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Abstract

Integrated micromorphology, plant macro, pollen, phytolith, and non-pollen palynomorph analyses from two 13th century Teutonic Order castles, Karksi (Livonia), and Elbląg (Prussia), examine the livestock management and alimentation practices by the initial military colonisers during the Crusades. At Karksi, a key administrative centre in Livonia, in the area which later became the High Castle, the investigation of a midden and of the organic-rich sediment beneath allow the diachronic use of this area to be examined. Freshwater aquatic indicators are consistent with the occurrence of shallow stagnant water, as also suggested by a water-laid pond sediment identified in thin-section. Coprophilous spore taxa suggest the use of the pond as a watering hole. Plant macrofossils from the midden represent a range of habitats, mostly from wet/damp areas, as well as pastures and meadows, and also woodlands. Fragments of millet are embedded within herbivore dung in micromorphological thin-section showing the use of this grain as fodder. At Elbląg in Prussia, the initial Order headquarters, *Trichuris* sp. eggs may derive from animal feces as dung with parasite eggs was observed in thin-section, and a range of coprophilous taxa were extracted. The results from both sites show early colonisers use a mixed grain/leaf fodder diet for livestock, with a move to grain and grass later on. The results represent an important study of medieval castles from the period of active Crusading, and reveal the diachronicity of the range of livestock that the Teutonic Knights kept, whereabouts within the castles they were stabled, and livestock alimentation.

Keywords

Crusades; micromorphology; plant macroremains; palynology, non-pollen palynomorphs

Introduction

The beginning of the 13th century A.D. sees a period of active crusading activity in the eastern Baltic region. Crusading armies unleashed a relentless holy war against the last indigenous pagan societies in Europe. The territories of these tribal groups were replaced with new Christian polities largely run by a militarised theocracy, consisting of the Teutonic Order, bishops and their cathedral chapters. They constructed castles, encouraged colonists, developed towns and introduced Christianity (Bartlett 1994; Berend 2005; Murray 2001; Pluskowski 2012; Pluskowski 2019). In this context of conquest and colonisation on the Baltic frontier, two 13th century Teutonic Order castles (Fig. 1), Karksi in Estonia (Ger. Karkus in medieval Livonia), and Elbląg in Poland (Ger. Elbing in medieval Prussia), were subjected to detailed environmental analysis (using micromorphology, plant macroremains, pollen, phytoliths, and non-pollen palynomorphs) to examine the livestock management and alimentation practices associated with the initial military colonisation during the period of active crusading. Livestock management and alimentation practices are examined at these strategic castles in relation to their use and the impact of the arrival of Teutonic Order and initial colonising behaviours. This research examines specifically what animals were kept, where were livestock stabled, how were livestock being fed, how does the use of fodder reflect the use of the wider landscape, and how do these issues change through time. The integrated application of these techniques enables plant macroremains and microfossils to be examined in relation to the microstratigraphic formation processes that occurred within the unit that they were collected from.

Before the Crusades, in the area that later became Livonia as more native territories were conquered, the indigenous societies of the eastern Baltic had an established pastoral culture, revolving around the raising of cattle, sheep, goats, pigs and poultry (Blomkvist 2009, 444; Maltby *et al.* 2019; Maldre 2003). Documentary sources, particularly Henry's *Chronicle of Livonia* (Brundage 2003) and the anonymous *Livonian Rhymed Chronicle*, indicate that a complex provisioning system was essential from the earliest arrival of crusading armies in order to support the influx of crusaders, merchants, colonists and their heavy cavalry. The pastoral economy at this time of flux would have been highly volatile, with raiding accentuating the impact of environmental factors on herds (Goldschmidt 1979).

Documentary sources, particularly Peter of Dusburg's *Chronicle of Prussia* (Scholz and Wojtecki 1984), describe the Prussians as maintaining herds of cattle, sheep and goats in valley meadows and woodland clearings. The historical sources all emphasise the importance of horses for riding, although like oxen they could also be used for ploughing. Consumption of horse meat is clearly evident, but the majority of chroniclers noted the consumption of mare's milk (Popłoński 1862, 7). The arrival of the

72 Teutonic Order in Prussia prompted new developments in animal husbandry and related alimentary

73 culture. The most significant changes occurred in livestock husbandry; whilst the older system was

74 dominated by pigs and cattle, the latter became the main staple meat under the new regime with pigs

75 still forming an important part of the diet (Makowiecki *et al*. 2019).

76

77 So far, excavations of Teutonic Order castles have provided little in the way of detailed environmental

78 evidence to understand the subsistence systems of the earliest colonisers (Pluskowski 2012, 296-297)

79 and the organisation of these systems within castle sites has primarily been reconstructed from

80 written sources (Pluskowski 2012, 151). This research, within the framework of The Ecology of

81 Crusading project, seeks to redress this imbalance to provide a more nuanced understanding of the

82 diachronic use of space and subsistence systems within castles and their commandaries, particularly

83 during the initial period of colonisation. The Ecology of Crusading research project has now

84 accumulated substantial environmental data from across the eastern Baltic to further our

85 understanding of the impact of the Crusades (Pluskowski 2019; Pluskowski *et al*. 2019b).

86

The Sites

88 Archaeological deposits were sampled from two castles: Karksi Castle (Ger. Karkus) located in present-

89 day Estonia, and Elbląg (Ger. Elbing) located in present-day northern Poland (Fig. 1)

90

91 Karksi Castle was an important administrative centre in Livonia, governed by an advocate. This official

92 was based in the castle and had the role of managing resources and the provision of security. The site

93 is situated above the valley of the River Halliste and on sandy clay loam glacial till surface geology. The

94 multi-proxy investigation in Trench 1 (Fig. 2) of a midden that overlies 'anthropogenic peats' in the

95 area directly below where the High Castle was later constructed, presented a unique opportunity to

96 examine the waterlogged deposits to understand development and diachronic use of this area during

97 the pre-construction and construction phases of the early castle (Banerjea and Badura 2019; Brown,

98 2019; Valk *et al* 2012). A spring ran through the site in the area of Trench 1, which became apparent

99 during the excavation of the site (Valk *et al* 2012). The radiocarbon dates, modelled using the BACON

100 Bayesian statistical program (Blaauw and Christen, 2011), suggest that these sediments were

101 deposited rapidly between AD 1230-1280 (Valk *et al* 2012). During excavation, the deposits above the

102 midden, contexts 8, 9, and 10, were described (respectively) as a dark soil with organics, red clayish

103 loam, and a dark grey soil with wood chips. The midden material comprised numerous leather

104 fragments, ceramics, wood chips, nut shells, abundant animal and fish bones, fragments of wooden

105   vessels, wooden gaming pieces and tally sticks (Valk *et al* 2012). The formation processes of these

106   stratigraphic units have been refined further using micromorphology (Banerjea and Badura 2019).

107

108   In the absence of comprehensive excavation and preservation of early occupation phases of Elbląg

109   castle, relatively little is known about the internal layout of the Order's thirteenth-century *castra* in

110   the eastern Baltic (Pluskowski 2012; Pluskowski 2019; Pluskowski *et al* 2019b). The *castra* at Elbląg

111   was the administrative centre of the Teutonic Order until 1308 when it moved to Malbork (Ger.

112   Marienburg), which then became its official headquarters. However, distinct spaces are specified in

113   the Order's Rule, and written sources provide information on the variety of spaces within some of the

114   larger convents from the 14th century (Jóźwiak and Trupinda 2012). The excavations that were

115   conducted in 2012 and 2013 ahead of development at Elbląg have produced the only example where

116   the timbers have survived *in situ* from multiple phases of rebuilding (Fig. 3). The early *castra* was

117   constructed in timber before it was rebuilt in stone (Fonferek, 2019). An exceptionally well-preserved

118   and well-stratified sequence of organic-rich deposits that were interspersed with depositions of

119   alluvial sediment was revealed. Geological, faunal and floristic investigations of the sediment under

120   the castle demonstrate that the sediments which underlie the courtyard of the Museum of

121   Archaeology and History in Elbląg document the evolution of this area from a relatively deep lake,

122   Lake Druzno, through a shallowing water body, to a waterside zone, where the Elbląg River flowed

123   into the Vistula Lagoon, by the time the timber castle was erected (Nitychoruk *et al*. 2016). Timbers at

124   the base of this sequence produced a dendrochronology date of *c*. AD 1245, which means that the

125   lowest deposits within this sequence represent the very earliest occupation and use of the *Vorburg,*

126   or outer ward, of the early *castrum*.

Materials and Methods

Sampling methods

129   Monoliths were collected from both sites to sample all major stratigraphic units and their boundaries.

130   At Karksi (Fig. 2), two, overlapping 0.5 m monoliths, 241 and 242, were collected from Trench 1 and

131   were sub-sampled for micromorphology, pollen, NPPs, and phytolith analysis, but only data from 241

132   is relevant to this study. The upper deposits in 242 are probably 14th century and there may have been

133   some truncation when the first of the cobble pavements was constructed – and that included artefacts

134   of 15th century date, and so do not relate to the period of active crusading. Archaeobotanical samples

135   (*c*. 5 kg) were collected from the separate contexts of Trench 1. All samples represent waterlogged

136   material with varying admixture of wood chips and small twigs. At Elbląg, two 0.25 m and two 0.1 m

137   monoliths were collected from an area of the profile from Trench 2 with some particularly organic

138   layers that were interspersed with deposits of alluvium (Fig. 3) and eight micromorphology thin-

139   sections were prepared from them, along with samples for pollen, NPPs and phytoliths from the key

140   stratigraphic units. During excavation in Trench 2 nine samples (*c.* 2 kg) for macrobotanical analysis

141   were also collected. They represent separate contexts connected with moat and nearby useful layers

142   in which organic material was visible. The uppermost context, 17, dated to the second quarter of 14th

143   century, was composed of charred grains and charcoals and there was evidence of fire.

144

145   Faunal remains were recovered during excavations at both sites (Makowiecki *et al*. 2019; Maltby *et al*

146   2019; Rannamäe, Lõugas 2019), and the data are drawn upon here.

147

Laboratory Methods

149   *Micromorphology*

150   Six thin-sections, 11.5 x 7.5 cm, were prepared from sub-samples monolith 241, Karksi (Fig. 2), and

151   eight from Elbląg were prepared in the thin section unit, University of Reading, UK (Fig. 3). The samples

152   were oven-dried to remove all moisture and then impregnated with epoxy resin while under vacuum.

153   The impregnated samples were placed in an oven to dry for 18 hours at 70 ˚C, then cut and mounted

154   to onto a frosted slide. The sample was then cut, ground and polished to the standard geological

155   thickness of 30 µm.

156

157   Micromorphological investigation is carried out using a Leica DMLP polarising microscope at

158   magnifications of 40x – 630x under Plane Polarised Light (PPL), Crossed Polarised Light (XPL), and

159   where appropriate Oblique Incident Light (OIL). Thin-section description is conducted using the

160   identification and quantification criteria set out by Bullock *et al.* (1985) and Stoops (2003), with

161   reference to Mackenzie, Adams (1994) and Mackenzie, Guilford (1980) for rock and mineral

162   identification, and Fitzpatrick (1993) for further identification of features such as clay coatings. The

163   identification of organic components was carried out with reference to materials at the IPNA,

164   University of Basel, Switzerland.

165

166   *Plant Macroremains*

167   At Karksi and Elbląg, a 300 cm^3 sub-sample of sediment was selected from each of waterlogged sample,

168   following the standard procedure use in the Laboratory of Palaeoecology and Archaeobotany,

169   University of Gdańsk, Poland. Samples from Karksi were pre-treated directly on the site. Flotation was

170   conducted with 2.0, 0.5 and 0.2 mm mesh sieves. In the laboratory all fractions were checked for the

171   presence of plant macroremains. At Elbląg, materials were soaked for 24 hours in weak solution of

172   KOH and washed through 2.0, 0.5 and 0.2 mm mesh sieves. The remaining material from the sample

173   was wet-sieved only through the coarse sieve in order to obtain large diasporas, normally

174   underrepresented in the base sample. Charred material from context 17 was dried and analysed as a

175   whole (1500 cm^3) to address the preservation bias arising from the charring process, which could

176   destroy completely disapores, such as weeds. Taxa names have been used after Mirek *et. al* (2002)

177   and their ecological affiliation was established according to Matuszkiewicz (2008). The set of results

178   presented in the tables is related to plants whose ecological affiliation was determinable.

179

180   *Pollen and Non Pollen Palynomorphs*

181   For analysis of pollen and non-pollen palynomorphs, samples *c*. 1 cm3 in volume were taken from

182   monolith 241 (Karksi) and samples E1 to E4 (Elbląg). One *Lycopodium* tablet was added to enable

183   calculation of pollen concentrations. Samples were prepared following standard laboratory

184   techniques (Moore *et al*., 1991) including the use of hydrochloric acid (removal of carbonates),

185   hydrofluoric acid (removal of silica) and acetolysis (removal of cellulose), with the caveat that this step

186   may dissolve some types of parasite eggs (Reinhard *et al*. 1986), but it was necessary in order to

187   analyse the same slides for both, pollen and non-pollen microfossils. Samples were mounted in

188   glycerol jelly and stained with safranin. A minimum of 500 pollen of terrestrial species were counted

189   for each level. Pollen percentages are calculated based on terrestrial plants. Fern spores, aquatics and

190   *Sphagnum* are calculated as a percentage of terrestrial pollen plus the sum of the component taxa

191   within the respective category. Identification of cereal pollen followed the criteria of Anderson (1979).

192   Identification of indeterminable grains was recorded according to Cushing (1967). The pollen diagram

193   was produced using Tilia version 1.7.16 program (Grimm, 2011).

194

195   The calculation for NPP concentration is based on a minimum sum of 200 (exotic markers +

196   microfossils), in order to obtain reliable estimates (Finsinger and Tinner 2005). Identifications were

197   made under light microscopy at 400x magnifications. Considering the anthropogenic nature of the

198   deposit, formed over a short span of time and probably including dumping events, the use of NPP

199   concentrations seems more appropriate than the use of accumulation rates, that appear more

200   suitable to investigate natural sequences (Baker *et al*. 2013, 2016; Wood and Wilmshurst 2013; Yeloff

201   *et al*. 2007).

202

203   *Phytoliths*

204   Phytoliths were extracted from each sample using the protocol developed at the Institute of

205   Archaeology, University College London, UK (Jenkins and Rosen 2007), which, in summary uses the

following stages: (1) removal of the coarse fraction >0.5 mm; (2) 1 g of the sieved fraction was weighed out; (3) removal of calcium carbonate using a dilution of 10% hydrochloric acid; (4) clay removal using a settling procedure and sodium hexametaphosphate (Calgon) as a dispersant; (5) samples were placed in a muffle furnace for two hours at 500 °C to remove organic matter; (6) phytoliths were separated from the remaining material using a heavy liquid calibrated to a specific gravity of 2.3; (7) approximately two milligrams of phytoliths per sample were mounted onto microscope slides, using the mounting agent Entellan®.

Microscope slides were assessed using a Leica DMLP polarising microscope using 100x and 400x magnifications. Slides were initially assessed to ascertain if there were a sufficient number of single cells phytoliths present to take the slide to a full count. Those with a sufficient concentration and preservation of remains were fully analysed. Analysis consisted of counting and identifying a minimum of 250 phytolith forms. Phytoliths were further classified as deriving either from woody (dicotyledon) or non-woody.

Formation processes within the microstratigraphic sequence at Karksi

Monolith 241 (Fig.2) was collected from the lowest stratigraphic layers infilling the shallow, basin-like depression located in the area of the later High Castle; deposits from the later, 14th century deposits are preserved in monolith 242. Modelling of radiocarbon dates from monolith 241 suggest that these deposits, which include midden material, formed rapidly between AD 1272 and 1290 (Valk *et al* 2012). Micromorphological analysis (Supplementary tables 1 and 2), outlined in detail in Banerjea and Badura (2019), refined the stratigraphic sequence (Fig. 2). Context 13, the 'peat deposit', comprises three separate depositional events: MU13a, MU13b, and MU13c. The lowest, MU13c, has been interpreted as pond sediment (Boyd 1995, 4–5). MU13b is a peat consisting mainly of organic components, 66%, with some mineral inclusions, 34%. There are no microlaminations and inclusions are unoriented, unrelated, random and unreferred, both of these features are different to MU13a above, which is also peat, but has a microlaminated bedding structure and plant fragments are strongly oriented, aligned parallel to basal boundary. These 'peat' deposits are better classified as anthropogenic peats (Ismail-Meyer *et al*., 2018). The formation process shows similar characteristics to natural peat forming processes, but where organic materials from around the settlement have rapidly accumulated where there is a high groundwater table, which has preserved the organic matter (Ismail-Meyer *et al*., 2013, 331; Ismail-Meyer *et al*., 2018). Context 12, the 'midden', comprises two separate depositional events: MU12a, and MU12b. MU12a is a thin, 0.6-1.5 cm accumulation of leaf litter (Fig. 4a), which overlies a more substantial horizon formed from midden material, MU12b; this leaf litter is considered to

240   represent a period of stabilisation. Micromorphology provided further information on the richness of

241   the midden material with fish bones, burnt egg shell, hazelnut shells, and herbivore dung identified.

242

243   Pollen was well-preserved within context 13, but a sizeable quantity of the cereal pollen was heavily

244   crumpled and is identified only generally as *Cerealia*-type (Fig. 5). No pollen survived in samples from

245   MU13b, with the majority of samples derived from MU13a. There is a wide range of herbaceous pollen

246   types suggestive of damp and meadow environments in the vicinity. The immediate area around the

247   castle appears to have been largely cleared of trees. There are clear differences between the pollen

248   signal from the base of the sequence (MU13a-c) and the 'midden' deposits (MU12a and b).

249   Microscopic indicators of freshwater habitats were recorded (Fig. 5), particularly in the lowest levels.

250   Spores of Zygnemataceae (*Spirogyra* sp.) characterise shallow (*c*. 50 cm) eutrophic pools, mostly

251   stagnant (van Geel 2001). Tests of thecamoebians, occurring on both sites (*Arcella* and *Euglypha* spp.),

252   also belong to taxa typical of damp environments, and confirm the presence of a shallow pond on the

253   site (Charman *et al*. 2000), as suggested by a water-laid pond sediment identified in thin section,

254   MU13c (Fig. 2). Furthermore, macroremains of *Chara* sp. (stonewort) oospores, typical aquatic green

255   algae, characteristic of fresh water occurred in context 14 at the very base of the dammed pond. Fish

256   scales (Villagran *et al*. 2017), were identified by micromorphology (Fig. 4b) within the remains of

257   MU13a and MU13b, the anthropogenic peats formed from leaf fodder accumulations. There is a

258   significant peak in *Betula* (birch) pollen at the top of the midden (Fig. 5), which corresponds to a thin

259   leaf litter layer identified on the top of the midden, MU12b (Fig. 4a).

Livestock management and alimentation at Karksi

261   All levels at Karksi Castle, in particular the lowermost one (MU13c) show the occurrence of obligate

262   fungal spores (Fig. 5) which only use herbivore dung as a growing substrate (*Sporormiella*, *Sordaria*,

263   *Arnium*, *Delitschia* and *Rhytidospora* spp.) (Krug *et al*. 2004). This evidence proves the presence of

264   animal feces in the vicinity of the sampled deposit, as dung spores have a relatively low dispersal and

265   are regarded as indicators of local events (van Geel *et al*. 2003; Mazier *et al*. 2009). Coprophilous spore

266   taxa within MU13c could indicate the use of the pond as a watering place for the livestock.

267   Micromorphological analysis showed fragments of coprolites from small herbivores such as sheep or

268   goat within the midden material, MU12b (Fig. 4c). These lines of evidence would suggest that

269   herbivores, including sheep or goats were kept in this area, which was to become the High Castle,

270   during this early colonising period.

271

272 Several of the different proxies applied at Karksi provided evidence for the types of animal fodder
273 used by the occupants of the site. Deposits MU13a and MU13b formed gradually, possibly as a result
274 of material (foliage) being dumped at the edge of the pond. The pond would have served as a water
275 source for livestock and mostly infilled with foliage that may represent the remains of leaf fodder, the
276 lower unit representing leaf fodder that has been broken up by trampling (Banerjea, Badura 2019)
277 (Fig. 2), with macroremains of *Betula* identified from sample 240 at the base of context 13 (Valk *et al.*
278 2012). MU13b comprises predominantly wood and twigs; and MU13a predominantly tree leaves.
279 Branches and twigs were an important addition to leaf fodder in times of food scarcity such as winter
280 (Rasmussen 1993), particularly for cattle and sheep in the Baltic where branches and twigs of trees
281 and shrubs were collected from wooded meadows (Kukk, Kull, 1997). Arguably, on the basis of their
282 large size observed using micromorphology, >1 cm in transverse section, the wood and twig fragments
283 within MU13b could represent uneaten fodder remains, which have been made available to the
284 livestock, possibly as a result of clearance activities, adjacent to their water source; twigs and leaves
285 with a diameter <5 mm have been recorded within cow pats and sheep/goat dung pellets (Akeret and
286 Jacomet 1997; Akeret and Rentzel 2001; Akeret *et al.*, 1999; Fauve and Jacomet 1998).

287

288 Pollen evidence from context 13 (Fig. 5) suggests that grain and hay fodder was also dumped alongside
289 the leaf fodder. There are large quantities of Poaceae (grass) and cereal pollen, particularly *Avena-*
290 *Triticum* (oat-wheat). The poor production and dispersal rates of most cereals, excluding wind-
291 pollinated *Secale* (rye) suggest nearby agricultural fields are unlikely to have been the direct source of
292 the significant quantities of cereal pollen recorded from context 13. Instead the majority of cereal
293 pollen is likely to derive from stored grain used for human consumption or as a component of animal
294 fodder. The large quantity of Poaceae grains could derive from hay harvested from meadows/pastures
295 as the primary component of animal fodder, but could also reflect pollen of a variety of grass species
296 transported by wind over longer distances from vegetation growing within the vicinity of the site.
297 Many of the ruderal and field weed pollen are likely to have been brought into the castle along with
298 grain and hay, carried by insects attracted by rotting waste or derived from plants growing in the
299 immediate vicinity. The dominance of both cereals and grass pollen within context 13 is therefore
300 consistent with the micromorphological evidence of the deposit primarily as dumped fodder.

301

302 The midden deposits, MU12a and MU12b, contained further evidence for livestock alimentation at
303 Karksi. Coprolites from small herbivores such as sheep or goats were identified in thin section within
304 MU12b. Small fragments of millet (*Panicum* sp.) were identified embedded within the actual herbivore
305 coprolites (Fig.4c). No macroremains of millet were recovered from the midden deposits, which

306 suggests that processing waste was not discarded here, but that the grain was instead ingested as
307 fodder. The other macroremains from Karksi represent a range of habitats, mostly diasporas of species
308 from wet/damp areas, as well as ruderal places (Banerjea and Badura 2019). It is possible that the
309 plant remains characteristic of the meadows/pastures come from places where animals were grazed.
310 Traces of cereals (rye, barley, oat, wheat) were recovered, which could be used both as an element of
311 human food or animal fodder. Preservation of pollen in 'midden' deposits (context 12) was more
312 sparsely preserved, with the exception of the upper sample from the accumulation of leaf litter,
313 MU12a (Fig. 5). There is less pollen of Poaceae and cereals and instead greater quantities of
314 Brassicaceae (mustards), Ranunculaceae (buttercups), Caryophyllaceae (champions), meadowsweets
315 (*Filipendula*) along with pollen of Rosaceae (rose family) and Apiaceae (carrot family).

Formation processes within the microstratigraphic sequence at Elbląg

317 Micromorphology identified four main changes in the deposition of sediment and use of the earliest
318 outer ward (Supplementary tables 3 and 4; Banerjea 2019). The earliest deposits were first trampled
319 by caprines, and were then followed by a period comprising several flooding events depositing
320 alluvium. The analysis shows that context 26 at the base of the sequence is three microstratigraphic
321 units (MU26i–26iii) comprising mixed lenses of trampled herbivore dung with low abundances of
322 faecal spherulites, and alluvium (Fig. 3); the survival of faecal spherulites in a waterlogged sequence
323 is unusual and may result from very localised preservation conditions that can occur in archaeological
324 occupation deposits (Banerjea *et al.* 2015). These mixed lenses most probably formed as a result
325 trampling activity by livestock while low level flooding took place, which deposited alluvial sediment
326 that was subsequently trampled by animals and mixed with dung. MU26i-26iii are then overlain by a
327 more substantial deposit of alluvium, MU25, which formed as a result of more substantial flooding of
328 this area of the earliest Vorburg. This is interspersed with a trampled occupation surface containing
329 fragments of charred wood and phytoliths (MU23b) with framboidal pyrite. These commonly occur in
330 marine and perimarine environments and form at the oxic-anoxic interface (Kattenberg and
331 Aalbersberg 2004; Mees, Stoops 2018), but also in freshwater environments due to bacterial
332 degradation of organic matter (Ismail-Meyer *et al.,* 2013) and in this context their formation is situated
333 with a changing marine, fluvial and lacustrine system (Nitychoruk et al. 2016) The occupation surface
334 is overlain by more alluvium, MU23a, although this is less substantial in thickness than MU25.

335

336 A floor-raising 'brush wood' (branches from small trees and shrubs) platform (MU20b and MU20c)
337 was constructed over the alluvial flooding deposits, on which stabling deposits from large herbivores
338 formed *in situ*. It is also possible that rather than being a platform, the 'brush wood' material

represents a collapsed fence. Micromorphology shows that there is change later in this sequence in MU16a4 and 18b, which represent *in situ* stabling waste: elongated organic strands rather than pellets are strongly oriented and aligned parallel with the basal boundary. This dung material is more characteristic of that of larger herbivores such as cattle or horses, the upper part of which, MU16a4, is characteristic of a stabling crust (Brönnimann *et al.* 2017). A stabling crust forms as a result of trampled dung and organics from stabling waste becoming cemented by the input of uric acid (Brönnimann *et al.* 2017), and, as observed in MU164a (Fig. 4d), appears to have the micromorphological properties of dopplerite, which forms as a result of the decay of organic materials under wet conditions (Ismail-Meyer *et al.*, 2018.).

The area is then inundated again with alluvial sediment, MU16a3, and when this has stabilised leaf litter, MU16a2, accumulated. The microstratigraphic sequence ends with a deposit of discarded material, MU16a1, which represents the abandonment of the area. This discarded material comprises brick, daub and burnt bone inclusions, as well as organic components such as leaves, charred cereals, wood, bark, and charred wood.

Livestock management and alimentation at Elbląg

Two horizons of livestock managements were identified within the sequence in Trench 2 through the outer ward of the *castrum* at Elbląg, both of which are characterised by the presence of herbivore dung in thin section (Figs. 3, 4e, 4f, 4g) and corresponding horizons of a range of coprophilous fungal spores and intestinal parasite eggs, *Trichuris* sp. as identified by extraction (Fig. 6), and possible *Ascaris* sp. (Fig. 3e) identified in thin-section (Pümpin *et al.* 2017). The earliest microstratigraphic units, MU26i-26iii, contain trampled ruminant dung from small herbivores such as sheep/goat (Brönnimann *et al.* 2017) with rare calcareous faecal spherulites. Intestinal parasite eggs, *Trichuris* sp., and coprophilous fungal spores are less abundant in the lower microstratigraphic units, which may be due to this area not being used at this point as a livestock stable, but as a yard area where livestock roamed and trampled around. The trampling of dung by animals may prevent the fungi from growing to disperse the spores (Morandi 2018). The stabling crust, MU16a4, contained the greatest abundances of coprophilous (*Sporormiella*-type, *Sordaria*-type, *Sordaria cf. fimicola*) and occasionally coprophilous fungal spores (*Chaetomium*) and intestinal parasite eggs (*Trichuris* sp.) (Fig. 6).

Phytolith (Fig. 7) and pollen evidence (Fig. 6) from MU26i in Trench 2 shows early colonisers use a mixed grain/leaf fodder diet for ruminant livestock, with a move to grain and grass later on for larger herbivores, which are represented in MU18b; a pattern which is also evident at Karksi. The phytolith

372 assemblage from the trampled lenses of herbivore, caprid pellets at the base of the sequence (MU
373 26i–iii) comprises arboreal (dicotyledon) and grass (monocotyledon) phytoliths, particularly spherical
374 (or globular psilate) forms that occur with broad-leafed foliage and the bark of twigs (Delhon *et al.*
375 2008; Piperno 2006). Monocotyledons can produce up to twenty times more phytoliths than
376 dicotyledons (shrubs/trees), and so dicotyledon phytoliths are under-represented in the phytolith
377 record; therefore, a direct comparison between monocotyledons and dicotyledons does not represent
378 the true ratio of grasses to trees/shrubs (Tsartsidou *et al.* 2007). Consequently, the woody species are
379 very likely to be much more prolific than indicated in the phytolith record, and could indicate the use
380 of leaf fodder in addition to grasses (Delhon *et al.* 2008) during the earlier occupation at the castle,
381 represented in unit 26. Pollen samples from MU20c, 23b, 26i and 26iii contain significantly higher
382 quantities of *Avena-Triticum* (67–80%), with a smaller component of weed, ruderal, grass or another
383 herb pollen. Cellular material from cereal husks is visible on the pollen slides along with clumps of
384 cereal pollen grains.

385

386 The range of phytolith morphologies from wetland species, field grasses and weeds, and cereal grasses
387 within stratigraphic units 16a and 18b, which contained the dung layers, suggest that horses (or
388 possibly cattle) were both put out to pasture in an area close to water, and also fed on grain, as
389 indicated by the presence of multi-cell dendritic forms from cereal husks (Fig. 4f, 4g). Pollen samples
390 within MU16a1, 16a2, 16a4, 18b and 20b (Fig. 6) show a high degree of uniformity in the pollen
391 sequence with large quantities of Poaceae pollen (up to c. 60%) and significant quantities of *Avena-*
392 *Triticum* (up to 27.6%). There are large quantities of pollen of weed taxa strongly associated with
393 arable fields within the dung layers, MU16a4 and 18b, particularly *Centaurea cyanus* (cornflower) (up
394 to 29.2%), along with *Agrostemma githago*, *Scleranthus*-type (knawels) and *Spergula*-type (corn
395 spurrey). Pollen of Ranunculaceae undifferentiated and *Anthemis* type (chamomiles) also occur in
396 large quantities.

397

398 In the samples containing waterlogged plant macroremains, a range of diasporas from different type
399 of plant communities were preserved (Pluskowski *et al.* 2019a). Although they were not numerous,
400 they still provide evidence for the range of habitats within the immediate vicinity of the castle, which
401 included meadows and pastures, which could be used as a place of pasturage; wild grass seeds were
402 identified in thin section embedded within the *in situ* dung (MU16a4) (Fig. 4h).

403

404 The charred plant macroremains from context 17, the uppermost context, dated to the 2nd quarter
405 of 14th century, are more interesting. The assemblage in it is interpreted as the remnants of fodder,

406 most likely for horses, which was stored in some kind of sack or wooden chest outside the building
407 and subsequently burnt. The sample included a significant quantity of charred oats (*Avena sativa*) with
408 a small admixture of barley (*Hordeum vulgare*) and rye (*Secale cereale*). The grains were not dehusked
409 and appear not to be separated from weeds, which include segetal weeds such as field cockle
410 (*Agrostemma githago*), false cleavers (*Galium spurium*) or sheep's sorrel (*Rumex acetosella*). Currently
411 in Poland oats are still the most popular feed for horses. In medieval Poland oats were viewed as
412 fodder for horses or as a component of a food made for hunting dogs. Historical and archaeobotanical
413 data indicate that oats are present in the human diet, but are not the main element (Dembińska *et*
414 *al.* 1999; Karg, 2007; Lityńska-Zając, Wasylikowa, 2005).

Discussion

416 The results of these analyses (integrated and summarised in supplementary tables 1 and 3) show that
417 at Karksi, livestock were stabled in the area that was to become the High Castle, prior to and during
418 the removal of vegetation probably for its construction as evidenced by a reduction in tree pollen in
419 the pollen record. The clearance of vegetation provided leaf fodder for the animals. Microstratigraphic
420 analysis shows that a spring was dammed to create a small pond to create a watering hole for
421 livestock, and that contained fish possibly used as a food source by occupiers during the construction
422 of the castle. The presence of herbivores is attested by the occurrence of coprophilous fungal spores
423 within the sediment that accumulated at the base of the pond. These microfossils are established
424 indicators of local herbivore activity (van Geel *et al*. 2003), as the spores are released close to the
425 ground and readily incorporated into the sediments. At Elbląg, the microstratigraphy shows that the
426 area of the outer bailey, the earliest outer ward of the *castrum*, regularly flooded leaving behind
427 deposits of alluvial sediment that interspersed deposits of occupation materials. The
428 micromorphology results suggest that flooding episodes that are documented in the sediments below
429 the early *castra* (Nitychoruk *et al.* 2016) continued during the occupation of the outer bailey.

430

431 The coprolite remains from both Karksi and Elbląg show that small ruminants such as sheep and goats
432 were kept in the areas of the early *castra* under construction and later to form important areas such
433 as the High Castle (Karksi) and the outer ward (Elbląg). In Teutonic Order castles, the High Castle
434 housed the Order's functional and communal rooms, and one or more Outer Baileys (or outer wards),
435 which were usually delineated by defensive walls and moats, contained a number of service buildings
436 and stables, and in the larger castles chapels and administrative spaces (Pluskowski *et al* 2019b). The
437 evidence at both sites indicates that ruminants were fed both leaf fodder and grain. Micromorphology
438 has been instrumental in identifying trampled sediment and *in situ* deposits of stabling waste. At

439 Karksi, dung fragments from sheep or goat were trampled in the midden. Coprophilous fungal spores

440 at the top of the midden (MU12b) indicate that livestock were roaming in the area. The

441 zooarchaeological evidence from medieval Livonian assemblages (Maltby *et al.* in press) indicates that

442 the incoming colonists adopted the indigenous livestock husbandry culture, and as a result the

443 absence of any regional diachronic variation is not so surprising. The provisioning of meat to castles

444 and towns was reliant on existing pastoral systems in the countryside, run by indigenous communities,

445 with the only significant change consisting of the reorientation of higher purchasing power

446 communities from strongholds to castles and towns. As attested by documentary sources, raiding was

447 prevalent at this time (Goldschmidt 1979), which may have resulted in the control of resources at the

448 Karksi site by the earliest colonists, with some caprines, as shown by the data presented here, kept in

449 the area that was to become the High Castle. Fish stocks, attested by the presence of fish scales, were

450 potentially retained on site by the creation of a small pond, despite there being a river in the valley

451 bottom.

452

453 The occupation material in the earliest outer ward of the *castrum* at Elbląg is characterised by

454 trampled sediment containing coprolites from small ruminants such as sheep or goats. The next phase

455 of occupation is also characterised by the presence of livestock, but of larger herbivores such as cattle

456 or horses, which is attested by depositions of *in situ* dung layers (MU16a4 and 18b) containing

457 intestinal parasite eggs and the highest concentrations of coprophilous fungal spores within the

458 profile. This could reflect a general trend evident in the zooarchaeological data from Prussia

459 (Makowiecki *et al.* in press), which shows a general change over the course of the medieval period in

460 animal husbandry practices with the arrival of the Teutonic Order to larger herbivores such as cattle

461 kept in preference to pigs. However, these *in situ* dung (stabling) layers (MU16a4 and 18b) could also

462 have been deposited by horses as horseshoes were recovered from mid-13[th]century contexts during

463 the excavation of the outer ward at Elbląg (Fonferek in press), and documentary sources indicate that

464 stud horses were more often stabled in the outer baileys of castles to ensure their safety (Ekdahl

465 1998). There are similarities between the formation of the *in situ* stabling layers (MU16a4 and 18b) at

466 Elbląg and a 13th century horse stable within a Moravian medieval bailey, Veselí nad Moravou, Czech

467 Republic (Dejmal *et al*. 2014), as in both cases the location of the stable is close to water as evident by

468 flooding depositing alluvium.

469

470 The uppermost context, 17 in the outer ward at Elbląg, dated to the second quarter of 14th century

471 included a significant quantity of charred oats with a small admixture of barley and rye, and is

472 interpreted as the remnants of fodder, most likely for horses, which adds further support that stud or

473 warhorses were stabled in this area. Warhorses were stabled in the outer bailey of Cesis castle,
474 Livonia, during the later phase of the Teutonic Order's rule, *c.* AD 1480-1503 (Pluskowski *et al.*
475 submitted). Stable isotope analysis (O and H) of bone collagen and trace element analysis (Ba and Mg)
476 of bone phosphate show that the horses consumed local water and consumed high Mg, Ba food,
477 possibly grain and fed differently to other horses (Pluskowski *et al.* submitted). At Veselí nad Moravou,
478 Czech Republic, horses were fed meadow grasses as well as woody vegetation, millet, oat, and less
479 commonly hemp, wheat and rye (Dejmal *et al*. 2014), which is similar to the mixed grain and pasture
480 evidence, probably hay from MU16a4 and 18b at Elbląg.

481

482 The multi-proxy analysis of earliest deposits at Elbląg shows that, in relation to the foddering regimes
483 of smaller ruminants (caprines), they consumed a mixed diet comprising leaf fodder and grain, possibly
484 at a time before more extensive cultivation which could provide sufficient grain for livestock. It is
485 possible that grain fodder is being supplemented with leaf fodder as a result of grain shortage and,
486 perhaps additionally, that this is a seasonal pattern and represents winter livestock alimentation with
487 ruminant enclosed in the outer bailey during the winter months. Isotopic data of sheep/goat remains
488 from the Kulmerland (Prussia) shows that $\delta^{15}N$ increased in value from the early to late medieval
489 period due to manuring during agricultural intensification (Müldner *et al.* in press).

490

491 At Karksi, micromorphological analysis of the earliest deposits that begin the infilling of the small pond
492 suggests the use of leaf fodder, with pollen evidence suggesting the dumping of cereal processing
493 waste, including rye, along with the leaf fodder. In later midden deposits, millet was consumed by
494 sheep/goats, which raises the question was millet cultivated or imported (animal) feed?
495 Archaeobotanical studies and research on the history of farming have concluded that until 16th century
496 it was only imported to the Baltic (Dąbrowsk 1962; Latałowa *et al*. 2007. In Livonia, during the
497 Hanseatic period, millet was the staple of secondary important, as well as lentils or buckwheat. Millet
498 was consumed by the urban middle classes and was presumably imported from the southern Baltics
499 region (Sillaso and Hiie 2007). Pollen evidence from the commandery (the area controlled by the
500 castle) of the *Vogt* (or Advocate) of Karkus shows oat or wheat from the mid-thirteenth century, rye
501 from the early fourteenth century, and buckwheat during the fifteenth century in the hinterland
502 around Karksi castle (Brown in press). Cereal pollen (from the pond sediment at Karksi, which includes
503 rye, possibly represents small scale production in a largely wooded environment. Charred barley and
504 wheat cereal grains were recovered from the later midden dating to the mid-13th century.

505

506

Conclusions

The results represent an important study of deposits from medieval castles, particularly from the period of active Crusading that are rarely revealed through excavation and in the past have rarely been subjected to an integrated environmental investigation. The integrated results have allowed the potential of these proxies to be powerfully exploited to show new perspectives on the function and development of these castle complexes and their relationships with castle hinterland. In particular, the integration of micromorphology and on-site NPPs has been instrumental in identifying stabling deposits. Where plant macroremains were too fragmentary to survive recovery for analysis, they survived in micromorphology thin-section, such as the remains of millet embedded within the herbivore coprolite at Karksi, and micromorphology provided a micro-contextual approach to understanding the depositional pathways of plant macrofossils and microfossils. The research has produced further information concerning the diachronicity of the range of livestock that the colonising Teutonic Knights kept, whereabouts within the castles they were stabled, and livestock alimentation. While no similar integrated geoarchaeological studies have been undertaken on other Teutonic Order castles in the eastern Baltic, pollen evidence from across Livonia suggests that agricultural intensification was most apparent around the key urban centres and castles where their establishment involved new concentration of people and animals (e.g. Stivrins *et al*. 2016; Banerjea *et al.,* 2017; Brown *et al.,* 2017). By comparison, rural areas show a measure of continuity in land-use from the preceding late Iron Age, with little evidence for intensification until the 14th century; castles and urban centres therefore play an important role in understanding changing patterns of food procurement and land-use associated with the early years of the Crusades.

References

Akeret, O., Jacomet, S. (1997) Analysis of plant macrofossils in goat/sheep faeces from the Neolithic lake shore settlement of Horgen Scheller - an indication of prehistoric transhumance? *Veget Hist Archaeobot* 6 pp. 235-239

Akeret, O., Rentzel, P. (2001) Micromorphology and Plant Macrofossil Analysis of Cattle Dung from the Neolithic Lake Shore Settlement of Arbon Bleiche 3. *Geoarchaeology: An International Journal,* 16, 6, pp. 687–700

Akeret, O., Haas, J. N., Leuzinger, U., Jacomet, S. (1999) Plant macrofossils and pollen in goat/sheep faeces from the Neolithic lake-shore settlement Arbon Bleiche 3, Switzerland. *The Holocene* 9,2 pp. 175–182

Andersen, S.T., 1978. *Identification of wild grasses and cereal pollen*. Dan. Geol. Unders.

Arbog. 1978, 69–92.Cushing, E.J., (1967). Evidence for differential pollen preservation in late quaternary sediments in Minnesota. *Review of Palaeobotany and Palynology*. 4, 87–101.

Baker, A.G., Bhagwat S.A., Willis K.J. (2013). Do dung fungal spores make a good proxy for past distribution of large herbivores? *Quaternary Science Reviews* 62, 21-31.

Baker, A.G., Cornelissen, P., Bhagwat, S.A., Vera, F.W.M., Willis, K.J. (2016). Quantification of population sizes of large herbivores and their long-term functional role in ecosystems using dung fungal spores. *Methods in Ecology and Evolution*. doi:10.1111/2041-210X.12580

Banerjea, R.Y. (2019). Settlement life in Prussia at the microscopic scale and the impact on the hinterlands. In A. Pluskowski (ed). *The environment, colonisation and the crusader states in medieval Prussia and Livonia: Terra Sacra 1.* Turnhout: Brepols. ISBN: 978-2503-55123-6 (In press)

Banerjea, R.Y., Badura, M. (2019). Settlement life in Livonia and the impact on the hinterlands: the geoarchaeological and archaeobotanical evidence. In A. Pluskowski (ed) *The environment, colonisation and the crusader states in medieval Prussia and Livonia: Terra Sacra 1*. Turnhout: Brepols. ISBN: 978-2503-55123-6 (In press)

Banerjea, R.Y., Badura, M., Kalējs, Cerina, A., Gos, K., Hamilton-Dyer, S., Maltby, M., Seetah, K., Pluskowski, A. (2017) A multi-proxy, diachronic and spatial perspective on the urban activities within an indigenous community in medieval Riga, Latvia. *Quaternary International* 460, 3-21

Banerjea, R. Y., Bell, M. G., Matthews, W. and Brown, A. D. (2015) Applications of micromorphology to understanding activity areas and site formation processes in experimental hut floors. *Archaeological and Anthropological Sciences*, 7 (1). pp. 89-112. ISSN 1866-9565 doi: https://doi.org/10.1007/s12520-013-0160-5

Bartlett, R. (1994). *The making of Europe: conquest, colonization and cultural change 950-1350*. Penguin books, London.

Berend, N. (2005). 'Frontiers', in ed. H. J. Nicholson, Palgrave *Advances in the Crusades*. Basingstoke: Palgrave Macmillan, 148-171.

Blomkvist, N. (2009). '12th–14th century European Expansion and its Reception in the Baltic North', in ed. J. Staecker, *The Reception of Medieval Europe in the Baltic Sea Region*, Visby: Gotland University Press, 431–84.

Blaauw, M. and Christen, A. (2011). Flexible palaeoclimate age-depth models using an auto-regressive gamma process. *Bayesian Analysis*, 6, 457–474.

Boyd, C. E. (1995). *Bottom Soils, Sediment, and Pond Aquaculture.* USA: Chapman & Hall

Brönnimann, D., Ismail-Meyer, K., Rentzel, P., Égüez, N. (2017). Excrements of Herbivores. In C. Nicosia, G. Stoops (eds) *Archaeological Soil and Sediment Micromorphology*. Chichester, John Wiley & Sons, pp. 55-66

574   Brown, A. D. Vegetation Changes in Livonia: The Palynological Data. (2019). A. Pluskowski (ed) *The*

575   *environment, colonisation and the crusader states in medieval Prussia and Livonia: Terra Sacra 1*.

576   Turnhout: Brepols. ISBN: 978-2503-55123-6 (In press)

577   Brown, A., Badura, M., King., G., Gos, K., Cerina, A., Kalnina, L., Pluskowski, A. (2017) Plant macrofossil,

578   pollen and invertebrate analysis of a mid-14th century cesspit from medieval Riga, Latvia (the eastern

579   Baltic): Taphonomy and indicators of human diet. *Journal of Archaeological Science: Reports* 11, 674-

580   682

581   Brundage, J. A., (trans. 2003). The Chronicle of Henry of Livonia / Henricus Lettus, New York: Columbia

582   university Press

583   Bullock, P, Fedoroff, N., Jongerius, A., Stoops, G. and Tursina, T. (1985) *Handbook for thin section*

584   *description.* Wolverhampton: Waine Reasearch.

585   Charman, D.J., Hendon, D., Woodland, W.A. (2000). *The Identification of Testate Amoeboe (Protozoa:*

586   *Rhizopoda) in Peats*. QRA Technical Guide No. 9, Quaternary Research Association: London.

587   Dąbrowski H. 1962. Rozwój gospodarki rolnej w Polsce od 12 do połowy 14 wieku. *Studia z Dziejów*

588   *Gospodarstwa Wiejskiego*, 5(1).

589   Dejmal, M., Lisà, L., Fišàkovà, M Nývltovà, Bajer, A., Petr, L., Kočàr, P., Kočàrova, R., Nejman, L.,

590   Rybníček, M., Sůvova, Z., Culp, R., Vavrčík, H. (2014) Medieval Horse Stable; The Results of Multi Proxy

591   Inter disciplinary Research. *Plos one* 9 (3)

592   Delhon, C., Martin, L., Argant, J., Thiébault, S. (2008) Shepherds and plants in the Alps: multi-proxy

593   archaeobotanical analysis of neolithic dung from ''La Grande Rivoire'' (Isére, France). *Journal of*

594   *Archaeological Science,* 35, pp. 2937–2952

595   Dembińska M., Weaver W. W. (1999). Food and drink in medieval Poland: rediscovering a cuisine of

596   the past. University of Pennsylvania Press, Philadelphia.

597   Ekdahl, S. (1998). 'Horses and crossbows: Two important warfare advantages of the Teutonic Order in

598   Prussia', in H Nicholson (ed.), *The Military Orders 2: Welfare and Warfare*, Aldershot: Ashgate, 119–

599   51.

600   Favre, P, Jacomet, S. (1998) Branch wood from the lake shore settlements of Horgen Scheller,

601   Switzerland: Evidence for economic specialization in the late Neolithic period. *Veget Hist Archaeobot*

602   7, pp.167-178

603   FitzPatrick, E.A (1993) *Soil microscopy and micromorphology*. Chichester : Wiley

604   Finsinger, W., Tinner, W. (2005). Minimum count sums for charcoal concentration estimates in pollen

605   slides: accuracy and potential errors. *The Holocene* 15 (2), 293- 297.

606   Fonferek, J. (2019). The environmental setting of the earliest Teutonic Order stronghold in Elbląg, in

607   *Ecologies of Crusading, Colonization, and Religious Conversion in the Medieval Baltic*, ed. A. G.

608   Pluskowski, Turnhout: Brepols (in press)

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

610   Collection Center.

611   Goldschmidt, W. (1979). 'A general model for pastoral social systems' in *Pastoral Production and*

612   *Society*, ed. L'Equipe écologie et anthropologie des sociétés pastorals, Cambridge: Cambridge

613   University Press, 15–27.

614   Ismail-Meyer, K., Rentzel, P., & Wiemann, P. (2013). Neolithic lake-shore settlements in Switzerland:

615   new insights on site formation processes from micromorphology. *Geoarchaeology*, 28, 317–339.

616   Ismail-Meyer, K., Stolt, M.H. & Lindbo, D.L. (2018) Soil organic matter. In: Stoops, G., Marcelino, V.,

617   Mees, F. (eds.) Interpretation of micromorphological features of soils and regoliths. Elsevier,

618   Amsterdam, pp 471-512.

619   Jóźwiak, S. and Trupinda, J. (2012)*. Krzyżackie zamki komturskie w Prusach*, Toruń: Wydawnictwo

620   Naukowe Uniwersytetu Mikołaja Kopernika.

621   Kattenberg, A.E., Aalbersberg, G. (2004) Archaeological prospection of the Dutch perimarine

622   landscape by means of magnetic methods. *Archaeol. Prospect*. 11, pp. 227–235

623   Karg, S. (ed.) (2007). Medieval food traditions in northern Europe. National Museum, Copenhagen,

624   PNM Studies in Archaeology and History 12.

625   Kukk T., Kull K. (1997). Wooded Meadows [Puisniidud]. - *Estonia Maritima* 2: 1-249.

626   http://www.zbi.ee/~kalevi/wooded.htm

627   Krug, J.C., Benny, G.L., Keller, H.W. (2004). Coprophilous fungi. In: Foster, M., Bill, G. (eds.), *Biodiversity*

628   *of Fungi. Inventory and Monitoring Methods*, 467-499. Elsevier Science: Amsterdam.

629   Latałowa M., Badura M., Jarosińska J., Święta-Musznicka J. (2007). Useful plants in medieval and post-

630   medieval archaeobotanical material from the Hanseatic towns of Northern Poland (Kołobrzeg, Gdańsk

631   and Elbląg). *National Museum (PNM), Studies in Archaeology&History*. Vol. 12, Copenhagen, p.: 39-

632   72.

633   Lityńska-Zając M., Wasylikowa K. (2007). Przewodnik do badań archeobotanicznych. Wyd. Sorus,

634   Poznań.

635   Makowiecki, D., Zabilska-Kunek, M., Seetah, K., Jarzebowski, M., Pluskowski, A. (2019) Farming,

636   Hunting and Fishing in Medieval Prussia: The Zooarchaeological Data. In A. Pluskowski (ed). *The*

637   *environment, colonisation and the crusader states in medieval Prussia and Livonia: Terra Sacra 1.*

638   Turnhout: Brepols. ISBN: 978-2503-55123-6 (In press)

639   Mackenzie, W.S. and Adams, A.E. (1994) *A Colour Atlas of Rocks and Minerals in Thin Section.* New
640   York: John Wiley and Sons.

641   Mackenzie, W.S. and Guilford, C. (1980) *Atlas of Rock Forming Minerals.* Harlow: Longman Group Ltd.

642   Maldre L (2003) Karjakasvatus Eestis. *Eesti aastal 1200*, ed Mägi M (Kirjastus Argo, Tallinn) pp. 163-
643   172.

644   Maltby, M., Pluskowski, A., Rannamäe, E., Seetah, K. Farming, Hunting and Fishing in Medieval Livonia:
645   The Zooarchaeological Data. (2019). In A. Pluskowski (ed). *The environment, colonisation and the*
646   *crusader states in medieval Prussia and Livonia: Terra Sacra 1.* Turnhout: Brepols. ISBN: 978-2503-
647   55123-6 (In press)

648   Matuszkiewicz W. (2008). Przewodnik do oznaczania zbiorowisk roślinnych Polski. Wydawnictwo
649   Naukowe PWN, Warszawa.

650   Mazier, F., Galop, D., Gaillard, M.J., Rendu, C., Cugny, C., Legaz, A., Peyron, O., Buttler, A. (2009).
651   Multidisciplinary approach to reconstructing local pastoral activities: an example from the Pyrenean
652   Mountains (Pays Basque). *The Holocene* 19(2)*, 171-188.

653   Mees, F. and Stoops, G., (2018) Sulphidic and Sulphuric Materials. In: Stoops, G., Marcelino, V., Mees,
654   F. (eds.) *Interpretation of micromorphological features of soils and regoliths.* Elsevier, Amsterdam, pp
655   347-376.

656   Mirek Z, Piękoś-Mirkowa H, Zając M (2002) Flowering plants and Pteridophytes of Poland: a checklist.
657   Szafer Institute of Botany, Polish Academy of Science, Kraków.

658   Moore, P.D., Webb, J.A., Collinson, M.E., (1991). *Pollen Analysis*. Blackwell, Oxford

659   Morandi, L. F. (2018). Non-pollen palynomorphs as an aid to the identification of ancient farming
660   activities: an experimental and archaeological approach. Unpublished PhD dissertation, University of
661   Reading

662   Müldner, M. Scull, C. and Makowiecki, D. (2018). 'Carbon and Nitrogen stable isotope evidence for
663   animal husbandry and environmental change in the medieval Kulmerland', in *Ecologies of Crusading,*
664   *Colonization, and Religious Conversion in the Medieval Baltic*, ed. A. G. Pluskowski, Turnhout: Brepols
665   (In press)

666   Murray, A. V. ed. (2001). *Crusade and Conversion on the Medieval Baltic Frontier*, Aldershot: Ashgate.

667   Nitychoruk, J., Szymanek, M., Bińka, K., Kasprzycka, M. and Zbucki, Ł. (2016). 'Changes of
668   Sedimentation in the Drużno Lake based on Geoarchaeological Data from the Teutonic Fortress in
669   Elbląg, North Poland', *Acta Geologica Polonica* 66/1, 85 –98.

670   Jenkins, E.L. and Rosen, A.M., (2007). The Phytoliths. In: Finlayson, B. and Mithen, S., eds. *The Early*
671   *Prehistory of Wadi Faynan, Southern Jordan: Archaeological survey of Wadis Faynan, Ghuwayr and al-*

672   *Bustan and Evaluation of the Pre-Pottery Neolithic A Settlement of WF16*. Oxford, England: Oxbow

673   Books, 429-436.

674   Piperno, D. R. (2006). *Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists.*

675   AltaMira Press

676   Pluskowski, A. G. (2012). *The Archaeology of the Prussian Crusade: Holy War and Colonisation.*

677   Abingdon, Routledge

678   Pluskowski, A. G. (2019). *The environment, colonisation and the crusader states in medieval Prussia*

679   *and Livonia: Terra Sacra 1.* Turnhout: Brepols. ISBN: 978-2503-55123-6 (In press)

680   Pluskowski, A.G., Badura, M, Jarzebowski, M. (2019a). Exploiting Plants: Macrobotanical Remains from

681   Prussia. In A. Pluskowski (ed) *The environment, colonisation and the crusader states in medieval*

682   *Prussia and Livonia: Terra Sacra 1*. Turnhout: Brepols. ISBN: 978-2503-55123-6 (In press)

683   Pluskowski, A.G., Brown, A.D., Banerjea, R., Makowiecki, D., Seetah, K., Rannamäe, E., Jarzebowski,

684   M., Kreen, J., Klavins, K. (2019b). From the convent to the commandery: the pivotal role of the

685   environment in defining the medieval Baltic Ordensland. Submitted to Quellen und Studien zur

686   Geschichte des Deutschen Orden (in press)

687   Pluskowski, A., Seetah, K., Maltby, M, Banerjea, R., Black, S., Kalniņš, G., (2018). Late Medieval Horse

688   Remains at Cēsis Castle (Latvia) and the Teutonic Order's Equestrian Resources in Livonia. *Medieval*

689   *Archaeology* 62:2, 351-379

690   Pümpin, C., Le Bailly, M., Pichler, S. (2017). Ova of Intestinal Parasites. In C. Nicosia, G. Stoops (eds)

691   *Archaeological Soil and Sediment Micromorphology*. Chichester, John Wiley & Sons, pp. 91-98

692   Rannamäe, E. and Lõugas, L. (2019). Animal exploitation in Karksi and Viljandi (Estonia), in the Late

693   Iron Age and Medieval Period, in In A. Pluskowski (ed) *The environment, colonisation and the crusader*

694   *states in medieval Prussia and Livonia: Terra Sacra 2*. Turnhout: Brepols (in press)

695   Rasmussen, P. (1993) Analysis of sheep/goat faeces from Egolzwil 3, Switzerland: evidence for branch

696   and twig foddering of livestock in the Neolithic. *Journal of Archaeological Science* 20, pp. 479-502

697   Reinhard, K. J., Confalonieri, U. E., Hermann, B., Ferreira, L. F. & De Aranjo, A. D. G. (1986). Recovery

698   of parasite remains from coprolites and latrines: aspects of paleoparasitological techniques. *Homo* 37,

699   217-239.

700   Scholz, k. and wojtecki, D., (trans. 1984). Chronik des Preussenlandes / Peter von Dusburg, Darmstadt:

701   wissenschaftliche Buch gesellschaft

702   Sillaso, Hiie (2007) – An archaeobotanical approach to investigating food of the Hanseatic period in

703   Estonia. *National Museum (PNM), Studies in Archaeology&History*. Vol. 12, Copenhagen, pp. 73-96.

704   Stoops, G. (2003) *Guidelines for Analysis and Description of Soil Thin Sections.* Madison: Soil Science

705   Society of America.

706 Tsartsidou, G., Lev-Yadun, S., Albert, R-M., Miller-Rosen, A., Efstratiou, N & Weiner, S. (2007) The
707 phytolith archaeological record: strengths and weaknesses evaluated on a quantitative modern
708 reference collection from Greece. *Journal of Archaeological Science* 34, 1262-1275.

709 Valk, H., Rannamäe, E., Brown, A.D., Pluskowski, A.G., Badura, M., Lõugas, L. (2012). Thirteenth
710 century cultural deposits at the castle of the Teutonic Order in Karksi. *Archaeological Fieldwork in*
711 *Estonia,* 73-92

712 van Geel, B. (2001). Non-pollen palynomorphs. In: Smol, J.P., Birks, H.J.B., Last, W.M. (eds.), *Tracking*
713 *Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal and Siliceous indicators*, 99-
714 119. New York.

715 van Geel, B., Buurman, J., Brinkkemper, O., Schelvis, J., Aptroot, A., van Reenen, G.B.A., Hakbijl, T.
716 (2003). Environmental reconstruction of a Roman Period settlement site in Uitgeest (The
717 Netherlands), with special reference to coprophilous fungi. *Journal of Archaeological Science 30(7),*
718 873–883.

719 Villagran, X. S., Huisman, D. J., Mentzer, S. M., Miller, C. E., Jans, M. M. (2017). Bone and other skeletal
720 tissues, In C. Nicosia, G. Stoops (eds) *Archaeological Soil and Sediment Micromorphology*. Chichester,
721 John Wiley & Sons, pp. 11-38

722 Wood, J.R., Wilmshurst, J. M. (2013). Accumulation rates or percentages? How to quantify
723 *Sporormiella* and other coprophilous fungal spores to detect late Quaternary megafaunal extinction
724 events. *Quaternary Science Reviews*,*77*, 1-3.

725 Yeloff, D., Charman, D., van Geel, B., Mauquoy, D. (2007). Reconstruction of hydrology, vegetation and
726 past climate change in bogs using fungal microfossils. *Review of Palaeobotany and Palynology*, *146*(1),
727 102-145.

728

729 Figure captions
730 **Figure 1.** Map showing the location of Karksi, in present day Estonia, and Elbląg, in present day Poland.
731 **Figure 2**. a) Plan of Karksi castle with the locations of excavation Trenches 1, 2 and 3- sample in this
732 research come from Trench 1; b) Photograph of the profile from Trench 1; c) Section drawing from
733 Trench 1, showing the location of monolith samples 241 and 242, and the red box highlights the area
734 of interest at the base of the sloping edge; d) scans of micromorphology slides prepared from
735 monolith 241, and the related microstratigraphic units (10a= levelling surface, 12a= leaf litter,
736 12b=trampled discard deposits, 13a=compacted accumulation of leaf fodder, 13b=trampled leaf
737 fodder, 13c=aqueous accumulation, 14a=accumulation, 14b=redeposited sediment).
738 **Figure 3** a) photograph of trench 2, from excavations in 2013 at the Archaeology and History Museum,
739 Elbląg- the red line shows the profile that was selected for sampling in photograph b; b) the profile in

740 Trench 2, Elbląg that was selected for environmental sampling; c) location of monoliths 1 (blue), 2

741 (green), 3 (yellow) and 4 (orange), and the white box shows the area in photograph d where samples

742 were collected for analysis of phytoliths and plant macroremains; d) the major stratigraphic units that

743 were identified during excavation and locations of the samples that were collected for analysis of the

744 plant macroremains; e) scans of micromorphology slides prepared from scans of micromorphology

745 slides prepared from monoliths 1-4, and the related microstratigraphic units (16a1=Discard/

746 abandonment debris, 16a2=Decayed leaf litter, 16a3= Alluvium, 16a4= *In situ* stabling crust, 18b= *In*

747 *situ* oxidised dung, 20b= Constructional/ levelling wood, 20c= Decayed constructional/ levelling wood,

748 23a= Alluvium, 23b= Reworked occupation surface, 25=Alluvium, 26i= Mixed: trampled dung and

749 alluvium, 26ii= Mixed: trampled dung and alluvium, 26iii= Mixed: trampled dung and alluvium).

750 **Figure 4.** Micromorphology photomicrographs from Karksi: a) Cross-section of a birch leaf, MU12a, b)

751 Fish scales, MU13a, c) Millet fragments embedded within a caprine coprolite, MU12b; and Elbląg: d)

752 stabling crust, MU16a4, e) Intestinal parasite ova, *Ascaris* sp., MU16a4, f and g) dendritic multi-cell

753 phytolith formations within dung, MU18b, h) cross-section of a wild grass seed, MU16a4.

754 **Figure 5.** Karksi: summary pollen and NPPs diagram showing the abundance of key pollen types, dung

755 spores and aquatic microfossils (values expressed as microfossil no./cm^3). Dots mark presence where

756 abundance was low.

757 **Figure 6.** Elbląg: summary pollen and NPPs diagram showing the abundance of key pollen types dung

758 spores, aquatic microfossils and eggs of intestinal parasites (values expressed as microfossil no./cm^3).

759 Dots mark presence where abundance was low.

760 **Figure 7.** Elbląg: diagram showing abundance monocotyledon and dicotyledon phytolith

761 forms.

762

763 Supplementary tables

764 **Sup 1.** Integrated plant macroremains, palynology and micromorphology datasets from Karksi,

765 Estonia.

766 **Sup. 2.** Micromorphology sediment descriptions, Karksi, Estonia

767 **Sup 3.** Integrated plant macroremains, palynology and micromorphology datasets from Elbląg, Poland.

768 **Sup. 4**. Micromorphology sediment descriptions, Elbląg, Poland.

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