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Vegetation response to rapid climate change in Central Europe during the past 140,000 yr based on evidence from the Füramoos pollen record

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Abstract

The response of Central European vegetation to rapid climate change during the late Quaternary period (Eemian to Holocene) is assessed by data from the new pollen record of Füramoos, southwestern Germany. This record represents the longest late Quaternary pollen record north of the Alps as currently known. Its high degree of completeness allows detailed correlations with Greenland ice cores and sea–surface temperature records from the North Atlantic. Our data show that if climate deteriorations were not long or severe enough to extirpate refugia of arboreal taxa north of the Alps such as during marine oxygen isotope stage (MIS) 5 (i.e., Würm Stadial A, Stadial B, and Stadial C), reforestation with the onset of warmer conditions in Central Europe occurred on a centennial scale. If arboreal taxa became completely extinct north of the Alps such as during MIS 4 (i.e., Würm Stadial D), several thousand years were necessary for the reimmigration from refugia situated in regions south of the Alps. Thus, Dansgaard–Oeschger interstades (DOIS) 24 to 20 and 15 to 11 are expressed in Central European pollen records, whereas DOIS 19 to 16 are not recorded due to migration lags.

Keywords: Pollen record; Vegetation dynamics; Land–sea correlation; Paleoclimate; Dansgaard–Oeschger interstades; Central Europe; Germany; late Quaternary; Würm

Introduction

Rapid climate fluctuations during the last glaciation are well documented in Greenland ice cores (e.g., Dansgaard et al., 1993; Grootes et al., 1993) and in marine sediments from high and low latitudes (e.g., Bond et al., 1993; McManus et al., 1994; Schulz et al., 1998). These so-called Dansgaard–Oeschger (DO) oscillations were presumably caused by rapid switches of North Atlantic deep-water formation (Ganopolski and Rahmstorf, 2001). The environmental impact of the DO oscillations on today's densely populated regions in the middle latitudes such as Central Europe is not yet well documented. It is in these regions, however, where future climate change will have the greatest effects on people's lives.

Within the wide range of terrestrial paleoclimate proxies, pollen has proven to be one of the most useful groups (e.g., Birks and Birks, 1980). Pollen is well suited to examine the impact of rapid climate fluctuations on terrestrial ecosystems since the response of vegetation to climate change is pronounced and can occur on a decadal time scale (Tinner and Lotter, 2001). However, the preservation of pollen records depends strongly on geographic and climatic conditions. Long and continuous pollen records are predominantly found in the Mediterranean region (e.g., Tzedakis et al., 1997, 2001; Allen et al., 1999). They show a more or less immediate vegetation response to rapid climate fluctuations in cold periods since they are situated close to the glacial refugia of plants (Tzedakis, 1993). Conditions for the preservation of long pollen records in Central and northern Europe, in contrast, were less favorable since periglacial

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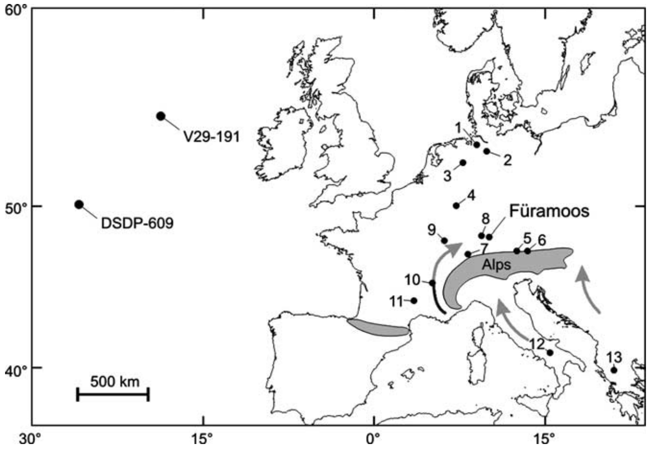


Fig. 1. Location map showing the Füramoos site and other sites mentioned in the text: (1) Oerel; (2) Groβ Todtshorn; (3) Quakenbrück; (4) Meerfelder Maar; (5) Samerberg; (6) Mondsee; (7) Dürnten; (8) Krumbach and Jammertal; (9) Grande Pile; (10) Les Echets; (11) Bouchet; (12) Monticchio; (13) Joannina. Arrows indicate migration paths of plant taxa from glacial refugia into Central Europe.

processes lead to erosion and unconformities (Tzedakis et al., 1997). Hence, long and continuous pollen records are scarce north of the Alps and the vegetation development in Central Europe during the last glaciation is yet poorly understood (e.g., Behre, 1989; Grüger, 1989).

Besides acting as a climatic divide, the Alps also play an important role in restricting the migration of plant taxa from glacial refugia in the Mediterranean region into Central Europe (Fig. 1). Therefore, the response of Central European vegetation to short-term warming episodes such as Dansgaard–Oeschger interstades (DOIS) is still unclear. The impact of DO fluctuations on the vegetation north of the Alps should be most pronounced and immediate in the vicinity of the migration paths of plant taxa toward Central Europe. These areas are well suited to indicate which DOIS can be reflected in Central European pollen records per se. Therefore we explored a long late Quaternary pollen record in southwest Germany, a region situated close to the potential migration paths of plant taxa (Fig. 1).

The Füramoos site

The Füramoos site is located in the southwest German alpine foreland at 47°59′N, 9°53′E, and 662 m a.s.l. between two moraine ridges of Riss glacial age. The sediment filling of the basin took place during the Riss glaciation, the Eemian interglaciation, the Würm glaciation, and the Holocene (Müller, 2001). The surface of the filled basin extends over an area of ca. 1000 × 600 m. A detailed description of the geomorphology of the Füramoos basin and the location of the coring site within the basin was provided by Müller (2001). A former reconnaissance study of the Füramoos site was carried out by Frenzel (1978).

Material and methods

To obtain information about the shape and filling of the Füramoos basin, 20 cores were drilled along two cross sections using a mobile Nordmeyer drilling rig (Winterholler, 1999; Müller, 2001). This resulted in the identification of a drilling location where a 16-m-long core well suited for palynological investigations could be obtained. On the organic-rich part of the core, 208 analyses of total organic carbon (TOC) content and 170 pollen analyses were performed (see Fig. 2 for sample positions). At least 500 pollen grains (average: 720 grains) were counted per sample. The calculation of percentages is based on total terrestrial pollen (TTP). Spores, pollen from aquatic plants, and Cyperaceae are not included in the sum of TTP. They refer, however, to the TTP. A simplified pollen diagram of the Füramoos record is presented in Figure 2 (for details see Müller, 2001). On selected samples, grain size measurements of *Betula* pollen were performed (Fig. 3) in order to obtain information on the contribution of different *Betula* species (Usinger, 1975). An age–depth model was established based on AMS ^{14}C dates and tuning of well-defined palynostratigraphic markers within the Füramoos record to age data from sea–surface temperature (SST) records (Fig. 4). As the palynostratigraphy of the Füramoos record will be developed next, the age model for the record will be presented later.

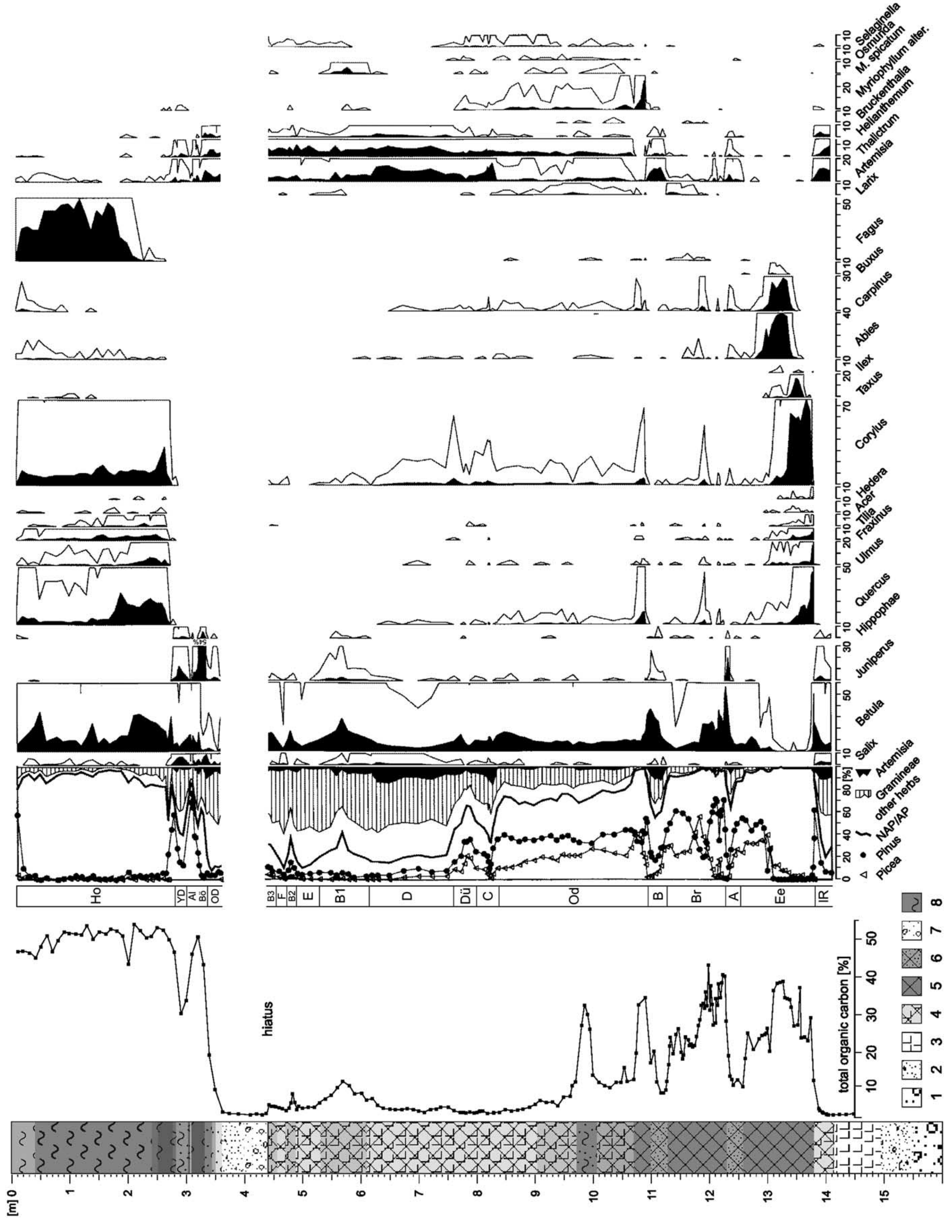
The Füramoos record

In the following, the sedimentological, palynological, and palynostratigraphical characteristics of the Füramoos record are presented. For the sake of greater clarity, we give the approximate correlations of terrestrial stages with marine oxygen isotope stage (MIS) (Mangerud, 1989) despite the various degrees of diachroneity between terrestrial and marine stages (Shackleton et al., 2002).

Late Riss glaciation (ca. late MIS 6)

The drilling reached a till at a depth of 15.53 m (Fig. 2). Sandy and calcareous meltwater deposits (15.53 to 14.88 m)

Fig. 2. Lithology, total organic carbon data, and pollen data of the Füramoos record. (1) Gray calcareous gravel and sand; (2) gray calcareous sand; (3) gray calcareous silt; (4) brown-gray silt mud; (5) dark brown foliated, strongly compacted fine detritus mud; (6) brown fine detritus mud with slightly increased content of fine sand; (7) gray noncalcareous gravel, and sand; (8) peat. Pollen diagram is given as summary percentage diagram, curves in silhouette indicate ×10 magnification. (IR) late Riss; (Ee) Eemian; (A) Stadial A; (Br) Brörup; (B) Stadial B; (Od) Odderade; (C) Stadial C; (Dü) Dürnten; (D) Stadial D; (B1) Bellamont 1; (E) Stadial E; (B2) Bellamont 2; (F) Stadial F; (B3) Bellamont 3; (OD) Oldest Dryas; (Bö) Bölling; (Al) Alleröd; (YD) Younger Dryas; (Ho) Holocene; (NAP/AP) nonarboreal pollen/arboreal pollen. For stratigraphy see also Figure 6.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Juniperus
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Ulmus
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Tilia
Acer
Hedera
Corylus
Taxus
Ilex
Abies
Carpinus
Buxus
Fagus
Larix
Artemisia
Thalictrum
Helianthemum
Bruckenthalia
Myriophyllum alter.
M. spicatum
Osmunda
Selaginella
54%

are overlain by calcareous silts (up to 14.12 m), which formed the base of lake sediments. All sediments encountered further upsection are noncalcareous. The lowermost pollen-rich samples of the core are preserved in a silt mud from 14.10 m upward. They reflect the end of an open late-glacial vegetation and a subsequent reforestation phase. Since this sequence is conformably overlain by interglacial sediments, which are assigned to the Eemian interglaciation, the late-glacial bed documents the end of the Riss glaciation.

Eemian interglaciation (ca. MIS 5e)

The onset of an interglaciation is documented by a major spread of *Pinus* and *Betula* at a depth of 13.82 m. Synchronously, sedimentation changed from silt mud to a finely foliated, strongly compacted fine detritus mud, coinciding with a strong rise of TOC values (Fig. 2). The immigration pattern and spread of arboreal taxa (*Betula, Pinus, Ulmus, Quercus, Fraxinus, Corylus, Taxus, Carpinus, Abies,* and *Picea*) is comparable to that known from Eemian pollen records in Central Europe, e.g., Oerel (Behre, 1989), Samerberg (Grüger, 1989), or Grande Pile (Beaulieu and Reille, 1992) (Fig. 1). Hence, this interglaciation is identified with the Eemian. *Abies* reaches slightly higher percentages than in Eemian records from the northern European lowlands. These higher *Abies* percentages do not point to an older interglaciation as it has been assumed by Frenzel (1978), but are characteristic of most Eemian pollen records from the northern alpine foreland (Grüger, 1995; Drescher-Schneider, 2000a; Müller, 2000). U/Th dating corroborates an Eemian age for the respective interval as sediments of the Eemian *Carpinus* phase (which is well recorded at Füramoos) at the nearby Jammertal site (Fig. 1; Müller, 2000) yielded an age of 128,000 ± 4,000 yr B.P. (Geyh, M., and Oezen, D., written communication, 1999). The end of the Eemian interglaciation is recorded at 12.55 m by substantial decline of arboreal pollen, a decline of TOC values, and a change in lithology (Fig. 2).

Early Würm glaciation

Stadial A (ca. MIS 5d). The Füramoos record shows a stadial period for the interval from 12.55 to 12.28 m (Fig. 2). Sediments attributed to this stade exhibit low TOC values and a slightly increased amount of fine sand of probably eolian origin. The pollen data indicate that even climatically less sensitive trees such as *Picea, Pinus,* and *Betula* became extirpated and tundra–steppe biomes developed. Since the pollen record documents a conformable sequence above the Eemian interglaciation, this stade is assigned to the first Würm stade (Herning).

Brörup interstade (ca. MIS 5c). The onset of the first Würm interstade is documented by pioneer forests at a depth of 12.28 m (Fig. 2). Subsequently, *Picea* spread and pollen grains of thermophilous deciduous trees are recorded. The occurrence of these taxa early within this interstade suggests that they had refugia in areas north or west of the Alps during the preceding Stadial A. Typical for the first Würm interstade is a short, but distinct climate deterioration known from various European sites, e.g., Amersfoort (Zagwijn, 1961), Samerberg (Grüger, 1989), Quakenbrück (Hahne et al., 1994), Monticchio (Allen et al., 1999), and Bouchet (Reille et al., 2000). It has been assigned an age of ca. 103,000 yr B.P. (Reille et al., 1992). In the Füramoos record, this so-called “Montaigu event” (Woillard 1978) occurs at a depth from 12.14 to 12.09 m and is documented by a sudden decline of *Picea,* an increase of *Pinus,* and reduced TOC values (Fig. 2). Slightly increased percentages of nonarboreal heliophytes such as *Artemisia* indicate a minor opening of the forests. Since the Montaigu event is clearly recorded, this interstade is assigned to the Brörup interstade. The subsequent recovery of forests is documented by a major spread of *Picea.* Thermophilous tree taxa reached a maximum of 15.6% at 11.95 m. This suggests that sediments of this depth correspond to the climate optimum of the Brörup interstade. It cannot be ruled out, however, that the climatic optimum of this interstade occurred earlier than the Montaigu event, but is not documented as such in the pollen record due to a possible lag in vegetation development. This scenario is suggested by a comparison with the pollen record from Les Echets, France (Beaulieu and Reille, 1984). In the middle part of the interstade, declining *Picea* and increasing *Pinus* values document a gradual cooling. However, a late Brörup climate oscillation of moderate amplitude toward higher temperatures is recorded by the rise of *Picea* values at 11.40 m before a further decline of *Picea* and *Pinus* indicates the end of the interstade at a depth of 11.28 m (Fig. 2).

Stadial B (ca. MIS 5b). The following stadial period (11.28 to 10.98 m) is characterized by a substantial deforestation accompanied by a major spread of *Betula* species (Fig. 2). High percentage of *Artemisia* during this stade indicate the presence of steppe biomes. The range of this stade is also well expressed in low TOC values and slightly increased proportions of fine sand in the sediment. Since the record represents a continuous sequence, this interval is assigned to the second Würm stade (Rederstall).

Odderade interstade (ca. MIS 5a). The onset of the second Würm interstade (Odderade) is documented by pioneer forests at a depth of 10.98 m (Fig. 2). Subsequently, *Picea* spread and thermophilous deciduous trees reimmigrated into the area. Thermophilous tree taxa reached a maximum of 19.9% at 10.93 m. This suggests that the climate optimum of the Odderade interstade occurred very early during this warming episode. The early recurrence of thermophilous deciduous trees indicates that their refugia must have persisted in areas north or at least west of the Alps during the preceding Stadial B. After the climatic optimum, *Picea* became dominant and later *Pinus* became the dominant taxon again. This shift in the pollen assemblages is associated with a change in sediment composition from fine detritus mud to silt mud at around 10.75 m. The silt mud is much less compacted than the fine detritus mud and changes in the pollen record appear noticeably stretched between 10.75 and 4.43 m (Fig. 2). Hence, an increased sedimentation rate caused an enhanced temporal resolution within this part of the record. The middle and upper part of the interval attributed to the Odderade interstade shows a continuous decline of *Picea*, indicating a gradual cooling. The end of the Odderade interstade is well expressed by a sudden decline of *Pinus* and *Picea* at a depth of 8.39 m.

Findings of *Bruckenthalia* pollen grains in several samples of the Brörup and the Odderade interstades (Fig. 2) corroborate our stratigraphic evaluation as low percentages of this taxon are characteristic of the first two interstades of the last glaciation in Europe (Lang 1994).

Stadial C (ca. MIS 5a). The continuous sequence documents a third Würm stade (8.39 to 8.00 m), which is indicated by a major decline of arboreal pollen and a strong spread of *Artemisia* (Fig. 2). The climate deterioration must have been substantial because even climatically less sensitive arboreal taxa such as *Picea* and *Pinus* became extirpated and steppe biomes developed.

Dürnten interstade (ca. transition MIS 5a to MIS 4). A third Würm interstade with forest vegetation is documented by an increase of pollen from coniferous taxa (8.00 to 7.60 m). The occurrence of *Selaginella selaginoides* within this interstade indicates that the timberline was in the area of the Füramoos site. Evidence for this third Würm interstade, named “Dürnten” (Welten, 1982) according to a site in Switzerland, has been found at several sites in the alpine foreland such as Les Echets (Beaulieu and Reille, 1984), Samerberg (Grüger, 1989), and Mondsee (Drescher-Schneider, 2000b) (Fig. 1).

The palynological findings for the Dürnten interstade indicate a stratigraphic position within the early Würm glaciation (e.g., Welten, 1988; Beaulieu and Reille, 1989; Küttel, 1989). This view is supported through the high-resolution loess record of Mainz–Weisenau, Germany, which documents three temperature periods during the early Würm (Bibus et al., 2001). The correlation of the Dürnten interstade with a marine isotope stage is as yet uncertain. This is why the three peaks within the MIS 5 oxygen isotope record have traditionally been correlated with the Eemian (MIS 5e), Brörup (MIS 5c), and Odderade (MIS 5a) interstades (e.g., Mangerud, 1989). This would place the Dürnten interstade into MIS 4 or MIS 3. Such a correlation, however, seems not appropriate since woodlands persisted in Central Europe during the Dürnten interstade, a fact that is not compatible with the cold climate of MIS 4 and 3. Hence, we suggest that the Dürnten interstade belongs to the uppermost part of MIS 5 (cf. Beaulieu and Reille, 1989) and that the long and severe Stadial D represents the approximate terrestrial equivalent of MIS 4. The reason the warming associated with the Dürnten interstade is not recorded as a peak within the late MIS 5 in the SPECMAP curve (Martinson et al., 1987) may be that this record does not resolve all high-frequency climatic fluctuations such as DOIS (Dansgaard et al., 1993).

Middle Würm glaciation

Previously known long late Pleistocene pollen records from Central Europe show major unconformities at the end of the early Würm glaciation at the latest, e.g., Oerel (Behre, 1989), Samerberg (Grüger, 1989), Grande Pile (Beaulieu and Reille, 1992), or Groβ Todtshorn (Caspers, 1997). The middle Würm interstades Oerel and Glinde (Behre, 1989) as well as Moershoofd, Hengelo, and Denekamp (e.g., van der Hammen et al., 1967; Zagwijn, 1974) are recorded from peaty layers which are separated by unconformities. Their stratigraphic positions are therefore not well constrained. Moreover, it is unclear which middle Würm interstades represent true climatic signals and which resulted merely from local geomorphological phenomena (Vandenberghe, 1985; Behre and van der Plicht, 1992). The Füramoos record, in contrast, covers the interval from the Eemian interglaciation to the middle Würm continuously and the interstades document clear climatic signals. Because a correlation of the middle Würm interstades at Füramoos with Oerel, Glinde, Moershoofd, Hengelo, and Denekamp would be rather hypothetical, the middle Würm interstades at Füramoos were informally named “Bellamont” after a nearby village.

Stadial D (ca. MIS 4). The fourth Würm stade documents the main opening of the vegetation (Fig. 2). This indicates an approximate correlation with MIS 4. High percentages of *Artemisia* and Gramineae suggest the presence of cold steppe biomes. To distinguish *Betula* species, grain size measurements of *Betula* pollen were performed (Fig. 3). The size of *Betula* pollen grains from the end of Stadial D almost follows a normal distribution (Fig. 3a; sample 6.2 m) with a maximum at a diameter of 21 μm (mean diameter = 21.5 μm, standard deviation = 2.2 μm). These results are well in agreement with the pollen grain size of *Betula nana* (Usinger 1975). Hence, the *Betula* pollen in sample 6.2 m originates predominantly from *B. nana* and *Betula* trees (*B. alba*) that were not present in the surroundings of Füramoos during the late Stadial D. Because *B. alba* requires only moderate climate conditions and the position of sample 6.2 m is close to the more favorable climate conditions of the following interstade (i.e., it does not represent the coldest interval of Stadial D), we concluded that most areas north of the Alps were complete treeless during Stadial D (ca. MIS 4).

Bellamont 1 interstade (substage of MIS 3). The Bellamont 1 interstade (6.15 to 5.3 m) reflects the reoccurrence of more favorable climatic conditions. This is not only expressed by a significant rise of *Betula* percentages, but also by the

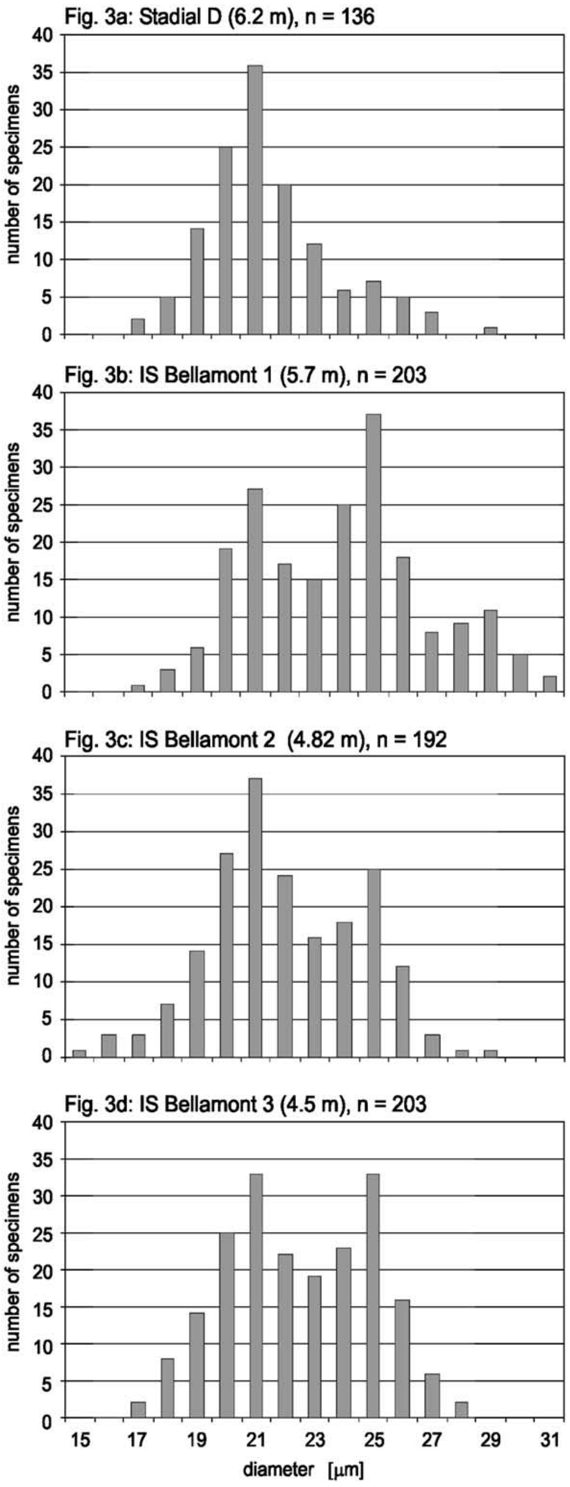


Fig. 3. (a–d) Measurements of *Betula* pollen grain sizes. See text for discussion.

reimmigration of taxa requiring higher summer temperatures such as *Juniperus*, *Hippophae rhamnoides*, and *Selaginella selaginoides*. The sediments attributed to this interstade show increased TOC values. Measurements of *Betula* pollen grains from sample 5.7 m, which represents the thermal optimum of the Bellamont 1 interstade (Fig. 2), yielded a pronounced bimodal distribution with peaks at 21 and 25 μm (Fig. 3b). This bimodal distribution documents the presence of at least two different *Betula* species, i.e., *B. nana* and *B. alba* (Usinger, 1975). The AMS ^{14}C dating of a wood fragment from the optimum of the Bellamont 1 interstade yielded a PMC-corrected age of 51,300 $+2{,}400/-1800$ yr B.P. (Grootes, P.M., written communication, 2001, KIA11709). As this age is close to the limit of radiocarbon dating, the age of the sample could also possibly be older. However, since the complete MIS 5 and 4 are documented downsection in the Füramoos core, we assume that the Bellamont 1 interstade represents the (delayed) terrestrial vegetation response to the onset of MIS 3.

Stadial E (substage of MIS 3). The next stade upsection (5.3 to 4.9 m) exhibits decreasing *Betula* values. *Juniperus* and *Hippophae rhamnoides* disappeared completely. *Selaginella selaginoides*, however, is still recorded, suggesting that this stade was warmer than Stadial D.

Bellamont 2 interstade (substage of MIS 3). The pollen data of the section from 4.9 to 4.75 m document a further interstade by an increase of *Betula* and *Pinus* percentages and the reoccurrence of *Juniperus*. Size measurements of *Betula* pollen from the sample at 4.82 m, representing the thermal optimum of the Bellamont 2 interstade (Fig. 2), yielded a bimodal distribution (Fig. 3c). Since that the peak for *B. nana* at 21 μm dominates over the peak of *B. alba* at 25 μm, we conclude the Bellamont 2 interstade was slightly less pronounced than the Bellamont 1 interstade. A wood fragment from Bellamont 2 sediment yielded a PMC-corrected AMS ^{14}C age of 43,920 $+930/-830$ yr B.P. (Grootes, P.M., written communication, 2001, KIA11708). Therefore, the Bellamont 2 interstade is attributed to a substage of MIS 3.

Stadial F (substage of MIS 3). The next stade upsection (4.75 to 4.55 m) shows again declining *Betula* and *Pinus* values. The *Juniperus* curve exhibits an interruption, whereas pollen of *Selaginella selaginoides* is continuously present. Hence, the character of Stadial F is comparable to that of Stadial E.

Bellamont 3 interstade (substage of MIS 3). The Bellamont 3 interstade is not completely preserved due to an unconformity at a depth of 4.42 m. Palynological results indicate an increase of *Betula* and *Pinus* percentages and the reoccurrence of *Juniperus*. Size measurements of *Betula* pollen from sample 4.5 m show that *B. nana* and *B. alba* peaks are of the same height (Fig. 3d). Therefore we conclude that the Bellamont 3 interstade was slightly warmer than Bellamont 2, but cooler than Bellamont 1. Based on AMS ^{14}C dates from sediment from the underlying two interstades and the calculated sedimentation rate for this interval of the record, we assume that erosion removed only sediments younger

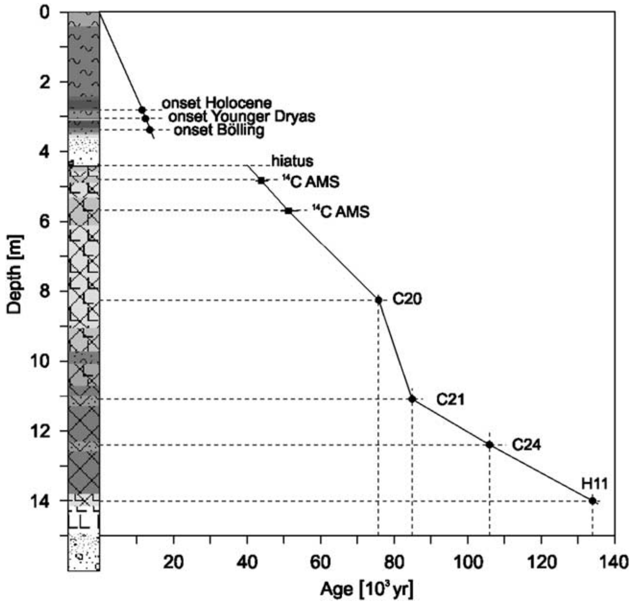


Fig. 4. Age–depth model of the Füramoos core based on AMS ^{14}C dates and tuning of well-defined palynostratigraphic markers to SST record age data (McManus et al., 1994) and to the late-glacial reference pollen record from Meerfelder Maar, Germany (Litt et al., 2001). Lithological explanations are given in Figure 2. See text for discussion.

than ca. 40,000 yr B.P. Hence, the age of the Bellamont 3 interstade should be well within MIS 3.

Late-glacial and Holocene (MIS 2 and MIS 1)

After a hiatus from ca. 40,000 to ca. 14,000 yr B.P. as a result of pronounced morphodynamics during the last glacial maximum, pollen-rich sediments reoccur at a depth of 3.6 m. The pollen data reflect the principal features of the late-glacial and Holocene vegetation development in Central Europe (Fig. 2), starting with the Oldest Dryas (3.60 to 3.38 m) and continued by the Bölling interstade (3.38 to 3.25 m), Older Dryas (3.25 to 3.19 m), Alleröd interstade (3.19 to 3.02 m), Younger Dryas (3.02 to 2.82 m), and Holocene (2.82 to 0.0 m).

Füramoos age–depth model

To develop an age–depth model for the Füramoos record, AMS ^{14}C dates as mentioned above were used for the interval of the middle Würm glaciation. Beyond the limit of radiocarbon dating, well-defined palynostratigraphic markers were tuned to age data from marine records. As palynostratigraphic markers, climatic reversal points such as the peaks of major cold events were chosen. These peaks can be clearly identified by a maximum decline in tree populations. As a basis for marine age data, we used sea surface temperature records from the eastern North Atlantic. For a correlation with Central European pollen records, these SST records are better suited than oxygen isotope data from benthic foraminifera (e.g., Kukla et al., 1997; Forsström, 2001). This is because the latter mainly reflect changes in global ice volume which are not necessarily in close relation to vegetation change (Shackleton et al., 2002). The SST records from the eastern North Atlantic (McManus et al., 1994; Chapman and Shackleton, 1999) document that the relatively mild conditions during MIS 5 were interrupted by three major ice-rafting episodes C24, C21, and C20 that extended into the middle latitudes. Similarly, the middle latitude Füramoos pollen record shows that the predominance of woodlands during MIS 5 was interrupted by three major deforestation episodes (i.e., Stadials A, B, C; Fig. 2). Based on this agreement, we tuned the maximum decline of arboreal pollen during Stadial A to the age of the maximum occurrence of *Neogloboquadrina pachyderma* and IRD during polar episode C24 as recorded at DSDP Site 609 (McManus et al., 1994). Accordingly, Stadial B was tuned to C21 and Stadial C to C20. Moreover, the last major peak of *Artemisia* prior to the onset of the Eemian interglaciation (located at a depth of 14.00 m at Füramoos) was tuned to the age of the last major cold episode prior to MIS 5 (i.e., H11) as recorded at DSDP site 609 (McManus et al., 1994) (Fig. 4).

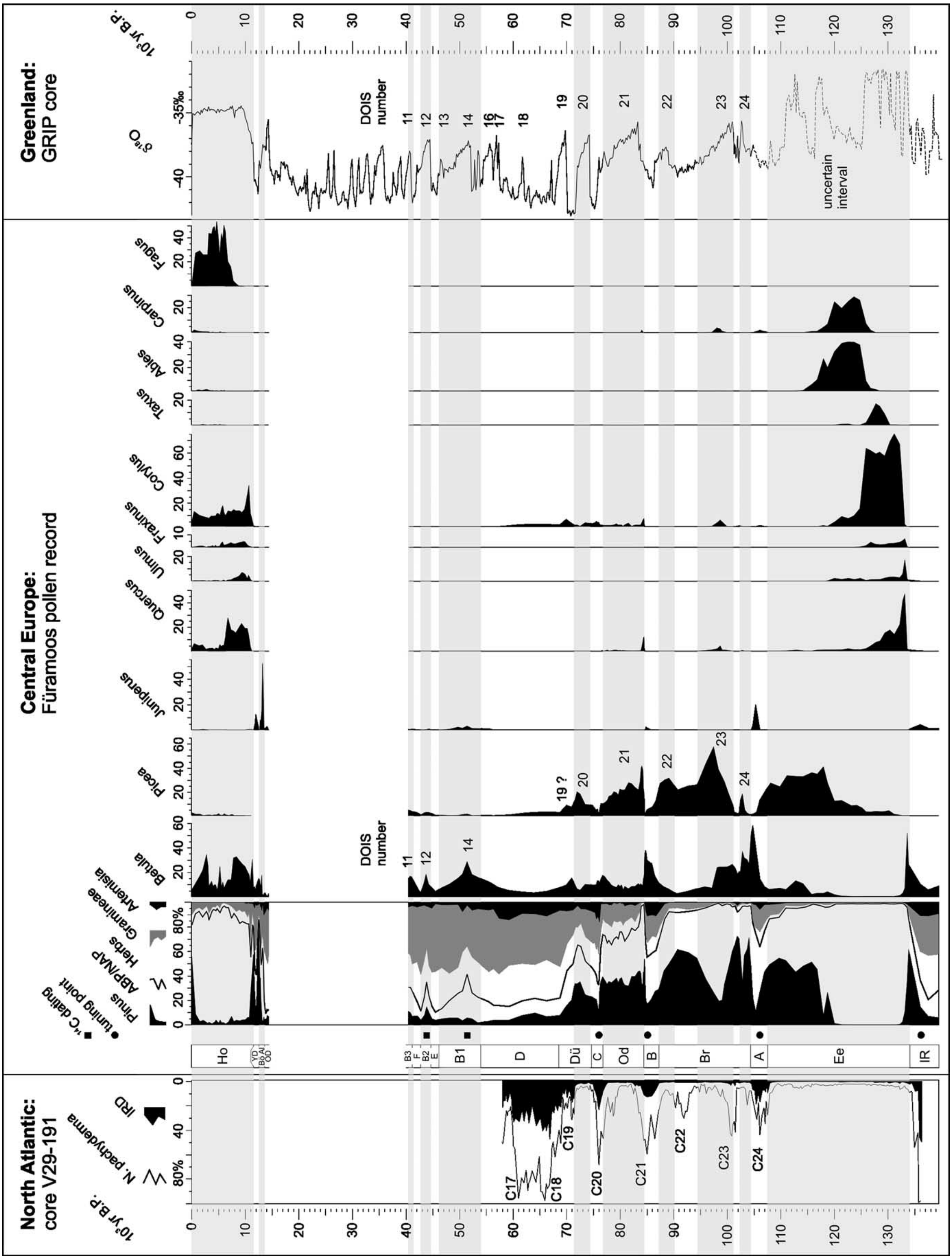
The age–depth model presented in Figure 4 indicates that changes in sedimentation rate correlate well with changes in sediment type. Hence, any given sediment type of the Füramoos record can be assumed to represent a specific sedimentation rate. On the basis of this correlation, the mean sedimentation rate in the fine-detritus-mud interval (13.8 to 10.75 m) was ca. 6 cm/10^3 yr. Within the interval assigned to the Odderade interstade, sediments change into a less compacted silt mud and the mean sedimentation rate increased to ca. 40 cm/10^3 yr. Further upsection, during the middle Würm interval, the mean sedimentation rate was ca. 12 cm/10^3 yr.

Vegetation response to rapid climate change

Based on the chronology established for the Füramoos pollen record and the comparison with SST records from the eastern North Atlantic (McManus et al., 1994) and the GRIP record (Dansgaard et al., 1993), the vegetation response to rapid climate change in Central Europe can be assessed (Fig. 5). In addition, the tuning employed in the development of the age– depth model can be verified.

Vegetation response during MIS 5

The SST record of core V29-191 from the eastern North Atlantic (McManus et al., 1994; Fig. 1) documents the pattern of polar water front incursions into the middle latitudes during MIS 5. Therefore it is used for a comparison with the Füramoos pollen record. The SST record of core V29-191 shows that polar episode C24 is documented by a major increase in *N. pachyderma* and IRD abundances (Fig. 5). In Central Europe, a major deforestation occurred and tundra–steppe biomes developed during this time as is documented at Füramoos (Fig. 5, Stadial A) and other pollen


Greenland: GRIP core
$\delta^{18}O$
-35‰
-40
DOIS number
11 12 13 14 16 17 18 19 20 21 22 23 24
uncertain interval
10^3 yr B.P.
0 10 20 30 40 50 60 70 80 90 100 110 120 130
Central Europe: Füramoos pollen record
^{14}C dating
tuning point
Pinus
AP/NAP
Herbs
Gramineae
Artemisia
Betula
Picea
Juniperus
Quercus
Ulmus
Fraxinus
Corylus
Taxus
Abies
Carpinus
Fagus
DOIS number
19 ?
Ho
YD
Bö Al
OD
B3
F
B2
E
B1
D
Dü
C
Od
B
Br
A
Ee
IR
North Atlantic: core V29-191
IRD
N. pachyderma
80%
C17
C18
C19
C20
C21
C22
C23
C24

records, e.g., Melisey 1 at Grande Pile (Beaulieu and Reille, 1992) and WF1 at Quakenbrück (Hahne et al., 1994) (Fig. 1).

In middle latitude marine sediments, polar advance C23 is documented by a major increase in *N. pachyderma* percentages and a subordinate rise of IRD (Fig. 5). In terrestrial ecosystems from Europe, this climate deterioration (Montaigu Event *sensu* Woillard, 1978) is recorded by a decline of thermophilous deciduous taxa in southern Europe (e.g., Les Echets: Beaulieu and Reille, 1984; Fig. 1), a decline of *Picea* in southern Central Europe (e.g., Füramoos; Fig. 5), and a decline of *Pinus* and *Betula* in northern Central Europe (e.g., Quakenbrück: Hahne et al., 1994; Fig. 1). In Central Europe, the northern borderlines of tree taxa were pushed southward, but no large-scale deforestation occurred during that time.

In the marine record, polar incursion C22 is recorded by an increase of *N. pachyderma* abundances only (Fig. 5), indicating a climate oscillation of lower magnitude (McManus et al., 1994). Based on the age model presented above, this incursion coincides with a temporary reduction of *Picea* at Füramoos during the late Brörup interstade (Fig. 5). In contrast, the strong polar incursions C21 and C20, which are documented by a major increase of *N. pachyderma* and IRD, correlate with major deforestations in Central Europe during Stadials B and C as is indicated at Füramoos (Fig. 5).

The comparison of the GRIP and Füramoos records documents that most DOIS during MIS 5 are recorded at Füramoos: DOIS 24 to 22 are equivalents to the Brörup, DOIS 21 to the Odderade, and DOIS 20 to the Dürnten interstades (Figs. 5 and 6). DOIS 19, however, is not clearly reflected in the pollen record although the temporal resolution of our data is ca. 500 yr in the respective interval. This is presumably due to the very strong cooling prior to DOIS 19 (cf. GRIP curve, Fig. 5) that extirpated the refugia of arboreal taxa north of the Alps and the resulting long time interval necessary for these plants to reimmigrate into this region from refugia in southern Europe (Figs. 5 and 6).

Based on the pollen data and the sedimentation rates calculated from the age–depth model for Füramoos, the duration of deforestation and reforestation periods during MIS 5 may be assessed. The transition from conifer forests at the end of the Eemian interglaciation (i.e., at a depth of 12.55 m) to tundra–steppe biomes in Stadial A (12.39 m) may have lasted ca. 3500 yr. This is in agreement with a record of annually laminated lake sediments from Krumbach in southern Germany (Fig. 1), which yielded a duration of more than 3000 yr for the respective interval (Frenzel and Bludau, 1987). The transition from conifer forests at the end of the Brörup interstade (11.28 m) to steppe biomes in Stadial B (11.10 m) may have lasted ca. 3000 yr. This is in agreement with the annually laminated pollen record of Monticchio in Italy (Fig. 1), which yielded a duration of ca. 2500 yr. for the respective interval (cf. transition pollen zones 19a to 18 in Allen et al., 1999). In contrast, the reforestation by pioneer woods with the onset of the Brörup and Odderade interstades required less than 1000 yr. Hence, deforestations during MIS 5 in Central Europe occurred over some millennia. Reforestation, in contrast, took place on a centennial time scale.

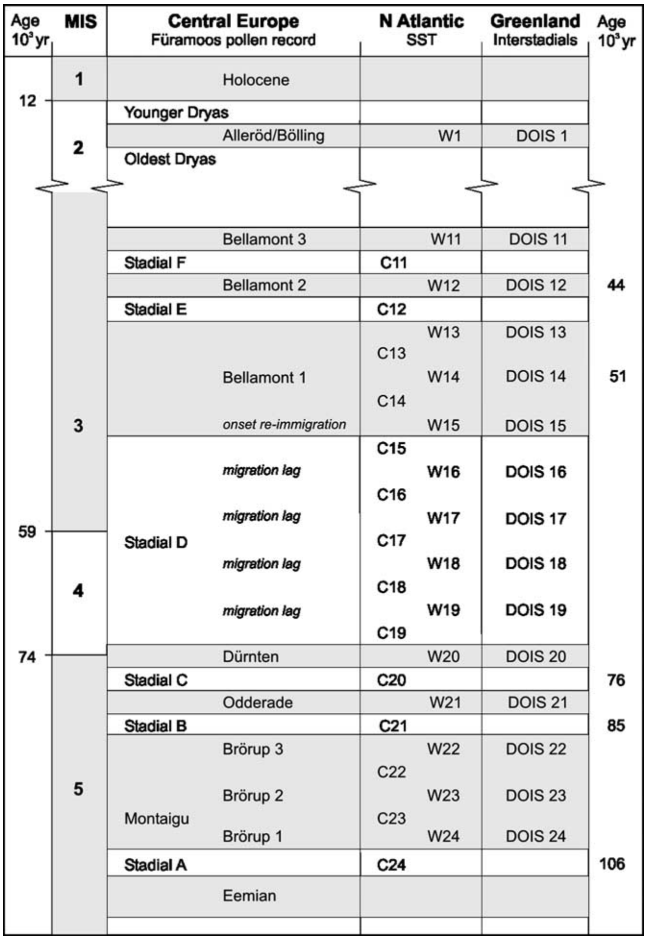


Fig. 6. Stratigraphy of the last glaciation in Central Europe as documented in the Füramoos pollen record and its correlation to MIS (Martinson et al., 1987), SST records from the North Atlantic (McManus et al., 1994), and the GRIP record (Dansgaard et al., 1993). Age data on the left side refer to MIS transitions (Martinson et al., 1987); age data on the right side refer to GRIP, SST, and Füramoos records.

Vegetation response during MIS 4

Figure 5 shows that the polar episodes C18 and C17, documented by the highest abundances of *N. pachyderma* and IRD in marine records, are associated with the strongest

Fig. 5. Correlation of the Füramoos pollen record with the GRIP record (Greenland: Dansgaard et al., 1993) and SST records of site V29-191 (North Atlantic: McManus et al., 1994). Shaded bars mark the correlation of Dansgaard–Oeschger Interstadials (DOIS) with the Füramoos and marine records. DOIS 24 to 20 and 15 to 11 are documented in the Füramoos pollen record, whereas IS 19 to 16 are not recorded due to migration lags.

opening of the vegetation in Central Europe as documented at Füramoos (cf. Stadial D). During this stade (approximately coeval to MIS 4), refugia of woody taxa were restricted to Mediterranean regions as evidenced by, e.g., the Monticchio (Allen et al., 1999) and Ioannina pollen records (Tzedakis, 1993) (Fig. 1).

Vegetation response during MIS 3

The climatic warming with the onset of MIS 3 (ca. 59,000 yr B.P.; Bond et al., 1993) should have allowed a northward migration of arboreal taxa. However, the optimum of the Bellamont 1 interstade in the Füramoos pollen record is documented at ca. 51,000 yr B.P. This dating and a tentative Bellamont 1 duration of ca. 7000 yr based on sedimentation rates indicate a correlation of this interstade with DOIS 14 and 13 (Fig. 5). The next younger Bellamont 2 interstade is dated at ca. 44,000 yr B.P. and has a calculated duration of ca. 1300 yr, suggesting a correlation with DOIS 12. Based on the stratigraphy of the Füramoos and GRIP records, the next younger Bellamont 3 interstade has to be correlated with DOIS 11 at ca. 40,000 yr B.P. (Fig. 5). As can be inferred from this stratigraphic evaluation, DOIS 18 to 15 are not recorded in the Füramoos pollen record (DOIS 15 is probably coeval with the onset of reimmigration during the Bellamont 1 interstade). This may be the result of their short duration (cf. GRIP curve, Fig. 5) in combination with the mountain barrier of the Alps, which hampered the reimmigration of arboreal taxa into Central Europe north of the Alps. The time necessary for reimmigration from southern refugia obviously exceeded the duration of warm conditions in the respective areas (Fig. 6).

Conclusions

Based on the palynostratigraphic evaluation of the Füramoos record, we conclude that the Füramoos site represents the longest late Quaternary pollen sequence currently known north of the Alps. It allows detailed correlations with Greenland ice-core and SST records from the eastern North Atlantic that in turn can be used to examine the vegetation response to rapid climate change in Central Europe north of the Alps. Our data show that the alpine mountain barrier and the duration of warm intervals exerted a strong control on the vegetation during MIS 4 and early MIS 3 in that region. During short warm intervals (i.e., DOIS 19 to 16), the time necessary for the reimmigration of arboreal taxa from southern refugia exceeded the duration of warm conditions. Hence, these intervals are not recorded in the Füramoos pollen record. The location of Füramoos close to the northward migration paths of plant taxa implies that DOIS 19 to 16 may not be reflected in pollen records from sites north of the Alps per se.

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