The potential of REVEALS-based vegetation reconstructions using pollen records from alluvial floodplains

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Abstract The two-step Landscape Reconstruction Algorithm (LRA) - comprising the models REVEALS and LOVE - translates fossil pollen assemblages into quantitative reconstructions of past vegetation cover. The REVEALS model has been applied to lakes and bogs of varied sizes, but application to records from alluvial sites is currently lacking and could further extend these reconstructions to areas where lakes and bogs are absent. In addition, since alluvial sites are often located in areas that experienced early anthropogenic impact, such data will provide more insight into land cover change in the context of agricultural development. In this paper, we test the performance of the REVEALS model using pollen records from multiple alluvial sites obtained from the floodplains of the Belgian Dijle catchment. The modelled vegetation cover is compared to the observed vegetation cover based on a historical land cover map of ca. AD 1775 (ca. 175 cal BP). The discrepancy between the modelled and the observed regional vegetation cover is relatively small and can largely be explained by local differences in land cover surrounding the sites, based on the results of the LOVE model. This study concludes that the LRA approach accurately reconstructs the regional vegetation cover of the river catchment based on pollen obtained from alluvial floodplains, and shows that it is able to reflect major local differences in land cover as well. Including pollen data obtained from alluvial floodplains could lead to a substantial increase in spatial coverage of future LRA-based land cover reconstructions.

Keywords Pollen · Landscape Reconstruction Algorithm · REVEALS model · LOVE model · Vegetation cover · Alluvial floodplains

Introduction

During the Early and Middle Holocene, most river floodplains in Northwestern Europe were stable environments mainly influenced by natural forces, resulting in

low-energy multichannel rivers in swampy floodplains. From the Neolithic period onwards, the clearance of forests for agricultural purposes exposed soils and resulted in an increase in soil erosion from the hillslopes, covering the peat deposits with thick layers of sediment and turning these environments into single channel meandering rivers with overbank deposits (e.g. Lespez et al. 2008; Notebaert and Verstraeten 2010; Fuchs et al. 2011; Broothaerts et al. 2014a). To gain a better understanding of the role of humans in this process, a reconstruction of Holocene land cover changes is needed (Verstraeten et al. 2009; Notebaert et al. 2018). Pollen-based land cover reconstructions are widely applied and while traditional methods based on the presence of anthropogenic indicators in the pollen data (e.g. cereals or weeds; Behre 1981), or on changes in vegetation composition (e.g. non-arboreal/arboreal pollen ratio; Faegri and Iversen 1989) can give an impression of the evolution of the landscape, these interpretations remain mainly qualitative, making determination of causal factors and comparisons between different study sites difficult.

In addition, the relationship between pollen and vegetation cover is not straightforward as different taxa produce different amounts of pollen that are not equally effectively dispersed through the landscape, resulting in an over- or underrepresentation of taxa in the pollen record (Berglund 1973; Prentice 1985; Broström et al. 1998). To translate pollen data into past vegetation, fossil pollen assemblages can be matched to present assemblages (Modern Analogue Technique; e.g. Overpeck et al. 1985). However, such approaches are limited by the availability of modern surface samples from locations representing possible past communities, which can be difficult to find in areas under long and intense human impact, such as Northwestern Europe (Bunting and Middleton 2009). Although alternative methods using a combination of modelling and analogue matching are available (Multiple Scenario Approach; Bunting and Middleton 2009) mathematical descriptions of the pollen-vegetation relationship have been most widely tested and applied to translate pollen counts into quantitative estimates of past vegetation composition.

A first attempt to correct for the pollen production and dispersal biases was undertaken by Davis (1963), and was later refined by Parsons and Prentice (1981). These approaches correct for differences in pollen production and dispersal at the same time, by a taxon-specific factor (R-value). The later two-step Landscape

Reconstruction Algorithm (LRA; Sugita 2007a, b) corrects for production and dispersal biases separately, while also taking into account the size and type of the sedimentary basin in which the pollen is deposited to translate pollen data into quantitative reconstructions of past vegetation cover, and is currently the most widely applied model.

The LRA-submodel REVEALS (Regional Estimates of VEgetation Abundance from Large Sites; Sugita 2007a) was developed to quantitatively reconstruct regional vegetation composition within a 50-100 km radius using pollen data from large lakes. Whilst it is difficult to define the size of a 'large lake', it is typically suggested to be similar to the size of the largest vegetation patches in the region (Sugita 2007a; Trondman et al. 2016). The model has been tested with numerous simulations (Sugita 2007a) and has successfully been evaluated for large lakes against actual vegetation in Sweden (Hellman et al. 2008a), Switzerland (Soepboer et al. 2010) and Norway (Hjelle et al. 2015). In addition, Hjelle et al. (2015) showed that using various sets of pollen surface samples from multiple small lakes yielded results comparable to those using one large lake. This is in line with simulations by Sugita (2007a) which predicted that pollen data from multiple small lakes within a region can be used instead of one or a few large lakes to estimate regional vegetation composition.

To extend the applicability of the model to regions of the world where large lakes are rare or absent, the model has been evaluated for groups of small sites including both lakes and bogs. These studies have shown that a group of such small sites can also be used to estimate regional vegetation with REVEALS, although standard errors of REVEALS-based land cover estimates will generally be larger when using a group of small sites (Mazier et al. 2012; Fyfe et al. 2013; Trondman et al. 2016), as predicted by the simulations of Sugita (2007a) using smaller lakes. These large error estimates can be explained by the generally higher variability of the pollen assemblages from small sites and will decrease with increasing pollen counts and site number (Trondman et al. 2016). The number of sites required to derive reliable REVEALS-based land cover estimates depends on the complexity of the vegetation cover in the region (Sugita et al. 2010). Again, the size of a 'small site' depends on the size and the distribution of vegetation patches in the region (Sugita 2007a; Trondman et al. 2016). A recent study suggested that even pollen records from sites as small as wells (diameter: max. 3

m) may be used for REVEALS reconstructions of past vegetation cover (Lagerås and Fredh 2020).

Whilst the integration of bogs into the land cover reconstructions led to a substantial increase of spatial coverage compared to only including lakes (Trondman et al. 2015; Kaplan et al. 2017), these bogs are often located in marginal areas that have experienced limited anthropogenic impact. This leads to the paradox that most of our current knowledge on land cover change, and in particular agricultural development, is based largely on pollen data obtained from the periphery of the agricultural landscape. In addition, the few suitable sampling locations in areas that experienced historical human impact have often been destroyed by drainage, ploughing and peat harvesting (Lagerås and Fredh 2020). Due to the lack of lakes and bogs in many Northwestern and Central European regions in general and the European loess belt in particular, no detailed pollen-based land cover reconstructions are available for these areas, which is also reflected by the data gaps in the currently available European REVEALS-based land cover reconstructions (Trondman et al. 2015; Kaplan et al. 2017; Githumbi et al. 2021). The river systems in these areas have been proven to fulfill a similar role as archives for environmental and land cover changes on a Holocene time scale (e.g. Lespez et al. 2008; Notebaert and Verstraeten 2010; Fuchs et al. 2011; Broothaerts et al. 2014a). Including pollen obtained from alluvial sites could improve the spatial coverage and the accuracy of pollen-based land cover reconstructions, especially with regard to understanding human transformation of the landscape.

Numerous pollen records from alluvial sites varying in terms of soil properties, topographies, and durations and intensities of human impact are available from locations within Belgium (e.g. Heyvaert 1983; Bakels 1992; Gelorini et al. 2007, 2008; Allemeersch 2010; Broothaerts et al. 2014b). Three pollen cores from alluvial sites near the Schelde river were used in previous studies (Roberts et al. 2018; Woodbridge et al. 2018, 2019). Yet these were only included in the application of the Pseudobiomization Method (Fyfe et al. 2010, 2015) and Plant Functional Types approach (Davis et al. 2015) in the studies, which do not take taxon-specific differences in pollen productivity and dispersal fully into account. Thus they have been excluded so far from REVEALS reconstructions as the data were not obtained from lakes or bogs as the model requires. Within this study, we

aim to test whether REVEALS is able to accurately reconstruct past regional vegetation composition based on pollen data obtained from groups of alluvial sites.

Traditionally, REVEALS has been validated by running the model using modern pollen assemblages and comparing the REVEALS estimates of modern regional vegetation with actual present-day land cover (Hellman et al. 2008a; Soepboer et al. 2010; Hjelle et al. 2015). Yet, for many regions no modern pollen data are available, which further restricts the potential for testing and validating REVEALS-based land cover reconstructions. Recently, however, the use of historical pollen data and land cover maps from the same period has been shown to be an effective alternative method for validating the REVEALS model (Lagerås and Fredh 2020).

In this study, REVEALS-based vegetation reconstructions for the Belgian Dijle catchment (750 km²) will be evaluated with vegetation data from a historical land cover map of ca. AD 1775 (ca. 175 cal BP). This land cover map only comprises the Dijle catchment and not the complete reconstruction radius of REVEALS (50-100 km). Therefore, the vegetation proportions at the local scale estimated by the second model included in the LRA, LOVE (LOcal Vegetation Estimates; Sugita 2007b), will be additionally compared to the historical land cover around each of the sites. Local land cover estimates by the LOVE model showed good correspondence with land cover extracted from historical maps in previous studies (Nielsen and Odgaard 2010; Fredh 2012; Overballe-Petersen et al. 2013; Cui et al. 2014; Mazier et al. 2015) supporting the idea that sufficiently detailed and reliable historical land cover maps can provide an effective alternative validation method.

Study area

The LRA will be evaluated for alluvial floodplains based on pollen data obtained from the Dijle catchment (750 km²), located in the central Belgian loess belt (Fig. 1). The catchment has been the subject of studies focusing on vegetation changes for several decades, although with poor chronological control (Mullenders and Gullentops 1957; Mullenders et al. 1966; De Smedt 1973; Geurts 1976). Therefore, we rely on well-dated pollen sequences obtained in the study by Broothaerts et al. (2014b). The studied deposits consist of Early to Middle Holocene peat covered by thick Late Holocene layers of (organic-rich) sediment.

The location of the pollen profiles within the river valleys was chosen based on a good preservation of this transition (e.g. no indications of erosion of the peat). The Linearbandkeramik culture arrived in the Belgian loess belt around 7,200 cal BP, although no indications of its presence in the Dijle catchment have been found (Vanmontfort 2007, 2008). The oldest known Neolithic settlement in the catchment - dated ca. 6,200 cal BP - is located in close proximity to one of the study sites (i.e. Archennes; Fig. 1) (Crombé and Vanmontfort 2007; Vanmontfort 2007). No large-scale human activities were detected during the Mesolithic or Neolithic periods, but from the Bronze Age onwards (ca. 3,900 cal BP) human impact was clearly recorded in the pollen data as a decrease in arboreal pollen and an increase in cereals and weeds (Broothaerts et al. 2014b). Human impact further increased from the Iron Age onwards (ca. 2,700 cal BP), interrupted by a temporary decrease during the Dark Ages (Broothaerts et al. 2014b, 2021). Besides some local variations in timing and intensity of human impact in the different subcatchments, general vegetation development and increasing human impact are similar at the catchment scale (Broothaerts et al. 2014b).

Current land use in the catchment is dominated by cropland. In the northeast (Meerdaal Forest) and northwest (Zoniën Forest) of the Dijle catchment, large deciduous plantation forests are present (Fig. 1), dominated by *Fagus* (beech). Historical documents indicate that these woodlands remained forested for several centuries: the Meerdaal Forest at least since the 14th century AD (Vanwalleghem et al. 2005), and the Zoniën Forest at least since the 12th century AD (Langohr 2001). No agricultural activities have taken place in these forests since the 14th century AD (Vanwalleghem et al. 2005). The floodplains are currently covered by grassland, with some patches of wet forest dominated by *Alnus* (alder).

Materials and methods

Historical land cover data

A first land cover map of the Dijle catchment is available from ca. AD 1775 (ca. 175 cal BP): the illustrative *de Ferraris* map (Fig. 2). This map is the first systematic topographic map of 'Belgium' (i.e. Austrian Netherlands) created between AD 1770 and 1778 by the count Joseph de Ferraris, commissioned by Maria-Theresia and Joseph II. It consists of 275 sheets (1:11,520 scale),

accompanied by 4,000 pages of descriptions. Forested areas on this map have been digitized for Belgium. Positional errors of this high-quality historical map have been corrected to obtain an accurate localization of forests (AGIV 2014; Vervust 2016; SPW 2020).

The Ferraris map for the Dijle catchment was manually digitized by Notebaert et al. (2011) using ten land cover classes: cropland, grassland, forest, orchards, gardens and houses, parks, built-up area, heathland, marshes, and water. Due to the lack of historical data on the plant taxa included in these land cover classes, we opted for a simplified approach in which for each land cover class an estimation of cover by trees, grass, cereals and heather has been made (Table 1). We assumed, following Lindemans (1994), that at the end of the 18th century AD wheat production dominated the Belgian loess belt and that a three course rotation was used with minimal fallow land. Consequently, we assume that ca. 2/3 of the cropland area was subject to cereal cultivation and ca. 1/3 were fallow fields on which grasses and herbs can grow (Table 1). The area covered by the individual land cover classes on the Ferraris map within the Dijle catchment was combined with the estimations of the abundance of trees, grass, cereals and heather within each land cover class to estimate the vegetation cover in the catchment around AD 1775:

cover estimate = (land cover class * area)/total percentage of land covered by vegetation

Eq. 1

We thus estimate for example that whilst cropland covers ca. 66% of the area on the Ferraris map, this land cover class is expected to represent only 46% in the pollen-based reconstructions as represented by the cereal plant taxa (Table 1). Likewise, grassland pollen taxa will be more prominent (32%) compared to the area that represents grassland (7%) as these pollen taxa are also present within other land cover categories (Table 1).

Pollen data

Detailed and well-dated pollen records from alluvial study sites in the Dijle catchment are already available (Broothaerts et al. 2014b). Within this study, the radiocarbon dates obtained in Broothaerts et al. (2014b) were recalibrated (95%

probability) using relevant and up-to-date atmospheric data (Reimer et al. 2020) and age-depth models were established with the package rbacon in R (version 2.5.0, Blaauw and Christen 2011; RStudio Team 2020). Based on the age-depth models, improved continuous timeframes for the sediment sequences were obtained.

Additional pollen samples were collected at four study sites using a gouge auger (diameter: 6 cm). Palynological analysis was performed for selected depths corresponding with the time of the Ferraris map, according to the constructed age-depth models (Table 2). Vegetation changes in the Dijle catchment are assumed to be relatively minor during this time (Van Rompaey et al. 2002; De Keersmaeker et al. 2015). Pollen samples were prepared following the standard techniques of Faegri and Iversen (1989). Beug (2004), Moore et al. (1991) and a modern reference collection were used for the identification of pollen types.

The LRA and (the violation of) its assumptions

The LRA (Landscape Reconstruction Algorithm) consists of two steps: the first step is to estimate regional vegetation composition within a 50-100 km radius by the REVEALS (Regional Estimates of VEgetation Abundance from Large Sites) model, and the second step is to estimate local vegetation composition within the relevant source area of pollen by the LOVE (LOcal Vegetation Estimates) model. The basic assumptions of the models include (Sugita 2007a, b):

1. The sedimentary basin for pollen deposition is a circular opening in the canopy, and no source plants for pollen exist on the basin;
2. The dominant agent of pollen transport is wind above the canopy, and no pollen inputs from water inlets or surface run-off are considered;
3. Pollen is dispersed and deposited under neutral atmospheric conditions;
4. Pollen dispersal is even in all directions;
5. Differences in height of pollen sources are not considered;
6. The regional vegetation factor is region-specific and does not vary among sites in a given region. Most of the pollen comes from within a radius of 50-100 km of the site. The amount of pollen loading coming from beyond this radius is negligible;
7. Within-site variation of pollen assemblages is insignificant and a pollen assemblage from a given basin is representative for the entire basin;

8. Pollen productivity is constant for each taxon for a given region;
9. There are no inter-taxonomic preservation biases of pollen grains in sediments.

Some of these assumptions will be violated when the approach is applied to alluvial sites. Firstly, the basin type from which the pollen data were constructed has to be specified in the models, and is either ‘lake’ or ‘peatland’ (Sugita 2007a, b). Depending on the type of site, a different model of pollen dispersal and deposition is used: Prentice's model for peatlands where pollen does not move once deposited (Prentice 1985); or Sugita's model for lakes where mixing of pollen occurs after deposition in the lake water before sedimentation (Sugita 1993). The floodplains of the Dijle used to be natural peatlands during the Early and Middle Holocene; these became covered by thick layers of sediment - in which pollen is also not assumed to move after deposition - during the Late Holocene. Therefore, we opted for the ‘peatland’ basin type to run the models. Moreover, the LRA assumes that no pollen is derived from plants growing on the basin (Sugita 2007a, b). The overestimation of locally occurring taxa is a common issue in REVEALS-based reconstructions and results in unreliable estimates of the regional land cover (e.g. Nielsen 2004; Mazier et al. 2012; Trondman et al. 2015, 2016). Therefore, the taxa belonging to the local wetland vegetation (i.e. *Alnus*, *Salix*, Cyperaceae and *Filipendula*) had to be excluded from the model runs. While the historical land cover map of the Dijle catchment shows that the land cover classes ‘marshes’ and ‘grassland’ are roughly confined to the river floodplains, pollen belonging to the Poaceae family cannot be completely excluded from the model runs as they are occurring in most of the land cover classes (Table 1). Therefore, it has to be kept in mind when interpreting the model output that the proportion of grassland might be overestimated.

In addition, the models assume that atmospheric pollen deposition is the major source of pollen input, thus sites need to be carefully selected to reduce biases caused by significant amounts of pollen transported to the sites by rivers, streams or surface-runoff (Sugita 2007a, b; Theuerkauf et al. 2016). However, fluvial input can be a significant source of pollen into alluvial wetlands. A more quantitative approach to stream-borne pollen could improve vegetation reconstructions based on pollen data obtained from sites experiencing major fluvial inputs but this is not currently available (Brown et al. 2007; Xu et al. 2012). Meanwhile, large lakes often have major water inlets and outlets and, as a

result, most of the pollen actually enters these lakes by stream-borne transport from river catchments (Peck 1973; Pennington 1973, 1979; Bonny 1978; Brown et al. 2007; Xu et al. 2012). Furthermore, some of the lakes used in the REVEALS validation studies also have water inlets and outlets, yet the model performs well (Hellman et al. 2008a; Soepboer et al. 2010). The fact that the dominant agent of pollen transport in alluvial settings might not be wind will thus not necessarily result in decreased model performance but nevertheless has to be kept in mind. Finally, the inclusion of entomophilous taxa also violates the assumption of atmospheric deposition and it is argued they should strictly be excluded (Mazier et al. 2012). Yet, some ecologically important taxa in our study (e.g. *Tilia* and Ericaceae) can be spread both by wind and animals. As more recently REVEALS has been successfully applied using both wind- and animal-pollinated taxa (Mariani et al. 2017; Marquer et al. 2020), we decided not to exclude any taxon based on its mode of dispersal.

Applying the REVEALS model to the pollen data

In this study, the REVEALS model was applied using the 'REVEALSinR' function within the R package disqover (version 0.9.08, Theuerkauf et al. 2016). The compilation of multiple sites was carried out using the R package for the Landscape Reconstruction Algorithm (version 0.1.0, Abraham et al. 2014), with mean standard errors calculated using the delta method (Stuart and Ord 1994). Results were subsequently plotted using the package ggplot2 (version 3.1.1, Wickham 2016).

The REVEALS model requires several parameters to be set according to site characteristics and information about the pollen productivity and dispersal of different plant types. REVEALS runs comprising only pollen data from ca. AD 1775 (ca. 175 cal BP) were performed for the Dijle catchment. The pollen data are provided as absolute counts. The pollen types were run separately within the REVEALS model and summed afterwards into the four simplified vegetation classes (trees, grass, cereals and heather) allowing comparison with observed vegetation cover. 'Peatland' was selected as basin type (see above) whilst basin diameter was set to the floodplain width at the pollen coring location (Archennes = 510 m, Loonbeek = 140 m, Sclage = 85 m, Cortil = 75 m).

By default, REVEALSinR uses a Lagrangian stochastic dispersal model (LSM; Kuparinen et al. 2007) as this model predicts the pollen dispersal pattern more realistically than the simple Gaussian plume model (GPM) based on Sutton's equations, used by Prentice (1985). The REVEALS model uses pollen productivity estimates (PPEs) to account for the plant production bias and fall speeds of pollen (FSPs) and the associated 'pollen dispersal-deposition coefficient' or K-factor to account for the dispersal bias. However, only one set of LSM-based PPEs is available thus far (Theuerkauf et al. 2015); considering their variations caused by various environmental and anthropogenic factors it is necessary to further evaluate LSM-based PPEs before common use (Marquer et al. 2020). Therefore, within this study the GPM was applied. Atmospheric conditions are assumed to be neutral (Sugita 2007a). A constant wind speed of 3 m/s was used, roughly corresponding to the modern mean annual wind speed in Europe (Trondman et al. 2015; Githumbi et al. 2021). The diameter of the reconstruction region (Zmax) was set to 100 km, based on earlier evaluations of the effect of this parameter on REVEALS-based estimates of land cover (Hellman et al. 2008b; Mazier et al. 2012; Trondman et al. 2016).

Pollen productivity estimates

The REVEALS model uses pollen productivity estimates (PPEs) to account for the plant production bias and fall speeds of pollen (FSPs) to account for the dispersal bias. While these factors are assumed to be constant for each taxon for a given region, PPEs for the same taxon can vary significantly between different study areas (Broström et al. 2008). It is argued that much of this variation is due to differences in vegetation survey methods or pollen sampling methods, although environmental factors such as climate, soils and land use might play a role as well (Broström et al. 2008; Bunting and Hjelle 2010). However, the current amount of PPE data available for individual taxa is not sufficient to confidently explain these differences between study areas (Mazier et al. 2012). Since such data is not available for the Atlantic mainland of Europe, GPM-based PPEs and FSPs obtained from several European datasets (Fig. 3) and European syntheses (Mazier et al. 2012; Wieczorek and Herzschuh 2020; Githumbi et al. 2021) were compared to assess their suitability for our study area.

Broström et al. (2008) suggests that for validation of models included in the LRA, the most relevant PPEs should be included. The datasets obtained in settings that are very different from the river catchments in central Belgium were therefore less suitable (i.e. datasets obtained in densely forested areas, and (sub-) alpine zones: Bunting et al. 2005; Hjelle and Sugita 2012; Matthias et al. 2012; von Stedingk et al. 2008). In addition, the LSM-based PPEs of Theuerkauf et al. (2015) were not considered meaningful to include in our GPM-based model runs.

PPEs represent the amount of pollen produced by a certain taxon in relation to a reference taxon. Poaceae is preferred as the reference taxon as this needs to be a medium pollen producer that is relatively abundant in both the pollen assemblage and the plant community at every site considered in the study (Bunting et al. 2013). For this reason, the PPE dataset of Matthias et al. (2012) is not suitable for this study, as the reference taxon *Pinus* is not sufficiently common in our data. In addition, PPE datasets were only regarded relevant when these include cereals, as cropland is the most common land cover class in the Dijle catchment. Therefore, datasets lacking cereals (i.e. Bunting et al. 2005; Hjelle and Sugita 2012; von Stedingk et al. 2008) were also excluded.

Several taxa for which PPEs are available in the European datasets had to be excluded from the model runs. Besides the previously mentioned taxa belonging to the local wetland vegetation (i.e. *Alnus*, *Salix*, Cyperaceae, and *Filipendula*), the taxa for which the model produced unrealistically high vegetation cover estimates (i.e. Apiaceae, Asteraceae, Brassicaceae, and Chenopodiaceae) were excluded as well (cf. Kulkarni et al. 2018).

Applying the LOVE model to the pollen data

Since the historical land cover map only comprises the Dijle catchment and not the complete reconstruction radius of REVEALS (50-100 km), the vegetation proportions at the local scale estimated by the second model included in the LRA, LOVE (LOcal Vegetation Estimates; Sugita 2007b), were compared to the historical land cover around each of the sites as well. The LRA-submodel LOVE quantifies the vegetation proportions of constituent taxa within the relevant source area of pollen (RSAP; Sugita 2007b). The RSAP is the area beyond which the correlation between pollen and vegetation data does not improve (Sugita 1994). The LOVE model includes the option ‘Backward modeling of LOVE’ to estimate

RSAPs using inverse modelling, which works well when pollen records from many similarly-sized sites are available (Sugita 2007b; Sugita et al. 2010). Since this is not the case in our study, we opted for a fixed RSAP based on the current knowledge of the range of RSAP estimates for (past) cultural landscapes, which varies between 1,000 and 3,000 m (Nielsen and Sugita 2005; Hellman et al. 2009a, b). Based on this information, a fixed radius of 2,200 m was used in this study.

Besides pollen counts, PPEs and FSPs, LOVE requires estimates of regional vegetation composition - obtained by REVEALS - to quantify local vegetation proportions within the RSAP. To avoid circularity in the LRA application, a 'leave-one-out' strategy (Efron and Tibshirani 1993) is used: one site is selected for local vegetation reconstruction with LOVE and the other three sites for regional vegetation reconstruction with REVEALS (cf. Sugita et al. 2010). Again, the pollen types were run separately and summed afterwards into the four simplified vegetation classes (trees, grass, cereals and heather). This process is repeated for each of the four sites included in this study, using LRA.REVEALS.v6.2.5.exe and LRA.LOVE.v6.2.5.exe (Sugita, unpublished). Since the LOVE model estimates distance-weighted vegetation proportions, the historical land cover data extracted from the Ferraris map needs to be distance-weighted as well to allow comparison between modelled and observed vegetation cover. Distance-weighting of these simplified vegetation classes requires their abundances (percentage cover) and fall speeds (FSP) for each simplified vegetation class. We extracted the historical land cover from the edge of each study site out to 2,200 m in 10 m increments using ArcGIS (Fig. 4). The observed vegetation cover on the historical map was converted to the simplified vegetation classes (trees, grass, cereals and heather) following Eq. 1. The fall speeds were calculated as the average values for the pollen types included within a simplified vegetation class weighted by the average proportion of each type in the pollen record (cf. Nielsen and Sugita 2005). Distance-weighted vegetation cover was subsequently calculated using DWPAcalculator.v7.4.exe (Sugita, unpublished) with the extracted land cover data at 10 m increments and the four sets of fall speeds. A Gaussian plume model (GPM) for peatlands based on Sutton's equations was used as the dispersal/deposition function (Prentice 1985).

Results

Pollen data

Pollen data for ca. 175 cal BP for the four study sites are shown in Fig. 5. These show low values of arboreal pollen (AP) and high values of non-arboreal pollen (NAP) including high values of grasses, upland herbs and cereals. Local pollen data indicates that the floodplains were dominated by Cyperaceae, with some *Alnus* occurring.

REVEALS performance with different PPE-datasets

Relevant European PPE-datasets (Fig. 3) and PPE-syntheses (Mazier et al. 2012; Wieczorek and Herzschuh 2020; Githumbi et al. 2021) were compared to assess their suitability for our study area (Fig. 6). Trees appear to be consistently underestimated by the REVEALS model regardless the choice of the PPE-dataset, while the results for other taxon groups are more variable. Overall, the European syntheses of PPEs (Mazier et al. 2012; Wieczorek and Herzschuh 2020; Githumbi et al. 2021) yield the best results (Fig. 6). These datasets are closely resembling the observed cereal cover, while slightly overestimating the proportion of land covered by grass as anticipated given the fact that grasses are also part of the local wetland vegetation. Since the dataset of Githumbi et al. 2021 is not only the latest but also the most complete European dataset currently at hand, we will focus on the LRA results produced using the PPEs and FSPs as synthesized in this dataset (Table 3).

Evaluation of the REVEALS-based land cover reconstruction

While the application of REVEALS using the PPE-dataset of Githumbi et al. 2021 overall yields the best results (Fig. 6) quite some discrepancy between the modelled and observed vegetation cover remains. The mean REVEALS estimates for the proportions of the Dijle catchment covered by trees, grass, cereals and heather do not correspond equally well to the observed vegetation cover, which has been estimated based on the Ferraris historical map. To evaluate to what extent the land cover proportions estimated by REVEALS are an improvement

compared to the uncorrected pollen proportions, they are compared with each other and the observed historical land cover in Fig. 7.

To gain more insight into the performance of the REVEALS model, the regional land cover estimates for the simplified vegetation classes are plotted against the observed land cover within the Dijle catchment in Fig. 8. The regional land cover estimates based on pollen data of each of the separate study sites and a mean estimate based on pollen data of all sites are depicted. The R^2 value of 0.846 indicates some scatter but overall the correlation between the modelled and observed cover is good. Moreover, in particular the mean land cover estimates - compiling the data of the four study sites - are satisfactory. Nevertheless, some differences in REVEALS-based land cover estimates between the sites can be observed. The LOVE model was applied to assess whether these differences in regional land cover estimates can be explained by the local vegetation surrounding these sites.

LOVE-based estimates of the local vegetation cover surrounding the four study sites and observed vegetation cover within a radius of 2,200 m around each respective site are shown in Fig. 9. The modelled and observed proportions for each of the four simplified vegetation classes correlate rather well for both Archennes and Cortil. For Sclage, the local tree cover is highly underestimated by the model. In the case of Loonbeek, the modelled proportion of cereals is much higher than the observed proportion.

Discussion

Performance of the REVEALS model using pollen records from alluvial sites

Overall, the REVEALS-based vegetation reconstructions correspond better to the observed vegetation than the uncorrected pollen proportions (Fig. 7), although there is a tendency to overestimate grassland cover and underestimate tree cover. The correlation between the modelled land cover based on REVEALS and the observed land cover based on the Ferraris historical map appears to be particularly good for the mean estimates, based on the pollen data of all four study sites (Fig. 8). Moreover, the REVEALS-based regional land cover estimates based on the pollen data of each of the separate study sites show quite some differences. This

494 fits with the theory that a ‘multi-site approach’ will provide more reliable
495 REVEALS-based land cover estimates than using a single site in the same region
496 (Hellman et al. 2008a).
497 While the modelled proportion of land covered by cereals is at some sites
498 overestimated and at others underestimated, the mean value for the catchment
499 correlates almost perfectly with the observed vegetation cover (Fig. 8). The model
500 results for heather are satisfactory as well, as its cover is consistently yet only
501 slightly overestimated. On average, the proportion of grass tends to be
502 overestimated by the REVEALS model. This was, however, anticipated since the
503 grassy land cover classes ‘marshes’ and ‘grassland’ are roughly confined to the
504 river floodplains. Yet, pollen belonging to the Poaceae family could not be
505 completely excluded from the model runs, as is usually done with taxa belonging
506 to the local vegetation, as grasses are part of most of the land cover classes (Table
507 1).
508 On the other hand, the REVEALS model consistently underestimates tree cover.
509 A first possible factor explaining this discrepancy between modelled and observed
510 vegetation is the fact that the forest cover within the Dijle catchment itself is much
511 higher than in the surrounding area (AGIV 2014; SPW 2020), which is also part
512 of the reconstruction radius of REVEALS (50-100 km). Forests were only
513 covering 10.8% of Flanders, the northern part of Belgium, around 175 cal BP (De
514 Keersmaeker et al. 2015). Moreover, De Keersmaeker et al. (2015) showed that
515 the potential forest vegetation as determined by the soil type might also have
516 included large patches of forest habitats dominated by alder. It is not clear
517 whether such habitats are classified as ‘marshes’ or ‘forest’ on the Ferarris
518 historical land cover map, but at least the forested areas near the river valleys
519 might have been occupied by alder-dominated forest types (Fig. 4). Since we
520 completely excluded taxa belonging to the local wetland vegetation (including
521 *Alnus* and *Salix*) from the model runs, this likely resulted in a mismatch between
522 observed and modelled tree cover.
523 In addition, most of the potential forest cover in the Dijle catchment and its
524 surroundings is beech-dominated (De Keersmaeker et al. 2015). This is in line
525 with the observed large deciduous plantation forests dominated by *Fagus* in the
526 northeast and northwest of the Dijle catchment (Langohr 2001; Vanwalleghem et
527 al. 2005). *Fagus* is a taxon with relatively heavy pollen (Table 3) that

consequently spreads less easily and can therefore be underrepresented in our cores. Furthermore, the largest patch of forest is located on the western border of the catchment; an area for which we do not have a pollen sequence. This reaffirms that a 'multi-site approach' (Hellman et al. 2008a) should be favored over using a single site in the same region, especially when this region is characterized by a mosaic of vegetation patches (Sugita 2007a; Trondman et al. 2016).

LOVE-based local vegetation cover estimates

To assess whether the differences in REVEALS-based regional land cover estimates between the sites can be explained by the local vegetation surrounding these sites, the LOVE model was applied (Fig. 9). The modelled and observed proportions for each of the four land cover classes correlate rather well for both Archennes - our largest site with a floodplain width of 510 m - and Cortil - our smallest site with a floodplain width of 75 m.

For Sclage, the local tree cover is highly underestimated by the model, whereas the grass cover is highly overestimated. Sclage is located in a cluster of forest patches (Fig. 4). While we assumed a 100% tree cover for the forest land cover class (Table 1), Poaceae can be widespread as ground floor vegetation in forests, especially beneath *Fagus* trees (Overballe-Petersen et al. 2013). In this way, forest undergrowth of grasses and herbs might have contributed a significant amount of grassland pollen that was interpreted as being derived from open areas.

The overestimation of grassland cover and underestimation of forest cover is frequently observed in LOVE-based reconstructions (Nielsen and Odgaard 2010; Fredh 2012; Overballe-Petersen et al. 2013; Mazier et al. 2015). Part of the explanation lies in the fact that the error estimates of the reconstructed proportions of Poaceae are large (Fig. 9), due to a large standard error on the PPE for Poaceae (Table 3; Nielsen and Odgaard 2010). In addition, it partly results from the violation of the LRA-assumption that no vegetation grows on the basin, whereas bogs are in reality often covered with sedges, grasses and herbs. Likewise, the underestimation of grass cover near Loonbeek by the LOVE-model might be related to the composition of the local wetland vegetation; while no difference in floodplain cover near Loonbeek and the other three sites is apparent from the historical land cover map, the pollen data reveals that typical wetland vegetation

is more abundant at Loonbeek compared to the other sites while the percentage of Poaceae is relatively low (Fig. 5).

Finally, in the case of Loonbeek, the modelled proportion of cereals is much higher than the observed proportion. The floodplain near this site is surrounded by relatively steep slopes that were already transformed to agricultural land ca. 175 cal BP (Fig. 4). None of the other studied sites in the Dijle catchment exhibits this combination of characteristics, being either located in a relatively flat area with cropland (i.e. Cortil) or being located in an area with forested slopes (i.e. Archennes). Moreover, this core is located in a rather narrow floodplain (140 m width), making it very plausible that this overestimation of cereals might be related to erosion and additional input of pollen from surface run-off.

Potential of the LRA approach for alluvial sites

Overall, the pollen-based reconstructions of both the regional and local vegetation correspond well with the observed vegetation, suggesting that the LRA-approach can be applied to pollen records from alluvial sites to reconstruct past vegetation cover. Although the number of sites we used within this study is rather low, previous studies with a low amount of sites have proved reliable in the past (e.g. Soepboer et al. 2010). In addition, there is not a minimum recommended number of small sites for REVEALS reconstructions, as the number depends on many factors such as the pollen count for each sample, the characteristics of the vegetation in the region (i.e. number and size of patches) and the distribution of sites within this vegetation mosaic (Trondman et al. 2016). The distribution of the sites within the landscape seems to be an important part of the explanation for the underestimation of tree cover in this study.

Now that its performance has been validated for pollen records from alluvial floodplains, the REVEALS model will be applied in a future study to a wide range of Belgian pollen records from alluvial sites - varying in terms of soil properties, topographies, and durations and intensities of human impact - to obtain the first quantitative land cover reconstruction for Belgium, thereby filling one of the data gaps in the currently available European REVEALS-based land cover reconstructions (Trondman et al. 2015; Kaplan et al. 2017; Githumbi et al. 2021). Including data from alluvial sites will not only improve the spatial coverage of these reconstructions, but is also expected to provide novel insights in Holocene

land cover change, especially with regard to human transformation of the landscape, as these sites are often located within the agricultural landscape rather than at its margins as is the case for most intact peatlands.

Conclusions

The two-step LRA was successfully applied to pollen records from multiple alluvial sites: the REVEALS model accurately reconstructs the regional vegetation cover of the Dijle catchment, and is a major improvement compared to land cover estimates based on the uncorrected pollen proportions that are often used in palaeoenvironmental reconstructions. The discrepancy between the modelled and the observed regional vegetation cover is relatively small and can largely be explained by local differences in land cover surrounding the sites, based on the results of the LOVE model. This also reaffirms that the use of multiple sites will provide more reliable land cover estimates than using a single site in the same region.

This study shows that even though the REVEALS model was developed to quantitatively reconstruct regional vegetation composition within 50-100 km using pollen data from large lakes, it also performs well with pollen data obtained from alluvial floodplains of variable width in reconstructing the land cover proportions of four simplified vegetation classes: trees, grass, cereals and heather. Including pollen data obtained from alluvial floodplains could lead to a substantial increase in spatial coverage of future LRA-based land cover reconstructions compared to only including lakes and bogs. In addition, since these sites are often located in areas that experienced early anthropogenic impact, rather than being located in the periphery of the agricultural landscape, it will provide more insight into land cover change in the context of agricultural development.

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Figure captions

Fig. 1 Dijle catchment with the main rivers (blue), cities (black triangles), forests (green) and the four pollen sites of Broothaerts et al. (2014b) used in this study (red dots) indicated. The smaller map shows the location of the Dijle catchment within Belgium

Fig. 2 Example of part of the original Ferraris historical land cover map (KBR 2006) and its digitized equivalent (Notebaert et al. 2011), with built-up area in grey, gardens and houses in dark green, forest in medium green, grassland in light green, cropland in yellow, heathland in purple, water in blue, parks in pink and orchards in orange. The smaller map shows the location of this area within the Dijle catchment

Fig. 3 Red dots indicate the locations of the cores obtained from the Dijle floodplains. Blue squares indicate the locations of the selected PPE datasets, those in bold (light blue on the map) were evaluated for the Dijle catchment: **1** = Broström et al. (2004), **2** = Fredh et al. (2012), 3 = Von Stedingk et al. (2008), 4 = Hjelle and Sugita (2012), **5** = Nielsen (2003, 2004), 6 = Matthias et al. (2012), 7 = Theuerkauf et al. (2015), **8** = Abraham and Kozáková (2012) , **9** = Abraham et al. (2014), **10** = Poska et al. (2011), 11 = Bunting et al. (2005), **12** = Soepboer et al. (2010)

Fig. 4 Ferraris historical land cover map of the Dijle catchment depicting the land cover ca. AD 1775 (ca. 175 cal BP) with the study sites at which palynological analysis was performed indicated. Distance-weighted percentage cover surrounding the sites within a 2,200 m radius is shown in the pie charts

Fig. 5 Percentage pollen data for ca. 175 cal BP for the four study sites in the Dijle catchment included in the validation runs, with trees in green, herbs and grasses in orange, heather in pink, cereals in red and wetland vegetation in blue. Only the most important taxa are included in the figure; taxa with less than 5% abundance in the four samples as a whole are not shown, unless they are occurring in multiple samples

Fig. 6 Overview of mean REVEALS-based estimates of the four land cover classes (cereals, grass, heather and trees) in the Dijle catchment, using different PPE-datasets. Results are presented as proportions ($\Sigma = 1$), with mean standard errors (SE). Observed vegetation cover is based on the Ferraris historical maps as digitized by Notebaert et al. (2011) and presented in Table 1

Fig. 7 Observed vegetation cover based on the Ferraris historical maps as digitized by Notebaert et al. (2011) and presented in Table 1, mean REVEALS-based estimates of the four land cover classes (cereals, grass, heather and trees) in the Dijle catchment using the PPE-dataset of Githumbi et al. 2021 and mean pollen proportions based on the pollen data used in this study. Results are presented as proportions ($\Sigma = 1$)

Fig. 8 Comparison between the REVEALS-based land cover estimates for each simplified vegetation class - for the separate study sites and as a mean for the Dijle catchment - and the historical land cover for the same classes extracted from the Ferraris historical land cover map. Cereals are depicted in red, grassland in orange, trees in green and heather in pink. The gray line is a linear regression through the data

Fig. 9 LOVE-based estimates of local distance-weighted (DW) land cover within a 2200 m radius surrounding the respective study sites in the Dijle catchment, with SEs of the estimates for each simplified vegetation class, compared to the DW historical land cover for the same simplified

vegetation classes extracted from the Ferraris historical land cover map. Results are presented as proportions (Σ = 1)

Table 1 Land cover classes and cover estimations for trees, grass, cereals, and heather (all in %) based on the manually digitized Ferraris historical land cover map for the Dijle catchment by Notebaert et al. (2011). Cover estimates are calculated by Eq. 1: cover estimate = (land cover class * area)/total percentage of land covered by vegetation

Table 2 Overview of the pollen data corresponding to the time of the Ferraris map (AD 1775; ca. 175 cal BP) used in the analyses

Table 3 Pollen fall speeds in m/s (FSP), and pollen productivity estimates (PPE) and their standard error estimates (SE) used in this study, as synthesized by Githumbi et al. 2021.

Declarations

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Conflicts of interest/Competing interests (include appropriate disclosures): The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material (data transparency): Original pollen dataset will be made available through Pangaea

Code availability (software application or custom code): Application of existing and freely available code.

Authors' contributions (optional: please review the submission guidelines from the journal whether statements are mandatory): All authors contributed to the study conception and design. Pollen data were collected by Nils Broothaerts, and subsequent data analysis was performed by Renske Hoevers. The first draft of the manuscript was written by Renske Hoevers and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Fig. 1

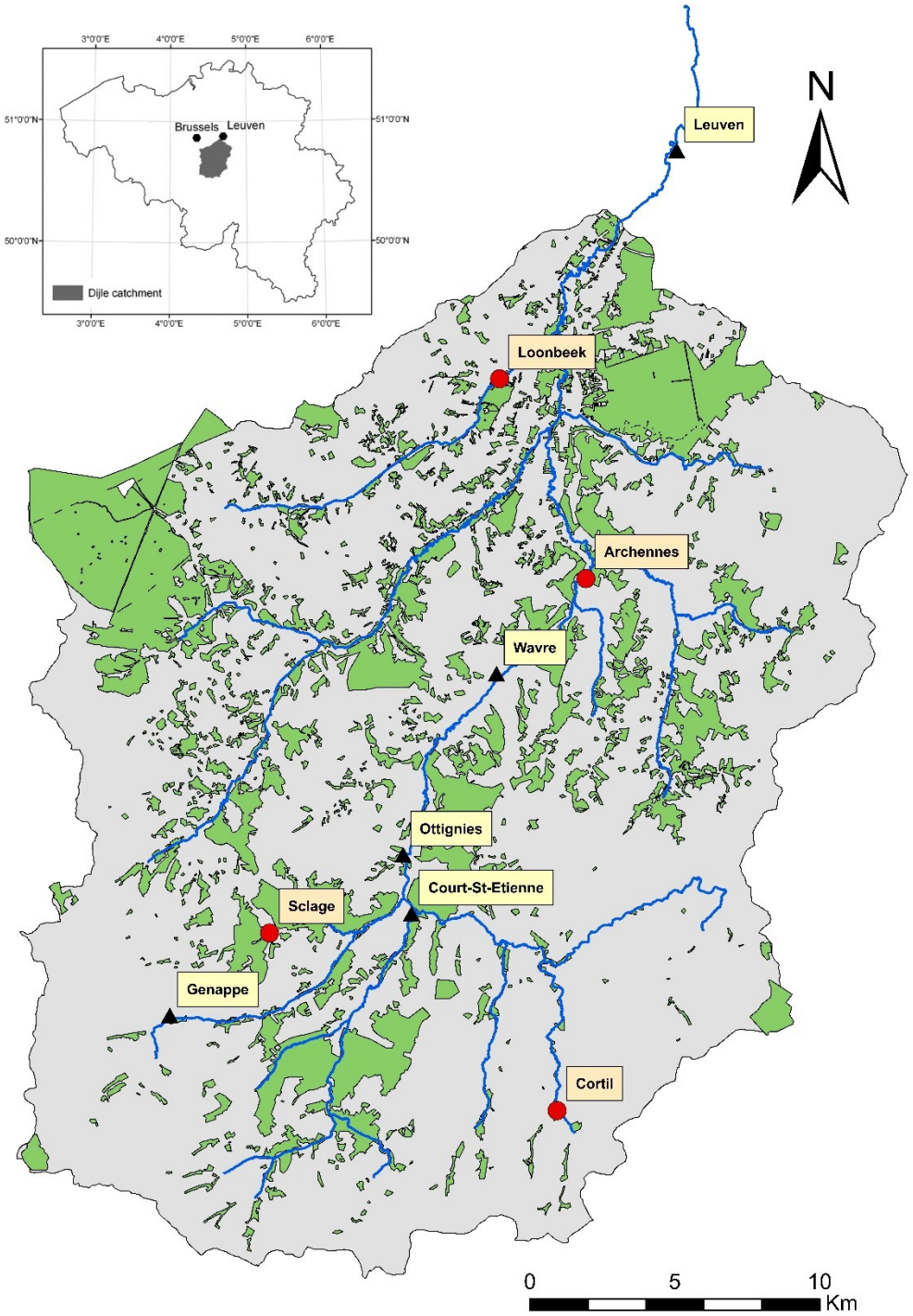

3°0'0"E
4°0'0"E
5°0'0"E
6°0'0"E
51°0'0"N
50°0'0"N
Brussels
Leuven
Dijle catchment
N
Leuven
Loonbeek
Archennes
Wavre
Ottignies
Court-St-Etienne
Sclage
Genappe
Cortil
0
5
10
Km

Fig. 2

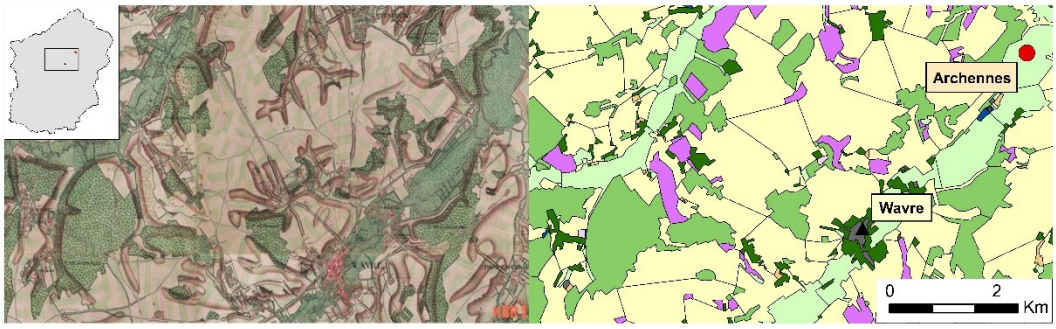


Fig. 3

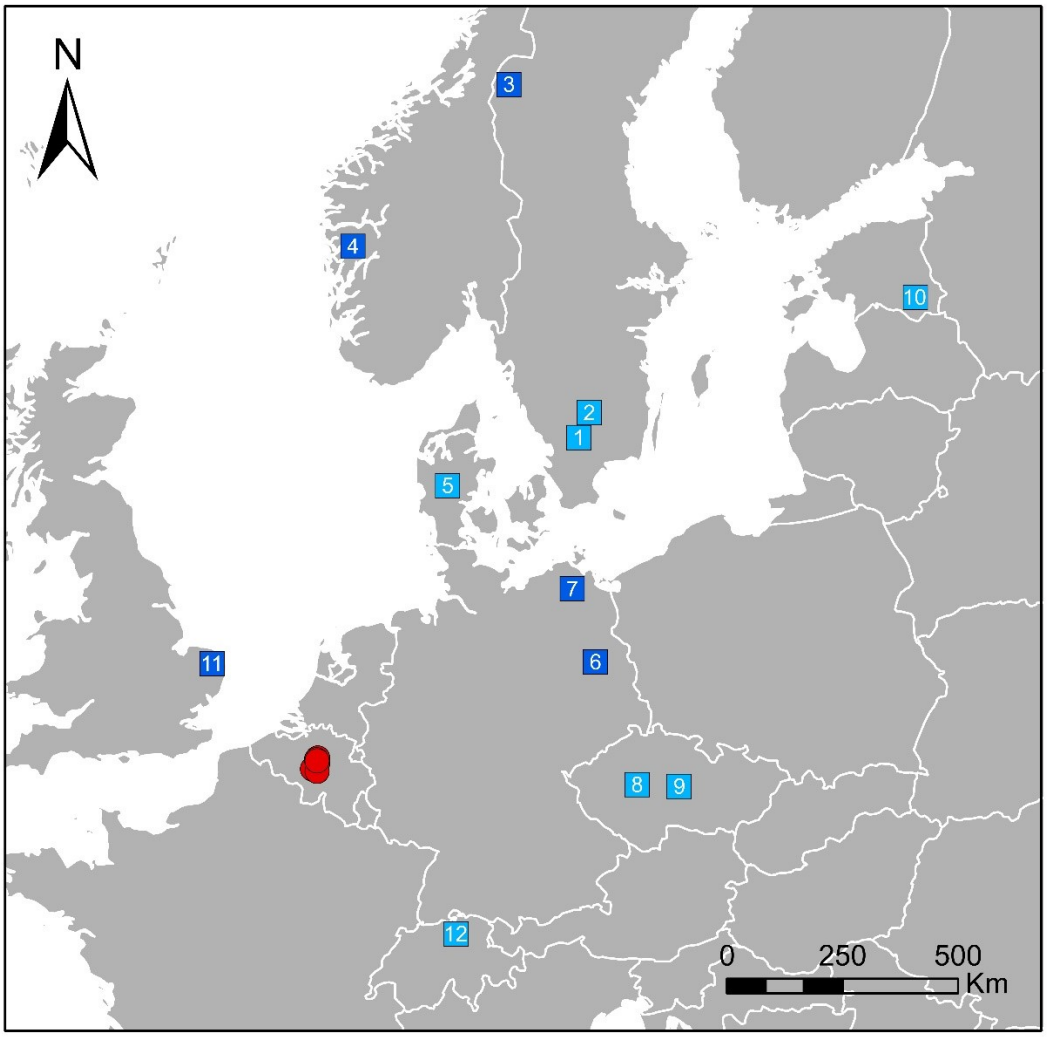


Fig. 4

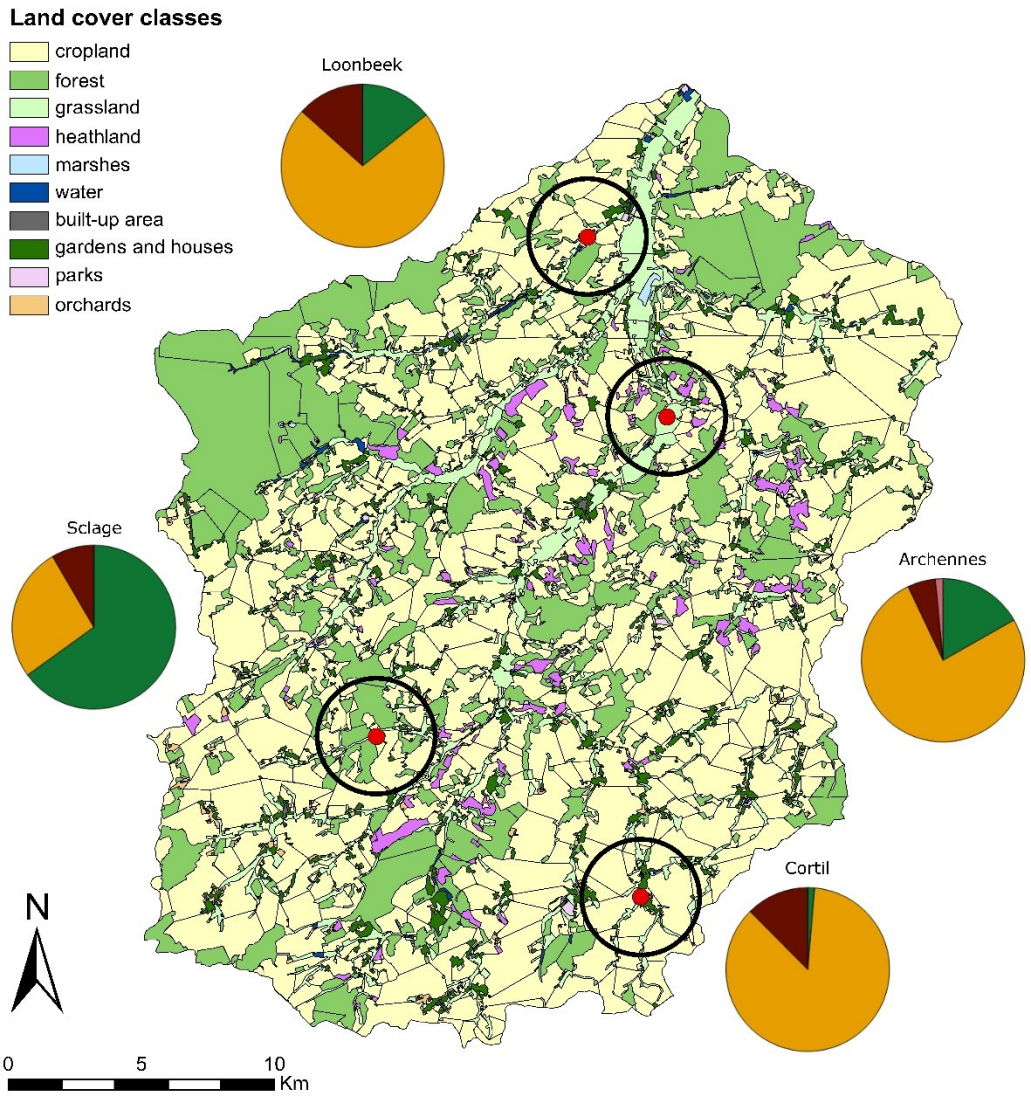

Land cover classes
cropland
forest
grassland
heathland
marshes
water
built-up area
gardens and houses
parks
orchards
Loonbeek
Sclage
Archennes
Cortil
N
0
5
10
Km

Fig. 5

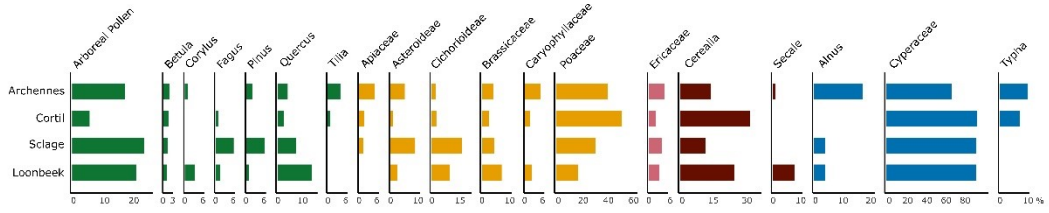

Arboreal Pollen
Betula
Corylus
Fagus
Pinus
Quercus
Tilia
Apiaceae
Asteroideae
Cichorioideae
Brassicaceae
Caryophyllaceae
Poaceae
Ericaceae
Cerealia
Secale
Alnus
Cyperaceae
Typha
Archennes
Cortil
Sclage
Loonbeek

Fig. 6

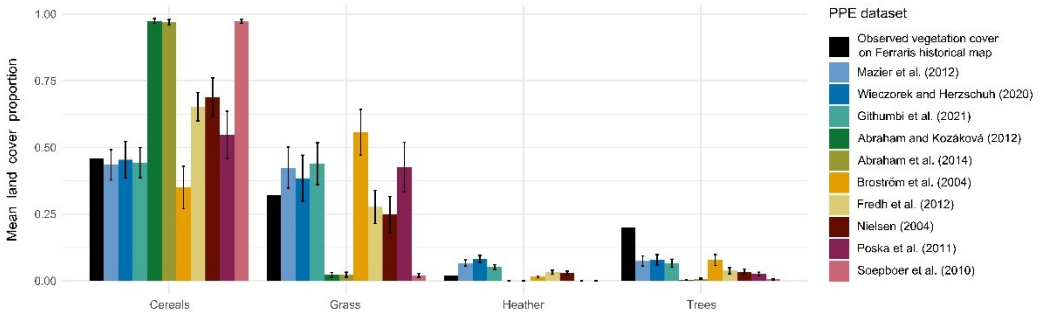

Mean land cover proportion
1.00
0.75
0.50
0.25
0.00
Cereals
Grass
Heather
Trees
PPE dataset
Observed vegetation cover on Ferraris historical map
Mazier et al. (2012)
Wieczorek and Herzschuh (2020)
Githumbi et al. (2021)
Abraham and Kozáková (2012)
Abraham et al. (2014)
Broström et al. (2004)
Fredh et al. (2012)
Nielsen (2004)
Poska et al. (2011)
Soepboer et al. (2010)

Fig. 7

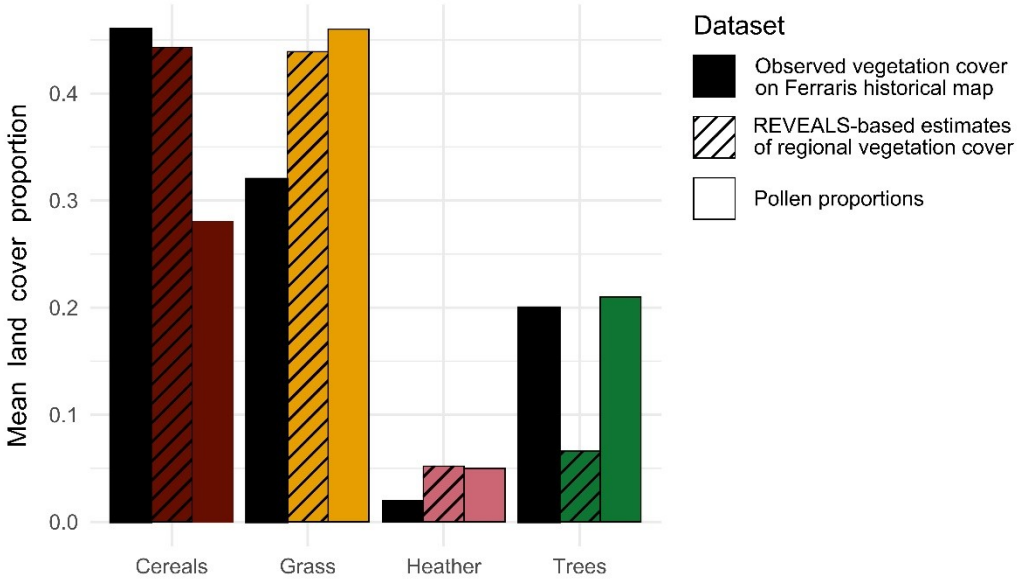

Mean land cover proportion
0.4
0.3
0.2
0.1
0.0
Cereals
Grass
Heather
Trees
Dataset
Observed vegetation cover on Ferraris historical map
REVEALS-based estimates of regional vegetation cover
Pollen proportions

Fig. 8

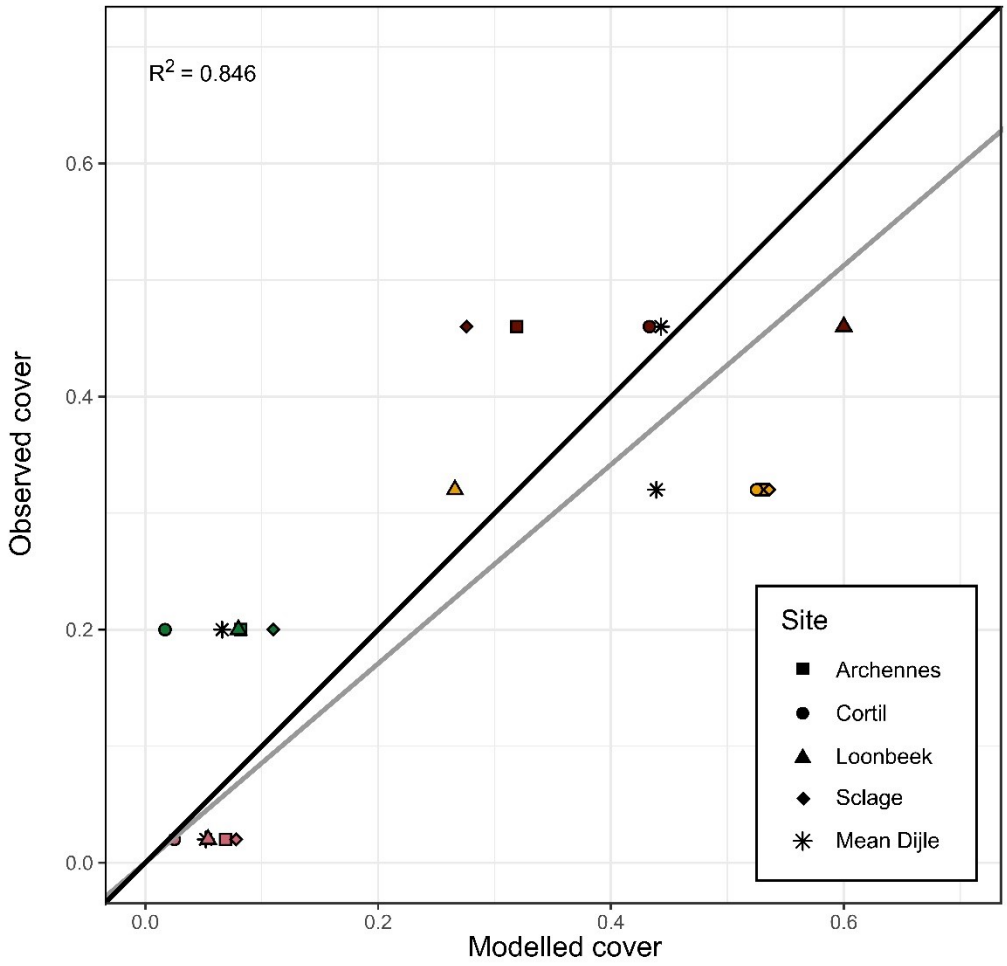

R2 = 0.846
Observed cover
Modelled cover
0.0
0.2
0.4
0.6
Site
Archennes
Cortil
Loonbeek
Sclage
Mean Dijle

Fig. 9

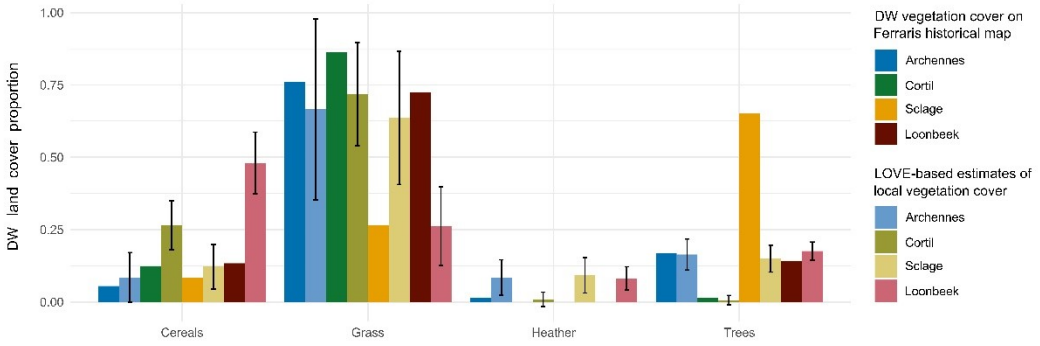

DW land cover proportion
1.00
0.75
0.50
0.25
0.00
Cereals
Grass
Heather
Trees
DW vegetation cover on Ferraris historical map
Archennes
Cortil
Sclage
Loonbeek
LOVE-based estimates of local vegetation cover
Archennes
Cortil
Sclage
Loonbeek

Table 1

Land cover classes	Trees	Grass	Cereals	Heather	Area (%)
Cropland	0	33	67	0	66.2
Forest	100	0	0	0	19.12
Grassland	0	100	0	0	7
Gardens and houses	0	0	0	0	4.08
Heathland	0	30	0	70	2.17
Orchards	40	60	0	0	0.7
Water	0	0	0	0	0.33
Marshes	0	100	0	0	0.16
Park	80	20	0	0	0.15
Build-up area	0	0	0	0	0.09
Cover estimates (%)	20	32	46	2	

Table 2

Site	Location	Depth (cm)	Age (cal BP)	Age (AD)
Sclage	50°38'13.41"N, 4°30'3.44"E	110-125	104 (±92) - 131 (±93)	1846 - 1819
Cortil	50°34'52.06"N, 4°38'21.95"E	76	146 (± 91)	1804
Loonbeek	50°48'30.75"N, 4°36'48.45"E	91-102	162 (± 93) - 192 (± 94)	1788 - 1758
Archennes	50°45'2.09"N, 4°39'35.97"E	87	161 (±86)	1789

Table 3

Taxa	FSP	PPE	SE
Betula	0.024	5.106	0.303
Calluna vulgaris	0.038	1.085	0.029
Carpinus betulus	0.042	4.52	0.425
Cerealia-type	0.06	1.85	0.38
Corylus avellana	0.025	1.71	0.1
Fagus sylvatica	0.057	5.863	0.176
Fraxinus excelsior	0.022	1.044	0.048
Pinus	0.031	6.058	0.237
Plantago lanceolata	0.029	2.33	0.201
Poaceae	0.035	1	0
Populus	0.025	2.66	1.25
Quercus	0.035	4.537	0.086
Rumex acetosa-type	0.018	3.02	0.278
Secale-type	0.06	3.99	0.32
Tilia	0.032	1.21	0.116
Ulmus	0.032	1.27	0.05