The Ecological Impact of Conquest and Colonization on a Medieval Frontier Landscape: Combined Palynological and Geochemical Analysis of Lake Sediments from Radzyń Chełminski, Northern Poland

Alex Brown,1,⁎ Rowena Banerjea,1 Amanda Dawn Wynne,1 Normunds Stivrins,2,3 Marc Jarzebowski,4 Lisa-Marie Shillito,5 and Aleks Pluskowski1

1Department of Archaeology, School of Archaeology, Geography and Environmental Sciences, University of Reading, Whiteknights, Reading, United Kingdom
2Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland
3Institute of Geology, Tallinn University of Technology, Tallinn, Estonia
4Friedrich-Meinecke-Institute, Free University of Berlin, Berlin, Germany
5School of History, Classics and Archaeology, University of Edinburgh, Teviot Place, Edinburgh, United Kingdom

Correspondence
⁎Corresponding author; E-mail: a.d.brown@reading.ac.uk

Received 7 January 2015
Revised 9 March 2015
Accepted 17 March 2015

Scientific editing by Jamie Woodward
Published online in Wiley Online Library (wileyonlinelibrary.com).
doi 10.1002/gea.21525

INTRODUCTION

Slavic and German colonization of the southern Baltic between the 8th and 15th centuries A.D. is well-documented archaeologically and historically. Despite the large number of pollen profiles from Poland, few palaeoecological studies have examined the ecological impact of a process that was central to the expansion of European, Christian, societies. This study aims to redress this balance through multiproxy analysis of lake sediments from Radzyń Chełminski, Northern Poland, using pollen, element geochemistry (Inductively Coupled-Optical Emission Spectroscopy [ICP-OES]), organic content, and magnetic susceptibility. The close association between lake and medieval settlements presents the ideal opportunity to reconstruct past vegetation and land-use dynamics within a well-documented archaeological, historical, and cultural context. Three broad phases of increasing landscape impact are visible in the pollen and geochemical data dating from the 8th/9th, 10th/11th, and 13th centuries, reflecting successive phases of Slavic and German colonization. This involved the progressive clearance of oak-hornbeam dominated woodland and the development of an increasingly open agricultural landscape. Although the castles and towns of the Teutonic Order remain the most visible signs of medieval colonization, the palynological and geochemical data demonstrate that the major phase of woodland impact occurred during the preceding phase of Slavic expansion; Germans colonists were entering a landscape already significantly altered. © 2015 Wiley Periodicals, Inc.
period (e.g., Latałowa et al., 2007; Wacnik, Goslar, & Czernik, 2012; Świąta-Musznicka et al., 2013), during which time the landscape was most intensively colonized.

Waves of external and internal conquest and colonization took place throughout Central Europe during the Middle Ages, characterized by successive invasions by Scandinavian, Slavic, and Turkic groups during the latter half of the first millennium A.D., but by increasing expansion from within Europe in the centuries after A.D. 1000. Before the appearance of Slavic groups two distinct cultural groups dominated Poland, the Przeworsk culture in southern and central Poland and the Wielbark culture east of the Vistula and on the lower Vistula. Archaeological evidence indicates a progressive depopulation from the 4th century onwards with these areas fully settled by Slavic groups by the 7th century (Buko, 2008). Powerful kingdoms emerged during the 10th century, most notably Bohemia, Hungary (Berend Urbańczyk, & Wiszewski, 2013), and Poland to the north (Buko, 2008). The formation of the Polish State (Piast Dynasty) by the mid–10th century (Buko, 2008) is characterized by increasing conquest and colonization, and following their conversion to Catholicism in A.D. 966, by increasing missionary activity to convert pagan communities in the southern Baltic. This is followed from A.D. 1230 by the crusades of the Teutonic Order and its allies against pagan Prussian tribes in the neighboring southeastern Baltic region. The conquest, which resulted in the annexation of tribal territories and the formation of a new Christian state, was secured by heavily fortified castles and followed by significant and protracted colonization, marked by the development of networks of towns and rural settlements. Conquest, colonization, and religious conversion occurred in tandem with agricultural intensification, economic expansion, and the growth of pan-European trading networks; most notably the development of the Hanse from the 13th century and the growing trade in Baltic timber and grain (Hybel, 2002; Haneca et al., 2005; Waźny, 2005).

This research examines the ecological signals of colonization and economic and agricultural intensification during the medieval period through a comparison of the pollen, geochemical (Inductively Coupled-Optical Emission Spectroscopy [ICP-OES]), and sedimentary records (magnetic susceptibility, loss-on ignition [LOI]) from a former lake (Castle Lake) at Radzyń Chełmiński (formerly German Rehden), located in Northern Poland within the Kujavian-Pomeranian voivodeship (Figure 1). The Castle Lake (German Schloßsee, Polish Jezioro Zamkowe) is well placed to consider the long-term impact of colonization because of the close association between the lake, an early medieval Slavic Stronghold occupied from the late 9th to mid-12th centuries, and the former Teutonic Order castle and adjacent town at Radzyń (formerly German Rehden), both founded in the 1230s. By taking a long-term approach offered by the palaeoenvironmental record, it will be possible to place the stronghold, castle, and town within the broader environmental, cultural, and historical context, and consider the extent that the landscape was transformed by archaeologically and historically documented processes of conquest, colonization, and economic intensification.

The application of geochemical analysis provides a useful comparison with more traditional pollen-based reconstructions of human activity by providing data on erosion history and element enrichment of lake sediments. Settlement and associated agricultural activity in the landscape surrounding the lake are likely to have resulted in increased mobilization and erosion of mineral sediments into the lake basin, enriched in elements indicative of human impact, although these elements can also reflect atmospheric inputs (Smol, 2008; Wilson, Davidson, & Cresser, 2008). The geochemical evidence is additionally important in the context of the generally low productivity and poor dispersal of pollen of many anthropogenic indicators, such as cereals. The comparison of palynological, geochemical, and sedimentary results has not previously been applied in the study of the direct impact of colonization on the medieval landscape of present-day northern Poland. The close association between stronghold, castle, town, and lake in such an intensively studied region also offers the ideal opportunity to compare the sensitivity of different analytical techniques in detecting aspects of past human impact and land-use.

**STUDY AREA**

**Archaeology and History of Radzyń Chełmiński and the Chełmno-Land**

Radzyń Chełmiński is located in the Chełmno-land (former German Kulmerland), a region in present-day northern-central Poland (Figure 1) that was previously part of Germany until 1919 (the first use of Polish site/region names is followed by the German equivalent in brackets). The Chełmno-land is one of the most intensively studied regions of the early medieval Slavic and subsequent Teutonic Order’s State (Polinski, 2003; Pluskowski, 2012). From the 8th century, the region witnessed increasing Slavic colonization and subsequently came under Polish control from the second half of the 10th century, representing an unstable border zone between Slavic and Prussian territories. Colonization was accompanied by increased missionary activity and unsuccessful attempts to Christianize the neighboring
colonization in this borderland increased into the 13th century and a network of fortified strongholds developed around the edge of the Chełmno-land, interpreted as reflecting the threat from neighboring Prussian tribes (Poliński, 2003). Polish attempts to conquer Prussia, framed as crusades from the early 1200s, eventually failed and in 1226 the Teutonic Order was granted territory in the Chełmno-land by Duke Konrad of Masovia in return for reclaiming the region and protecting Christian missionaries and colonists. Five years later the Teutonic Order launched its military campaigns which eventually stabilized the region, forming a base for further crusades into Prussia that would last for the next 50 years. The conquest of Prussia resulted in the formation of a theocratic state, run exclusively by the Teutonic Order and individual bishops.

The Slavic stronghold at Radzyń, situated adjacent to the lake at the edge of a bedrock peninsula, was occupied from the 11th to early 13th century; a layer of burned timber suggests its destruction, most likely by a Prussian attack (Chudziak, 1994). Following the Teutonic Order’s conquest of the Chełmno-land, a series of heavily fortified castles were constructed. The first timber fortification at Radzyń was constructed in 1234, possibly on the site of the Slavic stronghold. The surviving brick-built castle, dated to 1310–1340, is situated 500 m west...
of the stronghold, located on raised ground at the edge of the Castle Lake, surrounded by former wetland, now largely drained and reclaimed (Figure 2b–d). The landscape of the Order’s State was reorganized into administrative units called commanderies, headed by a single castle or convent run by a commander, and in turn supported by smaller subsidiary castles and officials. In total, 232 fortified structures were built across Prussia, most constructed in brick due to the lack of suitable building stone, and including 150 castles (Torbus, 1998; Bieszk, 2010). Radzyń headed one of 11 commanderies within the Chełmno-land (Figures 1 and 2), which increasingly shifted from a military to economic focus with the management of extensive provisioning networks stretching across the Order’s State. The commandery of Radzyń, as with the rest of the Chełmno-land, was increasingly colonized by Germans after the end of the Prussian Crusade in 1283. The castle remained an important commandery center into the 15th century, but was dissolved in 1454 during the Thirteen Years War (1454–1466), becoming the center of an eldership; a component of the late medieval administration of the Polish-Lithuanian state administered by an official known as a Starosta (elder). By the 16th century much of the western wing of the castle was a disused ruin, with the whole castle damaged further during the Swedish Invasion (known as “the Deluge,” 1626–1629). The castle was partly dismantled in the 19th century when elements of the structure were removed and incorporated into the town hall and other buildings within the town of Radzyń.

**Sample Site**

Samples for pollen and geochemical analysis were taken from the edge of the Castle Lake (53°23′08″ N 18°56′11″ E) adjacent to the Teutonic Order’s castle and 0.5 km north of the town of Radzyń Chełmiński (Figure 2a). The basin is approximately 1 × 1 km at its maximum
extent (75 ha), but formed part of a much larger system of wetlands, totaling 160 ha, surrounding the town and castle and extending to the east (Figure 2c and d). The wetlands, including the Castle Lake, are now largely infilled and covered in sedges, with surface water present to ca. 10–20 cm within the interior of the lake, mostly during the wet winter/spring months. The Castle Lake is ringed by occasional stands of broad-leaved trees, particularly *Alnus glutinosa*, with the surrounding landscape dominated by open arable land (Figure 2b); the nearest substantial woodland, dominated by *Pinus* plantations, are located 10 km east around Grudziądz (former German Grudenz), with larger tracts 20 km north-east forming part of the Iława Lakelands. The relief of Radzyń and the Chełmno-land is heavily influenced by the last (Weichselian) glaciation, characterized by flat and undulating morainic plateaus with numerous lakes and peatlands. The soils are largely brown and lessivé soils developed on glacial tills, sands, and gravels (Wasylikowa 2004, Figure 4; Noryśkiewicz 2013, Figure 3; Polish Geological Institute, 2015).

**MATERIALS AND METHODS**

A coring transect was made at the edge of the Castle Lake to identify suitable sediments located in close proximity to the castle, thereby containing the strongest pollen and geochemical signals for land-use on the adjacent dry ground. Samples were taken from the Castle Lake 50 m from the edge of the lake. The total depth of lake-edge sediments was not established as the aim of research was to investigate evidence for medieval land-use. However, the deepest core reached 733 cm, consisting of humified herbaceous peat (0–23 cm) overlying silty-clay/herbaceous peat (23–69 cm) and detrital organic lake sediments (69–733 cm). Half-meter cores were taken to a depth of 400 cm using a 5 cm diameter Russian auger, starting at the surface, with duplicate cores taken to cover the overlap. Cores were wrapped in cling film and foil, placed in plastic guttering, and refrigerated prior to sampling.

Samples for pollen analysis c. 1 cm$^3$ in volume were taken from the Radzyń sequence at 1–4 cm intervals from 24 to 128 cm (1 cm intervals, 32–64 cm; 2 cm, 64–88 cm; 4 cm intervals, 24–32 and 88–128 cm), focusing on sediments of Iron Age and medieval date. The sediments above 24 cm included significant modern root disturbance and were not analyzed. One *Lycopodium* tablet was added to enable calculation of pollen concentrations. Samples were prepared following standard laboratory techniques (Moore, Webb, & Collinson, 1991) and mounted in glycerol jelly stained with safranin. A minimum of 500 pollen of terrestrial species were counted.
for each level. Pollen percentages are calculated based on terrestrial plants. Fern spores, aquatics, and Sphagnum are calculated as a percentage of terrestrial pollen plus the sum of the component taxa within the respective category. Identification of cereal pollen followed the criteria of Andersen (1978). Identification of indeterminable grains was recorded according to Cushing (1967). The pollen diagram was produced using Tilia version 1.7.16 program (Grimm, 2011). Pollen zones are based on the principal archaeological periods rather than local pollen assemblage zones. The raw pollen counts are included as supplementary material (Supplementary Table SI). Microscopic charcoal was quantified using the point count method of Clark (1982).

In order to investigate the link between sedimentation history and human impact, concentration (ppm) was determined for 18 elements using ICP-OES (Figures 5 and 6, Supplementary Tables SII–SV). Elemental enrichments include those strongly associated with anthropogenic activity, such as phosphorus (Holliday & Gartner, 2007) and lead (Kemp et al., 1978; Fernandez et al., 2002; Wilson, Davidson, & Cresser, 2005; Hutson & Terry, 2006; Cook et al., 2010), and those associated with precipitation, sedimentation, and erosion processes, such as calcium and titanium (Ti; Lomas-Clarke & Barber, 2007; O’Connell, Ghilardi, & Morrison, 2013). Samples of sediment (0.5 kg dried weight) were taken at 2–4 cm intervals from 24 to 120 cm and pretreated with nitric acid to digest organic matter, with standards and blanks analyzed alongside the Radzyń samples. Geochemical concentration are expressed as parts per million (ppm) per 0.5 kg of dried sediment. A element enrichment index was calculated (sensu lato Belzile et al., 2004) dividing element concentration for each sample by the average
RESULTS

Chronology

The AMS dates provide an indication of sediment accumulation rates from 95 to 34 cm (Table I), with modeling using Clam 2.2 providing a broader age-depth chronology (Figure 3). The ¹⁴C dated sediments accumulated over a period of time of as little as 656 years between cal. A.D. 430 and 1412, covering the Roman Iron Age, Migration, and medieval periods. The accumulation rate is

\[ P_{ba} (x) = P_{b} \text{ total}(x) - \left[ \text{TiO}_2(x) + \text{TiO}_2(b) \right] P_{bb} \]

(suffix a is anthropogenic, \(x\) is any depth, and \(b\) is the background).

Magnetic susceptibility was measured on 2-cm interval samples using a Bartington model MS2B magnetic susceptibility meter (Figures 5 and 6). Measurements were taken in triplicate with an average taken of the three readings. Background atmospheric readings and checking against a lead standard was conducted every four sample readings with minimal deviation observed. Samples of sediment ≥5 grams were taken for quantification of mineral and organic context by LOI, following the method of Bengtsson and Ennel (1986) (Figures 5 and 6).

Eleven ¹⁴C radiocarbon AMS dates were obtained from SUERC (Scottish Universities Environmental Research Centre; Table I, Figure 3). Calibrated age ranges were calculated with OxCal 4.1. (Bronk-Ramsey, 2009) using the IntCal13 curve (Reimer et al., 2013), and modeled using the Clam 2.2 program (Blauw, 2010).
Table I  AMS radiocarbon dates.

| Laboratory No. | Depth (cm) | Age (B.P.) | $\delta^{13}$C (‰) | Age Range (cal. A.D.) |
|---------------|------------|------------|----------------------|-----------------------|
| GU-27673      | 34–35      | 595 ± 35   | $-27.3$‰             | 1296–1412             |
| GU-26408      | 37–38      | 625 ± 30   | $-26.7$‰             | 1290–1399             |
| GU-24506      | 41–42      | 690 ± 30   | $-26.9$‰             | 1350–1390 (27.8%)     |
| GU-27674      | 44–45      | 765 ± 35   | $-27.1$‰             | 1212–1288             |
| GU-26407      | 47–48      | 805 ± 30   | $-26.2$‰             | 1041–1109 (35.2%)     |
| GU-26406      | 51–52      | 890 ± 30   | $-27.6$‰             | 1116–1217 (60.2%)     |
| GU-26405      | 55–56      | 925 ± 30   | $-27.6$‰             | 1026–1180             |
| GU-26404      | 61–62      | 1000 ± 30  | $-28.2$‰             | 982–1052 (70.1%)      |
| GU-24507      | 70–71      | 1035 ± 30  | $-26.8$‰             | 1134–1153 (6.1%)      |
| GU-26409      | 79–80      | 1060 ± 30  | $-26.5$‰             | 940–1040 (89.8%)      |
| GU-24508      | 95–96      | 1505 ± 30  | $-27.6$‰             | 430–490 (11%)         |

aMaterial dated gyttia.  
b$2\sigma$ range.

particularly rapid between 79 and 61 cm (30 mm/yr) compared to 95–79 cm (3.6 mm/yr), 61–51 cm (9.1 mm/yr), and 51–41 cm (8.3 mm/yr). Age-depth modeling suggests the basal undated sediments (128–95 cm) are most likely of Roman and Migration Period date, with the transition between the Migration period/early medieval and early/late medieval correspond broadly to c. 91 and 47 cm (Figure 3). There was insufficient suitable material to radiocarbon date above 34 cm, but modeling suggests a probable late medieval (15th century) and later date for the top of the sequence.

### Magnetic Susceptibility and Organic Matter Content (Figures 5 and 6)

The results of magnetic susceptibility and organic content are shown relative to the geochemical data and archaeological periods. Organic content remains high through the detrital organic lake muds (c. 60%), but gradually decreasing from c. 70 cm with the transition to silty-clay/herbaceous peat, with low organic content (c. 20%) from c. 56 cm. Magnetic susceptibility shows little significant variation through the core, with small spikes at 74 and 62 cm, but with an increase in values from c. 56 cm and a significant spike in magnetic susceptibility at 34 cm. Palynology and geochemical data indicate that the decrease in organic content and higher magnetic susceptibility values from 56 cm may reflect increased soil erosion and input of ferromagnetic minerals into the lake associated with intensified land-use on the adjacent dry ground.

### Palynology and Geochemistry (Figures 4–6, Supplementary Tables SI–V)

#### Roman Iron Age (A.D. 0–300)

High arboreal pollen (AP) values and low nonarboreal pollen (NAP) values indicate a predominantly wooded environment surrounding Radzyń dominated by *Pinus* and *Betula*, with less *Alnus, Quercus, Corylus, Ulmus, Tilia, Fagus*, and *Fraxinus*. However, moderate values for Poaceae and small percentages of *Rumex acetosa*-type, *Plantago lanceolata, Artemisia*-type, and cereal-type pollen (*Secale, Avena-Triticum and Hordeum* groups) strongly suggest cultivated and grazed/disturbed ground in the vicinity. A proportion of the Poaceae pollen may also reflect stands of *Phragmites* growing with *Cyperaceae* along the lake margin, with stands of *Alnus, Betula*, and *Salix* growing on damper soils. Elements concentrations are low level and stable through this period.

#### Migration period (A.D. 300–700)

The Migration period is characterized by an increase in AP to their maximum values in the profile, accompanied by a major change in woodland composition. Deciduous trees dominate, particularly *Carpinus* and *Quercus*, with lesser quantities of *Corylus, Tilia*, and *Ulmus*, outcompeting *Pinus*. There is a decline in the frequency and variety of herbaceous pollen types, with a large decline in Poaceae. Pollen of *R. acetosa*-type increases, however, perhaps within nearby patches of grassland or waster ground, or reflecting the activities of
grazing animals. Small-scale cultivation is suggested in the vicinity by occasional cereal-type pollen grains, although these are largely absent during the *Carpinus* maximum. Concentrations of most elements begin to increase during this period with low enrichment factors of Ni (1.70–1.90), Cu (1.53–1.57), and Zn (1.50) (Figure 5; Supplementary Table SII). The application of the Ti ratio as a soil mineral tracer suggests that part of these enrichments is due to an anthropogenic trace element supply (Figure 6).

**Early medieval (A.D. 700–1234)**

Despite the continued high AP values there is a marked decline in pollen of *Carpinus*, gradual to start with but more marked from the mid-9th century, with a corresponding increase in *Betula* and *Pinus*. Both *Betula* and *Pinus* require relatively open conditions with limited species competition, and as pioneer species, typically expand in situations where the previous and more shade-tolerant woodland cover has been removed; this is aided by the production of large quantities of pollen and lightweight, buoyant seeds that are dispersed widely and grow fast (Latałowa, Tobolski, & Nalepka, 2004; Hynynen et al., 2010). The relatively high pollen productivity estimates (PPEs) for *Betula* and *Pinus* (Broström et al., 2008) typically result in an overrepresentation of these taxa in pollen profiles relative to their physical presence, suggesting they formed more fragmented and isolated stands within an increasingly open agrarian landscape. Poaceae values rise steadily, accompanied by a greater range of herbaceous taxa. There is a continuous curve for *Secale* pollen from the 8th century, albeit at low frequencies, with intermittent *Avena–Triticum* pollen and an increase in *Cannabis*-type pollen. Evidence for cultivation is accompanied by herbaceous pollen indicative of cultivated and grazed ground, including Brassicaceae, *Centauraea cyanus*, and *Artemisia*. The increase in cultivated, weed, ruderal, and open ground taxa is most apparent from the 11th century, particularly the curve for *Secale*, suggesting a phase of increasing agricultural intensification.

The geochemical data contain some interesting elements that coincide with pollen trends (Figures 4–6; Supplementary Table SII), occurring at the transition from detrital organic lake muds to silty-clay/herbaceous peat. There are medium to high enrichment factors of P (2.85), Ti (2.78–2.80), and Zn (4.43) approximately a third of which derive from an anthropogenic source. There is a general decline in elemental concentrations toward the end of the 10th century followed by elemental enrichment factors in P (1.56–1.60), Zn (2.03–2.11), Pb (2.22–2.29), Cd (1.82), and Ni (1.53–2.01) at the beginning of the 11th century. The trace element enrichments of Pb and Zn are in part attributed to an anthropogenic source. Elemental concentrations in the latter half of the 11th century and early 12th century are consistently enriched above background levels for P (1.56–1.72), Mn (1.58–1.92), Ti (1.55–2.02), Zn (1.80–2.47), Pb (2.04–2.64), Cu (1.74–2.53), and Ni (1.75–2.24); the Ti ratio suggests that the enrichments of Pb and Zn are also in part attributed to an anthropogenic source (Figure 6).

**Late medieval (A.D. 1234–1500)**

AP values decline to their lowest values in the profile, although subsequent fluctuations are largely in response to increases in the *Betula* and *Pinus* curves. Cereal pollen values reach their maximum frequencies during the 13th century, with a noticeable increase in pollen of ruderal species from the start of the late medieval period. Fluctuations are apparent however in the values for cultivated, ruderal, and other NAP taxa that may reflect subtle changes in the proportions of cultivated, grazed, and ruderal habitat. The 14th century by comparison is characterized by declining frequencies of cultivated plants, although the overall taxonomic diversity and representation of herbaceous pollen suggests continued arable activity although perhaps with an increase in pastoral land-use. The reduction in arable agriculture may be reflected by declining Ti levels occurring as a result of reduced soil erosion and sediment input into the lake. The 15th century is characterized by a decline in *Betula* and increase in *Pinus*, with cereal pollen values (mainly *Secale*) recovering to former levels. However, there is a general decline in ruderal pollen from the late 14th century, particularly in *R. acetosa*-type, that may represent a reduction in grazed and disturbed ground with some colonization by *Pinus*. Declining P levels might reflect a reduction in effluent from animal waste into the lake. In the later medieval period, the anthropogenic trace element supply is much higher for all the trace elements (Figure 6).

In the 15th century, levels of P and Zn begin to increase, which may reflect an increase in organic inputs into the lake. The spike in Pb concentrations are enriched at a factor of 13.12 times the background geology (Figure 5; Supplementary Table SII), and almost entirely attributed to an anthropogenic supply (Figure 6), and coincide with a spike in the magnetic susceptibility.

**DISCUSSION**

The pollen and geochemical data from Radzyń Chełmiński support a pattern of significant impact on the landscape that reflects the process of territorial expansion and colonization occurring across the
southern Baltic zone from the 8th/9th century. Previous studies have demonstrated the relevance of combining geochemical analyses with more traditional pollen-based landscape reconstructions, both in supporting palynological evidence for anthropogenic impact, as well as emphasizing the sensitivity of geochemical techniques in situations where the palynological data are inconclusive (e.g., Lomas-Clarke & Barber, 2007; O’Connell, Gilardi, & Morrison, 2013). Although lake sediments provide important records of past changes in land-use and human activity, interpretation of the geochemical record can be problematic because of the difficulties in identifying specific activities and the potentially wide-ranging source of element inputs, as well as additional changes in the lake chemistry. Previous studies of lake sediments have emphasized how the geochemical record can be influenced by a variety of within- and outside-lake processes, requiring careful consideration when interpreting the geochemical data. The loading of elements in lakes is determined by vertical (atmospheric) and lateral (erosion) inputs, and fluxes in either can affect the source, input, and therefore loading of elements in a lake basin. For example, atmospheric pollution of Pb has been well-documented globally in lake sequences and the Ice Core record (e.g., Hong et al., 1994; Shotyk et al., 1998), while the mobility of P in sediments makes it highly susceptible to lateral fluxes; both have been well-studied because of their relationship to modern and more recent industrial and agricultural pollution. Moreover, key elements such as Fe, Mn and P can be affected by within-lake processes, including the recycling of trace elements, redox recycling (Mackereth, 1966), and particularly in the case of Si with changes in the biological productivity of the lake, affecting the quantities of biogenic silica (see Boyle, 2001 for a review). However, recent studies of ombrotrophic mires have emphasized the sensitivity of Ti as a reliable indicator of soil erosion resulting from human activity as it is both chemically stable and unaffected by biological transformations (Lomas-Clarke & Barber, 2007; De Vleeschouwer et al., 2009a). Ti therefore forms the basis for our interpretations of the geochemical record, but is considered in the context of the concentrations and enrichments for other elements (Figures 5 and 6; Supplementary Tables SIII–V) that show significant similarity in their curves, suggesting little transformation from within-lake processes.

Geochemical studies of “known functional areas” have indicated a strong relationship between certain activities and elements; for example, organic waste disposal and elevated phosphorus (P) and manganese (Mn), and craft production/metalworking and elevated lead (Pb). Other elements including arsenic (As), zinc (Zn), copper (Cu), chromium (Cr), and potassium (K) have similarly been strongly linked with human activity (Entwistle, Abrahams, & Dodgshon, 2000; Wardas-Lasoń & Glowal 2010; Wilson, Davdison, & Cresser, 2008). In the case of the Castle Lake, the primary sources of increased element enrichment are most probably through soil erosion and the input of effluent from industrial and human activities, particularly following the construction adjacent to the lake of the early medieval stronghold and subsequent late medieval castle and town. Changes in land-use can have a major impact on soils made increasingly susceptible to erosion through the removal of vegetation and subsequent agricultural activity, derived either from the immediate surrounding landscape, from within the wider lake catchment via inflowing rivers and streams, or soil dust transported atmospherically by wind and rainfall. Although element enrichment is likely to reflect the background influence of airborne soil, the strong correlation between the palynological and geochemical data, particularly during the medieval period, is here argued to be most strongly reflective of activities occurring within the immediate surroundings of the lake.

**Roman Iron Age and Migration Periods (A.D. 0–700)**

The Roman Iron Age is considered a time of intensive settlement development within present-day Poland (Buко, 2008). Despite the high values for AP, the landscape surrounding the Castle Lake included an open component with relatively high values for Poaceae. *Pinus* and *Betula*, both pioneer species, would have expanded in a landscape increasingly cleared of dense mixed deciduous woodland; the small quantities of cultivated, weed, and ruderal pollen point to mixed, though not necessarily intensive, arable and pastoral activity (Figure 4).

However, there is a distinct increase in *Quercus* from the late 1st century that in other pollen sequence from central Poland has been linked to various factors, including higher summer temperatures, selective clearance of woodland, and particularly the development of a heavily grazed open *Quercus* forest noted elsewhere in Europe (Vera, 2000; Makohonienko, 2004). The possibility of forest grazing seems unlikely in this case because of the decline in the range and frequency of herbaceous pollen that appears more likely to reflect the start of a general process of woodland regeneration into the Migration period. Regeneration is most apparent in the increase in *Carpinus*, which reaches its highest Holocene pollen values by A.D. 500. *Carpinus* values reach 40% in the Castle Lake sequence and consistent values of between 20% and 40% in pollen sequences across the Kulmerland (Noryškiewicz, 2013) show it formed the
dominant woodland component. Within the strict reserve of the Białowieża National Park in NE Poland, considered by many to reflect the primeval vegetation of central Europe (e.g., Peterken, 1981; Falinski, 1986; Bernardzki et al., 1998; Rackham, 2003), Carpinus typically dominates the lower woodland canopy. The second layer includes Quercus, Ulmus, Acer, and Tilia with Picea forming the highest part of the canopy, although the latter tree does not form a significant component of the woodlands in the Chełmno-land. Because of the dense nature of the canopy, the ground flora is relatively species poor, but an increase in R. acetosa-type could suggest an increase in grazing, most probably around the edges of the lake.

Early Medieval (A.D. 700–1234)

Renewed clearance from the c. 8th century is associated with a rise in pollen taxa indicative of increasing human impact (Filbrandt–Czaja & Noryśkiewicz, 2003; Noryśkiewicz, 2004a, b, 2005, 2013). The deforestation of the Chełmno-land during the early medieval period has been linked to the settlement of populations from Kujavia and Greater Poland (Chudziak, 1996; Buko, 2008).

The initial decline in Carpinus is relatively gradual during the course of the 8th century, but is followed by a rapid decline in the 9th century, with Betula and Pinus expanding within an increasingly open landscape. Woodland clearance is accompanied by defined spikes in concentrations for P, Ti, and trace elements. The close correlation between geochemical and palynological data suggests that woodland clearance resulted in increased soil erosion and element enrichment of lake sediments, with a corresponding increase visible in the mineral content of the sediment from the late 8th century (Figure 6). The comparatively low levels of cereal-type pollen could be taken to suggest a predominantly pastoral focus to land-use. However, the significant levels of early medieval woodland clearance yet relatively small increase in cereals compared to the late medieval, apparent in pollen sequences throughout the Vistula Basin region, have led to suggestions that communities may have been cultivating more Panicum miliaceum in the early medieval period (Latałowa, personal communication), with Secale becoming more popular in the later medieval. Neither hypothesis can be tested through the pollen data as P. miliaceum is indistinguishable from wild Poaceae pollen, but a greater emphasis on P. miliaceum in archaeobotanical samples from early medieval urban contexts, including Gdańsk (former German Danzig; Badura, 2011), lends some circumstantial support for the latter hypothesis.

The pollen record shows renewed woodland clearance and agricultural intensification from the mid-11th century. This is preceded in the early 11th century by a rise in concentrations of several elements, including Ti, Fe, and Mn (Figure 5, Supplementary Table SII), occurring at the transition (69 cm) from detrital organic lake muds to silty-clay/herbaceous peat, and supported by the decreasing organic content and magnetic susceptibility of the sediment. The increase in element concentrations is most likely linked to increasing anthropogenic erosion of soil into the lake basin, and emphasizes the sensitivity of the geochemistry in identifying changes in land-use within the surrounding landscape not visible in the pollen record until the mid-11th century. Changes in land-use at this time therefore result in a sudden change in the sediment regime of the lake, visible in both the geochemical, LOI, MS, and sedimentary records. In addition to the evidence for increased erosion of soil into the lake, the peat component of the sediment suggests that the edges of the lake may have been increasingly colonized by semiterrestrial plant communities, similar to the tall-herb swamp that now covers the entire area of the former lake.

This horizon corresponds with the development of the Polish regional castellany (administrative unit of a voivodeship) centered on the settlement at Kaldus (Chełmno; Makowiecki, 2007; Buko, 2008; Pluskowski, 2012), and which saw intensive land-use during a period of increasing Polish colonization of the Chełmno-land. Frequencies of cereal pollen, particularly Secale, increase noticeably through the course of the 11th and 12th centuries, along with pollen of taxa, such as C. cyanus, a weed typically associated with cereal cultivation and which has been argued to reflect the presence of permanent Secale fields (Vuorela, 1986).

At Linje mire renewed woodland clearance is dated 1015 ± 50 B.P. (Gd–15645, cal. A.D. 943–1155; Noryśkiewicz, 2005), at Lake Czyste just above a date of 1155 ± 30 B.P. (Poz–21899, cal. A.D. 778–971) and at Lake Robakowski 15 cm above a date of 1260 ± 30 B.P. (Poz–28058, cal. A.D. 862–669; Noryśkiewicz, 2013). At Uśc, the increase in anthropogenic indicators occurs midway between two closely spaced dates of 1340 ± 35 B.P. (Poz–3633, cal. A.D. 640–772) and 830 ± 70 B.P. (Ki–10270, cal. A.D. 1040–1281; Noryśkiewicz, 2004b), while at Chełmno/Rybaki, the increase in cereal pollen occurs between dates of 1360 ± 70 B.P. (Ki–9673, cal. A.D. 640–772) and 1030 ± 70 B.P. (Ki–9672, cal. A.D. 863–1175; Noryśkiewicz, 2004a). Agricultural intensification is apparent also in nearby sequences from Czystochleb and Napole (Filbrandt–Czaja & Noryśkiewicz, 2003), and from Lakes Melno and Kamionkowskie (Noryśkiewicz, 2013), but in the latter two cases chronological precision is
limited by the single dates with large uncertainties, and in the former two cases by hard-water errors. However, despite the variable chronological resolution, the similarity in pollen signal between sites argues for a broadly coeval process of landscape change and intensifying land-use over the course of the early medieval period.

The Chełmno-land became an important frontier with Pomeranian lands to the west, Prussian tribal lands to the north-east and Masovian lands to the south-east. The early Slavic stronghold at Radzyń was situated in a particularly vulnerable location within this ring, in immediate proximity to Prussian Pomesania, yet both the archaeological and palynological data suggest the region was stable enough in the second half of the 10th and 11th centuries for sustained agriculture to develop (Chudziak, 1996). However, during the second half of the 12th century sites in the Chełmno-land began to be abandoned, coinciding with a documented period of Prussian incursions, culminating in Konrad of Masovia’s attempts to regain this territory, using his own military order and subsequently collaborating with the Teutonic Order. This phase of settlement instability is not obviously apparent in the either the pollen or geochemical record, perhaps because of the intermittent nature of Prussian incursions, suggesting some measure of stability in land-use within the immediate landscape despite the destruction of the stronghold at Radzyń in the second half of the 12th century/start of the 13th century. Following the destruction of the stronghold, there is a hiatus in the settlement record until 1234 when the Teutonic Order establishes the castle and town.

Late Medieval (A.D. 1234–1500)

Although the early history of the castle, first documented in 1234, and associated town, is poorly understood, the early phases of settlement were tumultuous. Much of the surrounding landscape would have been an unstable frontier zone during the initial decades of the crusades with Prussian armies and warbands periodically laying waste to the countryside. The town itself was captured by the Prussians during the Great Prussian Uprising in the 1260s, although the castle remained in the hands of the Order. Poliński (2003) has argued that settlement within the region was largely hindered until the 1280s when military action against the Prussians ceased. However, the main colonies and towns, including Rehden, were not only all founded but prospered very quickly during the 1230s–1280s. These towns required provisioning to support their populations, suggesting sufficient stability existed in the countryside for their maintenance. Many of the larger pitched battles would have taken place along the edges of the Chełmno-land as the crusading armies moved further north. The impact of intermittent Prussian raiding is unlikely to show up in the pollen records from the Chełmno-land. Indeed, the increasing pollen values from the Castle Lake for arable and pastoral land during the first half of the 13th century support a picture of relative stability in land-use. Pollen sequences from within the Chełmno-land likewise show an increase in cereal pollen, particularly Secale, during the late medieval, and suggest a picture of increasing agricultural intensity on a regional scale contemporary with the archaeological and historical evidence for intensive colonization, urban development, and economic growth (Poliński, 2003; Noryśkiewicz, 2004a, b, 2005, 2013). The presence of granaries in both castles and urban sites, many located along the banks of the Vistula, can be related to the intensive production of grain within the Order’s State used for both internal consumption and export (Pluskowski, 2012). Large volumes of grain, particularly Secale, were exported across north-west Europe through the major Hanseatic ports at Gdańsk and Elblag (German Elbing; Hybel, 2002), along with increasing quantities of timber from the upper and middle Vistula areas during the mid-13th to 15th centuries (Haneca et al., 2005). It is probable that the Chełmno-land played an important role in the production of grain and timber for both internal use and export.

Increasing German colonization of the Chełmno-land followed the end of the Prussian Crusade in 1283, representing a period of relative stability free of major conflict that lasted until 1409, with an increase in documented rural settlements within the commandery of Radzyń. Until the early 14th century, the castle was served by the Vorwerk (manor), and later village, at Radzyń Wieś situated to the south-west, and 38 other documented settlements within the commandery. From 1343 to 1466, the population of the commandery increased, with 48 settlements (including smaller strongholds) and nine Vorwerks documented (Poliński, 2003: 75, 104). However, pollen and geochemical evidence suggest some reduction in the intensity of agricultural activity within the immediate hinterland of the castle, despite the documentary evidence demonstrating intensifying rural settlement within the wider landscape from the 14th century. Pollen of cereal, weed, and ruderal species decrease from the latter half of the 13th century, with values decreasing particularly during the mid-14th century, most notably Secale, C. cyanus and R. acetosa-type; a contemporaneous increase in Pinus pollen suggests some possible recolonization of former agricultural and/or open-disturbed ground. Concentrations of element decline during the 14th century, corresponding with evidence for a reduction in the intensity of agricultural activity apparent in the pollen record. The trend visible in the pollen and geochemical signals
may reflect a shift in the focus of agricultural production away from the immediate castle hinterland following the crusade as the political situation stabilized and settlement of the wider commandery intensified. The majority of rural settlements servicing Rehden are located within the northeastern section of the commandery with relatively few located near the town and castle; the two nearest Vorwerks are located 2.5 km to north (Nowy Dwór) and 5 km to the south-west (Radzyń Wies; Polinski, 2003, Figure 2).

Similar fluctuations in the pollen curves for cereal, weed, and ruderal plants are apparent at some, but not all, sites across the Chełmno-land. Fluctuations, including both decreases and increases in pollen values, are most apparent in those sequences with higher sample intervals, including lakes Czyste, Robakowskie, and Melno (Noryśkiewicz, 2013). The possible synchronous nature or otherwise of these fluctuations is difficult to assess because of a lack of chronological resolution for medieval sediments at these sites. At Lake Robakowskie, cereal and ruderal pollen values are higher during the 10th and 11th, mid-13th, and 17th century onwards, with lower values in the intervening periods; at other sites values appear more stable. The pattern is clearly complex; homogeneity between pollen profiles is reflected in regional-scale vegetation changes (e.g., the reduction in Quercus-Carpinus woodland), while heterogeneity is reflected in variations between sequences in the curves for cereals, weed, and ruderal pollen. This likely reflects the individual histories of the sampled pollen sites with respect to the surrounding settlement pattern, intensity of land-use, but also the influence of the pollen catchment and influx over time.

In addition to the palynological and geochemical data from Radzyń there are 22 separate inventory records for the castle between 1377 and 1449 (Ziesemer, 1921; Table II). Inventory records from the late 14th century show significant provisioning of cereals, horses, and livestock in the castle from across the commandery and can be linked in some cases to the changing political situation within the region at this time. The inventory records reflect the role of the castle as a center for storage and provisioning, particularly in preparation for war. The relative stability of the late 13th and 14th centuries was followed by a series of conflicts that lasted from 1409 until 1466 and which resulted in the destruction and abandonment of many villages, with rural communities fleeing to the shelter of the fortified towns and an overall decrease in the population of the Chełmno-land from the mid-15th to the start of the 16th century (Polinski, 2003: 122). Inventories from 1409 and 1411, before and after the defeat of the Teutonic Order at the Battle of Grunwald, show a dramatic drop in the provisioning of cereals, horses, and livestock (Table II); the role of the castle significantly diminishes after 1410 and the on-going conflict with Poland-Lithuania. The pollen record, however, indicates continued cereal cultivation in the surrounding landscape, suggesting some continuity in land-use, but with the castle no longer fulfilling a major role as a center for storage and provisioning. Some regeneration of woodland is suggested within the wider landscape by the marked increase in Pinus during the 15th century (Figure 4), characteristic of the majority of later Holocene pollen profiles from Poland. However, although Pinus is well adapted to occupying disturbed habitats (Tobolski, & Nalepka, 2004), increased Pinus values do not necessarily equate with increased woodland; the widely dispersed nature of both pollen and seeds is facilitated by open conditions, and may reflect a change in the vegetation composition focused on mono-stands of Pinus rather than mixed woodland.

In addition, there is a large increase in Pb concentrations from c. 28 cm (Figure 5), associated with an elevated enrichment factor. The spike in Pb is 13.12 times the background geology (Table II), and almost entirely attributable to an anthropogenic supply (Figure 6). Although undated, the depositional model suggests a probable 15th century date for the increase in Pb. Geochemical studies of the Greenland Ice core and several European bogs show broadly comparable increases in atmospheric Pb concentrations during the medieval period (Hong et al., 1994; Shotyk et al., 1998; le Roux et al., 2004; De Vleeschouwer et al., 2009b), interpreted as resulting from mining, smelting, and other anthropogenic activities. The increase in Pb within the Radzyń core could reflect background global atmospheric Pb deposition. However, the lack of similar detailed geochemical records for comparison from both the Chełmno-land and central Europe make it difficult to determine more precisely the contribution of local activities to Pb concentrations in the Radzyń sequence. However, potential local sources for increases in Pb might include industrial activity associated with the castle and town, perhaps linked with increased provisioning requirements during the wars with Poland-Lithuania that culminated with the Battle of Grunwald (1410), the Thirteen Years War (1454–1466), or during subsequent Polish-Lithuanian control of the Castle and town from the mid-15th century.

The town appears to have survived the instabilities of the 15th century largely intact, and given the absence of villages in the immediate hinterland, the vegetation changes evident in the lake profile can be confidently linked directly with impact of the castle, the town, and surrounding agricultural, pastoral, and wetland estates.
### Table II: Inventory stores for Radzyń Castle recording stores of (a) grain (bushels), (b) livestock, and (c) horses. Data compiled from Ziesemer (1921).

| Date       | July | October | July | October | July | November | February | May | October | July | November | February |
|------------|------|---------|------|---------|------|----------|---------|-----|---------|------|----------|---------|
|            | 1377 | 1382    | 1390 | 1391    | 1402 | 1404     | 1409    | 1411| 1412    | 1415 | 1422     | 1434    |
| Grains (Bushels) | 1000 | 0  | 499  | 480  | 0  | 510  | 0  | 30 | 330  | 60 | 285  | 382     |
|             | 4739 | 420    | 50   | 86     | 132 | 794  | 0  | 1105| 587  | 0   | 926  | 1200    |
| Wheat      | 1100 | 1400   | 0    | 0      | 0   | 360  | 0  | 0  | 112  | 224 | 0    | 16      |
| Barley     | 3700 | 1000   | 0    | 0      | 0   | 800  | 0  | 115| 441  | 215 | 0    | 832     |
| Oat        | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 60      |
| Rye        | 2000 | 1000   | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Hop        | 2800 | 500    | 500  | 950    | 0   | 400  | 0  | 0  | 0    | 110| 404   | 150     |
| Malt       | 1000 | 1400   | 0    | 0      | 0   | 360  | 0  | 115| 215  | 0   | 832  | 158     |
| Peas       | 370  | 0      | 0    | 221    | 0   | 600  | 0  | 0  | 80   | 298| 740   | 382     |
| Total Grain| 21,470| 7890 | 5900 | 15,538 | 9130| 7400 | 12,170| 7269| 450  | 460 | 1820   | 2713    |
| Livestock  | 1890 | 1990   | 2300 | 1463   | 2050| 1900 | 1900| 2354| 620  | 919| 1203  | 487     |
| Sheep      | 360  | 256    | 319  | 344    | 404 | 390  | 336| 350 | 44   | 85 | 77    | 64      |
| Lambs      | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Cows       | 900  | 925    | 750  | 543    | 702 | 690  | 469| 684 | 13   | 81 | 244   | 127     |
| Bulls      | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Oxen       | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Calves     | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Pigs       | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Piglets    | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Goats      | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Goating    | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Geese      | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Beehives   | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Total livestock | 3150 | 3321 | 3369 | 2350 | 3174 | 2980 | 2705| 3888| 677  | 1085| 1550  | 694     |
| Horses     | 0    | 0      | 0    | 0      | 0   | 0    | 0  | 0  | 0    | 0   | 0    | 0       |
| Horses for riding | 0  | 6   | 16   | 24    | 0   | 20   | 31 | 12 | 13   | 69 | 13    | 45      |
| Horses for work | 0  | 48  | 424  | 57    | 54  | 60   | 40 | 26 | 3    | 24 | 25    | 2       |
| Foals      | 7    | 9    | 9    | 15    | 16  | 14   | 14 | 12 | 0    | 0   | 0     | 0       |
| Stallions  | 298  | 324  | 16   | 0     | 79  | 0    | 0  | 26 | 86   | 0   | 25    | 116     |
| Mares for breeding | 33 | 0   | 0    | 284  | 217 | 330 | 309| 316| 66   | 114| 1400  | 44      |
| Horses for pulling | 0  | 0   | 25   | 22    | 11  | 0    | 0  | 0  | 0    | 0   | 0     | 0       |
| Mares for breeding | 0  | 0   | 0    | 0     | 0   | 0    | 0  | 0  | 0    | 0   | 0     | 0       |
| Horses for servants | 0  | 0   | 25   | 22    | 11  | 0    | 0  | 0  | 0    | 0   | 0     | 0       |
| Total horses | 424 | 473  | 483  | 542   | 475 | 485  | 473| 471| 179  | 225| 235   | 202     |

The gray shading highlights the dramatic drop in stores of grain, livestock, and horses between 1409 and 1410.
CONCLUSION

The palynological and geochemical data from the former Castle Lake at Radzyń represent the most intensively studied and radiocarbon-dated palaeoecological sequence covering the historic period in the Chełmno-land, and display a strong correlation in evidence for the effects of increasing colonization and agricultural activity in the surrounding landscape over the course of the medieval period. Although the late medieval castles, towns, and rural settlements of the Chełmno-land are the most visible traces of medieval colonization and economic intensification, the most significant phase of ecological activity in the pollen and geochemical record occurs during the early medieval period associated with Polish control of the Chełmno-land from the latter half of the 10th century. This is surprising given the close proximity of the pollen sequence to the castle and town established shortly after the start of the crusades. Instead, the pollen and geochemical records suggest that the crusaders and German colonists entered an already significantly altered landscape, with the late medieval characterized instead by broad stability in the intensity of land-use.

The authors thank Marta Gołąbiewska for assisting with fieldwork at Radzyń Chełmiński. The research leading to this publication has received funding from the European Union’s Seventh Framework Programme (FP7/2007-2013) under grant agreement no.263735. Elements of the pollen and geochemistry were undertaken by ADW as part of an MSc Geoarchaeology dissertation at the University of Reading, funded by a scholarship from the Natural Environmental Research Council. NS involvement was supported by the European Social Fund Doctoral Studies and International Programme DoRa, project ETP9031 and IUT 1-8. We also thank Marcin Wiewióra and two anonymous reviewers for their constructive comments.

REFERENCES

Andersen, S.T. (1978). Identification of wild grasses and cereal pollen. Danmarks Geologiske Undersøgelse, Årbog, 1978, 69–92.

Badura, M. (2011). Rośliny Użytkowe w Dawnym Gdańsku. Studium Archeobotaniczne. Gdańsk: Wydawnictwo Uniwersytetu Gdańskiego.

Belzile, N., Chen, Y., Gunn, J.M., & Dixit, S.S. (2004). Sediment trace metal profiles in lakes of Killarney Park, Canada: From regional to continental influence. Environmental Pollution, 130, 239–248.

Bengtsson, L., & Enell, M. (1986). Chemical analysis. In B.E. Berglund (Ed.), Handbook of Holocene palaeoecology and palaeohydrology (pp. 423–445). Chichester: Wiley.

Berend, N., Urbańczyk, P., & Wiszewski, P. (2013). Central Europe in the high middle ages. Cambridge: Cambridge University Press.

Bernadzki, E., Bolibok, L., Brzeźiecki, B., Zajaczkowski, J., & Zybura, H. (1998). Composition dynamics of natural forests in Białowieża National Park, north-eastern Poland. Journal of Vegetation Science, 9, 229–238.

Bieszk, J. (2010). Zamki państwa krzyżackiego w Polsce. Warszaw: Bellona.

Blaauw, M. (2010). Methods and code for “classical” age-modelling of radiocarbon sequences. Quaternary Geochronology, 5, 512–518.

Boyle, J.F. (2001). Inorganic geochemical methods in palaeolimnology. In W.M., Last and J.P. Smol (Eds.), Tracking environmental change using lake sediments, Volume 2: Physical and geochemical methods (pp. 83–141). Dordrecht: Kluwer Academic Publishers.

Bronk-Ramsey, C. (2009). OxCal calibration programme version v4.10. Radiocarbon Accelerator Unit, University of Oxford.

Brostrom A., Nielsen, A.B., Gaillard, M-J., Hjelle, K., Mazier, F., Binny, H., Bunting, J., Fyfe, R., Meltsov, V., Poska, A., Räsänen, S., Soephoer, W., vom Stedingk, H., Suutari, H., & Sugita, S. (2008). Pollen productivity estimates of key European plant taxa for quantitative reconstruction of past vegetation: A review. Vegetation History and Archaeobotany, 17, 461–478.

Buko, A. (2008). The archaeology of early medieval Poland: Discoveries—hypotheses—interpretations. Leiden: Brill.

Chudziak, W. (1994). Podstawy klasyfikacji chronologicznej grodzisk. In J., Chudziakowa (Ed.), Wczesnosredniowieczne grodziska ziemi chełmiskiej (pp. 24–28). Toruń: Uniwersytet Mikolaja Kopernika.

Chudziak, W. (1996). Zasiedlenie strefy chełmińsko-dobrzyńskiej we wczesnym średniowieczu (VII-XI wiek). Toruń: UMK.

Clark, R.L. (1982). Point count estimation of charcoal in pollen preparations and thin sections of sediment. Pollen et Spores, 24, 523–535.

Cook, S.R., Banerjea, R.Y., Marshall, L.J., Clarke, A., & van Zweiten, C. (2010). Concentrations of copper, zinc and lead as indicators of hearth usage at the Roman town of Calleva Atrebatum (Silchester, Hampshire, U.K.). Journal of Archaeological Science, 37, 871–879.

Cushing, E.J. (1967). Evidence for differential pollen preservation in late Quaternary sediments in Minnesota. Review of Palaeobotany and Palynology, 4, 87–101.

De Vleeschouwer, F., Piotrowska, N., Sikorski, J., Pawłyta, J., Cheburkin, A., LeRoux, G., Lamentowicz, M., Fagel, N., & Maquoy, D. (2009a). Multiproxy evidence of “Little Ice Age” palaeoenvironmental change in a peat bog from northern Poland. The Holocene, 19, 625–637.

De Vleeschouwer, F., Fagel, N., Cheburkin, A., Pazdur, A., Sikorski, J., Mattielli, N., Renson, V., Fialkiewicz, B., & Piotrowska, N. (2009b). Anthropogenic impacts in North Poland over the last 1300 years. The Science of the Total Environment, 407, 5674–5684.
Entwistle, J.A., Abrahams, P.W., & Dodgshon, R.A. (2000). The geoarchaeological significance and spatial variability of a range of physical and chemical properties from a former habitation site, Isle of Skye. Journal of Archaeological Science, 27, 287–303.

Faliniski, J.B. (1986). Vegetation dynamics in temperate lowland primeval forests. Ecological Studies in Bialowieza forest. Geobotany & Dordrecht: Dr W. Junk Publishers.

Fernandez, F.G., Terry, R.E., Inomata, T., & Eberl, M. (2002). An ethnoarchaeological study of chemical residues in the floors and soils of Q’eqchi’ Maya Houses at Las Pozas, Guatemala. Geosarchaeology, 17, 487–519.

Filbrandt–Czaja, A., & Noryśkiewicz, B. (2003). Osadnictwo na pograniczu słowiańsko–pruskim we wczesnym średniowieczu w świetle analizy pyłkowej. In K. Grążyński (Ed.), Pogranicze polsko–pruskie I krzyżackie (pp. 57–65). Wrocław: Wrocławsko-Brodnicza.

Grimm, E.C. (2011). Tilia 1.7.16 Software. Springfield, IL: Illinois State Museum, Research and Collection Center.

Hanczak, K., Wańzy, T., Vanacker, J., & Beeckman, H. (2005). Provenancing Baltic timber from art historical object: Success and limitations. Journal of Archaeological Science, 32, 261–271.

Holliday, V.T., & Gartner, W.G. (2007). Methods of soil P analysis in archaeology. Journal of Archaeological Science, 34, 301–333.

Hong, S., Candoleone, J.P., Patterson, C.C., & Boutron, C.F. (1994). Greenland ice evidence of hemispheric lead pollution two millennia ago by Greek and Roman civilizations. Science, 265, 1841–1843.

Hutson, S.R., & Terry, R.E. (2006). Recovering social and cultural dynamics from plaster floors: Chemical analyses at ancient Chunchucmil, Yucatan, Mexico. Journal of Archaeological Science, 33, 391–404.

Hybel, N. (2002). The grain trade in northern Europe before 1350. Economic History Review, 45, 219–247.

Hynynen, J., Niemistö, P., Viherä-Aarnio, A., Brunner, A., Hein, S., & Velling, P. (2010). Silviculture of birch (Betula pendula Roth and Betula pubescens Ehrh.) in northern Europe. Forestry, 83, 103–119.

Kemp, A.L.W., Williams, D.H., Thomas, R.L., & Gregory, M.L. (1978). Impact of man’s activities on the chemical composition of the sediments of Lake Superior and Huron. Water, Air and Soil Pollution, 10, 381–402.

Karg (Ed.), Medieval food traditions in northern Europe (pp. 39–72). Copenhagen: National Museum.

LeRoux, G., Weiss, D., Gratian, J., Givet, N., Cheburkin, A., Rausch, N., Kober, B., & Shotyk, W. (2004). Identifying the sources and timing of ancient and medieval atmospheric lead pollution in England using a peat profile from Lindow bog, Manchester. Journal of Environmental Monitoring, 6, 502–510.

Lomas-Clarke, A.H., & Barber, K.E. (2007) Human impact signals from peat bogs—A combined palynological and geochemical approach. Vegetation History and Archaeobotany, 16, 419–429.

Mackereth, F.J.H. (1966). Some chemical observations on post-glacial lake sediments. Philosophical Transactions of the Royal Society of London, B250, 165–213.

Makohonienko, M. (2004). Late Holocene period of increasing Human impact. In M. Ralska–Jasiewiczowa, M. Latałowa, K. Wasylkowka, K. Tobolski, E. Madeyska, H.E. Wright, & C. Turner (Eds.), Late Glacial and Holocene history of vegetation in Poland based on isopollen maps (pp. 411–416). Kraków: Polish Academy of Sciences.

Makowiecki, D. (2007). Gospodarka zwierzeta w strefie chelmnińskiej pogranicza słowiańsko–pruskiego i krzyżackiego w średniowieczu. In K. Grążyński (Ed.), Pogranicze polsko–pruskie i krzyżackie (pp. 23–37). Wrocławsko-Brodnicza: Lega.

Moore, P.D., Webb, J.A., & Collinson, M.E. (1991). Pollen analysis, 2nd ed. Oxford: Blackwell.

Noryśkiewicz, A.M. (2004a). Analiza pyłkowa osadów biogenicznych terasy zalewowej Wisły w profile Chełmno/Rybak. In W. Chudziak (Ed.), Wczesnośredniowieczny zespół osadniczy Kalduś. Studia przyrodniczo–archeologiczne (pp. 143–150). Toruń: UMK.

Noryśkiewicz A.M. (2004b). Przemiany w szacie roślinnej okolic Uścia w okresie ostatnich dwóch tysięcy lat. In W. Chudziak (Ed.), Wczesnośredniowieczny zespół osadniczy Kalduś. Studia przyrodniczo–archeologiczne (pp. 151–163). Toruń: UMK.

Noryśkiewicz, A.M. (2005). Preliminary results of study on vegetation history in the Linje mire region using pollen analysis. Monographiae Botanicae, 94, 118–133.

Noryśkiewicz, A.M. (2013). Historia roślinności I osadnictwa ziemi Chełmskiej w późnym Holocenie. Studium paleolozniczne. Toruń: Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika.

O’Connell, M., Ghilardi, B., & Morrison, L. (2013). A 7000-year record of environmental change, including early farming impact, based on lake-sediment geochemistry and pollen data from County Sligo, western Ireland. Quaternary Research, 81, 35–49.

Peterken, G. (1981). Woodland conservation and management. London: Chapman and Hall.

Pluszkowski, A.G. (2012). The archaeology of the Prussian crusade: Holy war and colonization. London: Routledge.
Poliński, D. (2003). Późnośredniowieczne osadnictwo wiejskie w ziemi chełmińskiej. Toruń: UMK.

Polish Geological Institute. (2015). Central geological database. http://bazagis.pgi.gov.pl/website/cbdgen/viewer.htm.

Rackham, O. (2003). Ancient woodland. Its history, vegetation and uses in England. Colvend: Castlepoint Press.

Ralska–Jasiewiczowa, M., Latałowa, M., Wasylkowa, K., Tobolski, K., Madeyska, E., Wright, H.E., & Turner, C. (Eds.) (2004). Late glacial and Holocene history of vegetation in Poland based on isopollen maps. Kraków: Polish Academy of Sciences.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., & van der Plicht, J. (2013). IntCal13 and marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon, 55, 1869–1887.

Shotyk, W., Weiss, D., Appleby, P.G., Cheburkin, A.K., Frei, R., Gloor, M., Kramers, J.D., Reese, S., & VanDer Knaap, W.O. (1998). History of atmospheric lead deposition since 2,370 14C yr BP from a peat bog. Jura Mountains, Switzerland. Science, 281, 1635–1640.

Smol, J.P. (2008). Pollution of lakes and rivers: A palaeoenvironmental perspective, 2nd ed. London: Blackwell.

Święta-Musznicka, J., Latałowa, M., Badura, M., & Gołembnik, A. (2013). Combined pollen and macrofossil data as a source of reconstructing mosaic patterns of the early medieval urban habitats—A case study from Gdański, N. Poland. Journal of Archaeological Science, 40, 637–638.

Torbus, T. (1998). Die Konwentsburgen im Deutschordensland Preussen. Munich: Oldenbourg.

Vera, F.W.M. (2000). Grazing ecology and forest history. Wallingford: CABI.

Vuorela, I. (1986). Palynological and historical evidence of slash-and-burn cultivation in South Finland. In K-E. Behre (Ed.), Anthropogenic indicators in pollen diagrams (pp 53–64). Rotterdam: Balkema.

Wacnik, A., Goslar, T., & Czernik, J. (2012). Vegetation changes caused by agricultural societies in the Great Masurian Lake District. Acta Palaeobotanica, 52, 59–104.

Wardas-Lasoń, M., & Góńska, W. (2010). Rozpoznanie stanu zanieczyszczenia medzią I ołowiem poziomów użytkowych w rejonie Kramów Bogatych. In A. Biedrzycka (Ed.), Krzysztofory. Scientific Bulletin of the Historical Museum of the City of Kraków, 28, 209–224.

Wasylkowa, K. 2004. Present-day natural environment of Poland. In M. Ralska–Jasiewiczowa, M. Latałowa, K. Wasylkowa, K. Tobolski, E. Madeyska, H.E. Wright, & C. Turner (Eds.), Late Glacial and Holocene history of vegetation in Poland based on isopollen maps (pp. 13–20). Kraków: Polish Academy of Sciences.

Ważyń, T. (2005). The origin, assortments and transport of Baltic timber. In C. Vande Velde, H. Beeckman, J. VanAcker, & F. Verhaeghe (Eds.), Constructing wooden images (pp. 115–126). Brussels: Brussels University Press.

Wilson, C.A., Davidson, D.A., & Cresser, M.S. (2005). An evaluation of multi-element analysis of historic soil contamination to differentiate space use and former function in and around abandoned farms. Holocene, 15, 1094–1099.

Wilson, C.A., Davidson, D.A., & Cresser, M.S. (2008). Multi-element soil analysis: An assessment of its potential as an aid to archaeological interpretation. Journal of Archaeological Science, 35, 412–424.

Ziesemer, W. (1921). Das Grosse Aemterbuch des Deutschen Ordens. Danzig: Kalemann.