leuvenumse beek, Haaksbergerveen).
- Removal of forest to reduce evaporation losses (general practice in all Dutch bog remnants).

The relevance of a spatiotemporal LESA based on palaeoecology

A general characteristic of many management plans that were produced within the scope of Natura 2000 was that they were developed for individual habitats or ecosystems and focused on their current status and functioning. In NW Europe, they generally described atmospheric deposition (particularly of nitrogen) as a serious or even the main threat to sustainability of the habitats concerned. In the case of the Aamsveen, the main thrust of these plans concerned the bog remnant, the low-productivity grasslands of the adjacent lagg, and the Glanerbeek. Each of these was considered as a specific and independent set of habitats which were to be protected because of their species richness and presence of endangered species. This is a common approach in Natura 2000, where habitats are being distinguished that, in practice, are often delineated by rather haphazard artificial boundaries.

In a LESA that is limited to analysis of the current landscape system, the persistent and dominant role of geohydrology that we found might be easily overlooked and priority instead given to mitigation of the effects of atmospheric deposition on the currently existing habitats. As an example, it was thought originally that the renewed growth of *Sphagnum* in the bog remnants resulted in acidification of the grasslands in the adjacent lagg through discharge of acid water from the bog in combination with the input of acidic precipitation. Thus, removal of this acid water by drainage ditches would be required for successful restoration of the basiphilous grasslands (Van Mullekom *et al.* 2016). However, such a measure would have led to reduction of the lateral groundwater flow from bog to lagg. This could have hampered further restoration of bog and lagg by lowering the phreatic water level, and endangered recovery of the rare basiphilous grasslands because of the reduced inflow of base rich groundwater, as we showed in our LESA. A second example is the Glanerbeek, which even recently was considered by the ‘Waterschap Vechtstromen’ (the responsible Water Authority) in its ‘Watermanagement plan 2016–2021’ to be a natural river system with brook forests, requiring restoration to function again as an active stream (https://www.vechtstromen.nl/water beheerplan). Within the Aamsveen area it is a man-made canal that threatens the geohydrological functioning and conservation of the lagg and its rare habitats. Discharge by this canal should be reduced, and lateral groundwater flow from the ridge towards the lagg enhanced, to mimic its natural functioning in the past.

Our spatiotemporal LESA demonstrates that sustainable management of the bog-lagg system encountered in the Aamsveen may be endangered if based on plans that do not articulate with its complex history and geohydrological functioning at the level of an entire landscape ecosystem. It further demonstrates that the management of more complex and dynamic landscape ecosystems may greatly benefit from an approach that involves a spatiotemporal analysis based on palaeoecological data and goes beyond an analysis of the current landscape and its individual habitats. Moreover, our palaeoecological analysis incorporated both micro remains which generally provide information at the regional scale, and macro remains which reflect the truly local vegetation. It thus enabled a far more detailed insight into the spatiotemporal development of the system than traditional pollen analysis, and formed a basis for the process-oriented landscape ecosystem reconstructions presented in Figure 7.

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