Quantifying the relationship between pollen sedimentation in lakes and land cover using historical maps

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Pollen records from lake sediments have a great potential for providing information on the quantitative composition of past vegetation and land cover in the surrounding landscape. This can contribute to a better understanding of the development of the cultural landscape and interactions between human impact on the landscape and natural conditions like soil and climate. A good understanding of the history of cultural landscapes is necessary for choosing appropriate management strategies for areas dependent on cultural impact, such as heaths, meadows and dry pastures. It is also important for archaeological research concerning utilisation of the landscape in earlier periods. Furthermore, quantitative reconstructions are relevant for climate research. Here they can be used to test climate models, since model predictions of past climate can be translated into past vegetation, which can then be compared to pollen-based reconstructions. Past vegetation cover is also a necessary input to climate models, as it influences albedo, evapotranspiration and carbon storage and cycling.

Quantifying vegetation from fossil pollen samples requires a detailed understanding of the way vegetation is reflected in pollen assemblages, including the approximate size of the area of vegetation represented. The relationship between pollen and vegetation is complicated by the fact that different plant species produce different amounts of pollen, and that pollen types are dispersed differently in the atmosphere, depending on their size, shape and weight. These pressing challenges in pollen analysis have attracted much attention in recent years. Models have been developed to describe and simulate species specific pollen dispersal, to quantitatively relate pollen proportions to plant abundance, as well as estimate pollen productivity and to quantify the pollen source area of different types of basins (Parsons & Prentice 1981; Prentice & Parsons 1983; Prentice 1985; Sugita 1993, 1994; Sugita *et al*. 1997, 1999; Broström 2002; Bunting *et al*. 2004).

The Geological Survey of Denmark and Greenland (GEUS) has in recent years contributed to the development and validation of such models through the project *AGRAR 2000* (Odgaard 1999; Nielsen 2003), where quantitative estimates of past land cover in different regions of Denmark were one of the main objectives, and through participation in the international research network POLLANDCAL (POLlen LANdscape CALibration), funded by NORDFORSK (Nordic Research Board), which focuses on further model development, validation and application.

The historical analogues approach

Modern analogues of past landscapes are very rare in Denmark due to extensive changes to the cultural landscape during the past two centuries. These include intensification of agricultural practices, such as drainage, fertilisation and use of pesticides, plantations of introduced tree species and reductions in areas of pasture, wetland and heathland. The resulting changes in species composition, vegetation structure and growing conditions have affected the relationship between vegetation and pollen sedimentation through changes in pollen productivity and dispersal (Nielsen & Odgaard 2004).

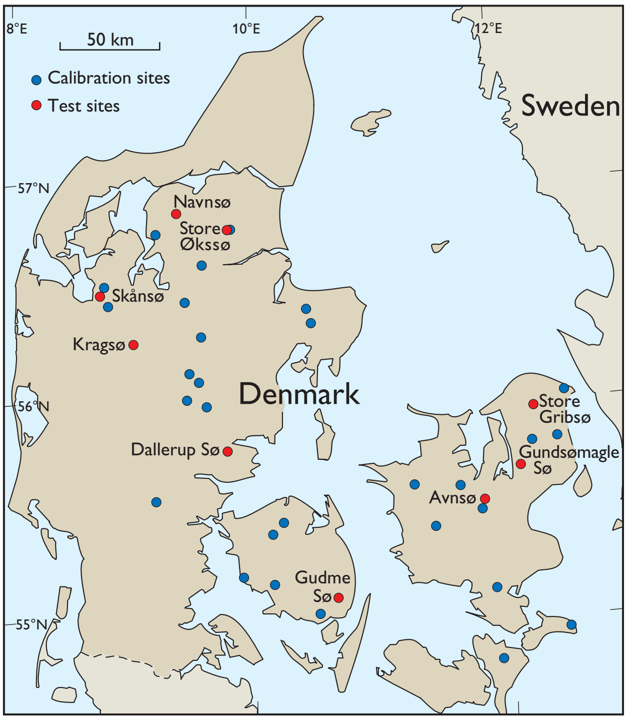

Fig. 1. Map showing the location of the 30 Danish calibration sites and nine test sites used to assess the use of historical land cover and pollen assemblage data and the ERV model for vegetation reconstruction. Modified from Nielsen & Odgaard (2005).

Modern pollen datasets are thus not suitable as a standard for reconstructing cultural landscapes from fossil pollen samples. These problems may be overcome by using historical data (Odgaard & Rasmussen 2000; Nielsen & Odgaard 2004), although this approach involves several sources of error and potential bias, including a lack of spatial precision and detail, problems in interpretation of land cover signatures, biased species selection, changes in nomenclature and potential dating problems. In spite of these problems, most of which arise because the historical data were usually not created with the purpose of describing the plant species distribution in detail, this and other studies have shown that historical analogues can provide new insights and assist the interpretation of palaeoecological data.

The historical calibration dataset collected for this study consists of pollen samples from around A.D. 1800 (identified by ^{210}PB dating) from 30 small (3–30 ha) Danish lakes (Fig. 1), and land cover data from historical maps around the lakes (Nielsen 2003). The historical maps used were the so-called 'parish maps', which show areas of different land cover, such as arable fields, forest, meadow and heath around A.D. 1800 at scale 1:20 000. Spatial plant distribution was estimated from the land cover using historical data (B. Fritzbøger and J.R. Rømer, personal communication 2000) and comparison to modern analogues of old cultural landscape types in southern Sweden (Broström 2002), where areas of traditional land use are more common than in Denmark.

The nine study sites of the *AGRAR 2000* project (Nielsen & Odgaard 2005) were not included in the calibration dataset, so these could be used as independent test sites (Fig. 1) for the vegetation reconstructions.

Distance weighting vegetation data

Plants growing near a depositional basin contribute more to the pollen assemblages in the basin than plants farther away. Vegetation data should therefore be distance weighted to reflect the 'pollen sample's view' of the landscape, before pollen/vegetation calibration is applied (Prentice 1985). The vegetation data from the historical maps were distance weighted according to the Prentice/Sugita model of pollen dispersal and deposition (Prentice 1985; Sugita 1993) using computer programs developed by S. Sugita (1994, unpublished data 2002). In this model, pollen dispersal is assumed to follow Sutton's (1953) equation for the dispersal of small particles in the atmosphere, and depends on the weight and size of pollen grains, which are species specific, and on wind speed and atmospheric conditions. Only windborne pollen is considered by the model, so only lakes with small or no inlet streams were used as calibration sites. The model's predictions of pollen assemblages deposited in different basins have been validated for forested landscapes in North America (Calcote 1995; Sugita *et al.* 1997; Davis 2000) and for cultural landscapes in Sweden and Denmark (Broström 2002; Nielsen 2004; Nielsen & Sugita in press).

The extended R-value model

The quantitative relationship between the pollen assemblages from the lakes and the distance weighted plant abundance estimated from the historical maps was analysed using the Extended R-Value (ERV) model (Parsons & Prentice 1981; Prentice & Parsons 1983; Sugita 1994). This model was developed to achieve quantitative vegetation reconstructions from pollen proportions. The basic assumption is that the pollen loading of species k at site i (P_{ik}) is linearly related to the distance weighted plant abundance of species k in the relevant source area of site i (x_{ik}):

$$P_{ik} = \alpha_i x_{ik} + y_{io} \quad (1)$$

where α_i is the pollen productivity of species i, and y_{io} is the amount of pollen of species i originating outside the relevant source area. Both are assumed to be constant among sites in a region. If y_{io} is furthermore assumed to form a constant proportion (z_i) of the total plant abundance at the site (ERV submodel 2), it is possible to relate pollen percentage to vegetation percentage, and estimate α_i and z_i from a dataset of pollen counts and distance weighted plant abundance, using a maximum likelihood method (Prentice & Parsons 1983). Once these parameters are estimated, the inverse form of the ERV model can be used to reconstruct plant proportions from pollen proportions.

Pollen productivity (α_i) and the background component (z_i) for four groups of plants (trees, Poaceae, Cerealia and *Calluna*) were estimated from the A.D. 1800 vegetation and pollen data (Table 1; Nielsen & Odgaard 2005). The estimated values of α_i are relative, as one taxon (here Poaceae) is chosen as reference taxon. The relative pollen productivity estimates of Cerealia and *Calluna* are lower than those for southern Sweden (Broström *et al.* 2004), whereas the estimate for trees in Denmark is higher than that for Sweden (Sugita *et al.* 1999). The differences may be explained by the Swedish estimates being based on analyses of moss polsters, while the Danish estimates derive from lake sediments. Tree pollen may be more easily dispersed to lakes than herb pollen, because it is released at a greater height. A difference in species composition within the plant groups between Denmark in A.D. 1800 and Sweden today may also contribute to the observed differences (Nielsen 2004).

Table 1. ERV parameter estimates

	α_i (sd)	z_i (sd)	α, southern Sweden
Poaceae	1.0 (0.0)	0.94 (0.022)	1.0
Cerealia	0.95 (0.20)	0.11 (0.025)	3.2
Calluna	2.06 (0.042)	0.10 (0.005)	4.7
Trees	9.41 (0.48)	1.33 (0.002)	5.95

Pollen productivity (α_i) and background component (z_i) estimated from the calibration sites, using ERV submodel 2. For comparison, pollen productivity estimated from moss samples from southern Sweden (Sugita *et al.* 1999; Broström *et al.* 2004) are also listed.

Estimating pollen source area

The spatial scale reflected by pollen samples is vital for quantitative reconstructions of past vegetation and landscape inferred from fossil pollen data, and a rigorous definition of the pollen source area is needed. Sugita (1994) proposed the concept of the 'Relevant Source Area of Pollen' (RSAP), defined as the area beyond which the correlation between pollen deposition at each site and the surrounding vegetation does not improve. The pollen loading (in terms of amount and composition) coming from beyond RSAP is constant between sites within a region, corresponding to y_{io} in equation (1).

The radius of RSAP can be estimated simultaneously with ERV model parameters from the dataset of pollen counts and distance weighted plant abundance, and the distance where the likelihood function score of the ERV calculations no longer decreases, because fit of the model no longer improves (Sugita 1994).

By analysing the data from the calibration sites, the radius of RSAP for the Danish lakes is estimated to *c.* 1800 m from the centre of lakes for all sites (Nielsen & Sugita in press). A difference in RSAP radius of 400–500 m between eastern and western Denmark was observed. This can be explained by a difference in the average patch size of the vegetation between regions (33 ha around eastern sites, 79 ha around western sites). Both simulations (Sugita 1994; Broström 2002; Bunting *et al.* 2004; Nielsen & Sugita in press) and empirical data (Calcote 1995; Nielsen & Sugita in press) suggest that RSAP is affected primarily by the spatial distribution of vegetation, especially patch size. RSAP has been shown to be largely independent of fall speed or relative pollen productivity of the taxa present in the landscape, so the species involved have little effect on RSAP (Bunting *et al.* 2004; Nielsen & Sugita in press).

The size of RSAP is important for the interpretation of fossil pollen assemblages, as it is only vegetation within this area that potentially can be reconstructed.

Reconstructing land cover

The estimates of α_i and z_i from the calibration sites were used to reconstruct vegetation composition around the nine test sites, applying the inverse form of the ERV model (Prentice & Parsons 1983). The reconstructions are compared to distance weighted vegetation composition in RSAP of the test sites from historical maps (Fig. 2). The reconstructions based on the ERV model reflect actual differences in vegetation among the test sites much more clearly than the pollen pro-

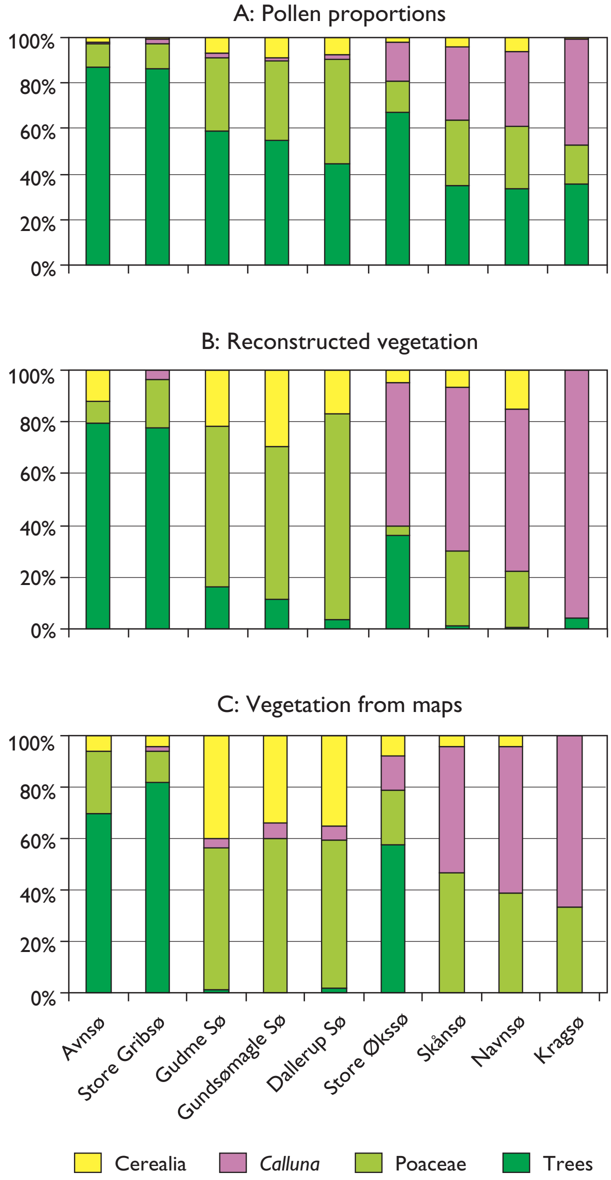

Fig. 2. **A**: Pollen proportions in the A.D. 1800 sediment of the nine test sites. **B**: Distance weighted vegetation proportions reconstructed from the pollen counts using the reverse ERV model, and the parameters estimated from the calibration sites (Table 1). **C**: The distance weighted vegetation proportions within 1800 m of the centre of the test sites, calculated from the A.D. 1800 land cover maps.

portions of the samples. For example, the samples from all test sites contain more than 25% tree pollen, although the surroundings of many sites contain very little woodland, a fact which is reflected by the reconstructions. The amount of *Calluna* tends to be higher in the reconstructions than estimated from the maps, which could indicate that the estimated α_i for this species is too low, or that the A.D. 1800 heathlands were richer in *Calluna* than was assumed based on present-day heathlands in southern Sweden. However, the reconstructions clearly distinguish the sites where heathland was common (Store Økssø, Skånsø, Navnsø and Kragsø; Fig. 1). The reconstructed amounts of Cerealia reflect very well the differences in the amount of arable land between the test sites.

Conclusions

The use of historical maps has proved very useful for quantifying the relationship between pollen sedimentation and vegetation. It has provided an empirical validation of the Prentice/Sugita model of pollen dispersal for open cultural landscapes (Nielsen 2004), made it possible to estimate the relevant source area of pollen, and provided insights into the factors affecting RSAP (Nielsen & Sugita in press). Finally, it has provided a set of ERV model parameters and shown that ERV-based reconstructions reflect the actual patterns of vegetation composition around the lakes (Nielsen & Odgaard 2005). The next step is to apply these findings to fossil pollen diagrams and reconstruct the cultural landscape of earlier periods, from which no maps are available. This research will continue at GEUS in the coming years, thanks to a grant from the Carlsberg Foundation.

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