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# Use-wear evidence for the use of threshing sledges in Neolithic Greece

N. Mazzucco [a,*], J.J. Ibáñez [b], P. Anderson [c], K. Kotsakis [d], A. Kita [d], F. Adaktylou [e], J.F. Gibaja [f]

[a] *Department of Civilizations and Forms of Knowledge, University of Pisa, Via dei Mille 19, 56126 Pisa, Italy*
[b] *Archaeology of Social Dynamics, Institución Milà y Fontanals de investigación en humanidades, CSIC, C/ Egipcíaques, 15, 08001 Barcelona, Spain*
[c] *University of Nice Sophia Antipolis, CNRS, CEPAM, UMR 7264, 06300 Nice, France*
[d] *School of History and Archaeology, Aristotle University Thessaloniki, Thessaloniki, Greece*
[e] *Ministry of Culture, Ephorate of Antiquities of Chalkidiki and Mount Athos, Konstantinoupoleos 5, 631 00 Polygyros, Chalkidiki, Greece*
[f] *Investigación y Divulgación en Arqueología, Institución Milà y Fontanals de investigación en humanidades, IMF-CSIC, C/ Egipcíaques, 15, 08001 Barcelona, Spain*

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ABSTRACT

Threshing sledge or *tribulum* represents an important innovation in agricultural techniques. It allows processing huge amounts of cereals and it has often associated to an increased agricultural production. Their use is attested during the Late Neolithic/Chalcolithic and Early Bronze Age both in south-western Asia and Europe. In the Mediterranean area, their use lasted until few decades ago. Recently, as part of project focused on the analysis of the early agricultural tools of Neolithic Greece, a few elements bearing macro- and microscopic use-wear traces visually similar to ethnographic and archaeological threshing sledges have been identified from a number of Early and Middle Neolithic sites (i.e., Achilleion, Platia Magoula Zarkou, Revenia Korinos, Paliambela Kolindros). In this paper, we present the result of their study, including technological and traceological analysis. To provide a stronger assessment of the nature of the observed use-wear traces a quantitative comparison with ethnographic and experimental use-wear traces is carried out by integrating confocal microscopy. Despite the low number of recorded artefacts, obtained results suggest that threshing sledges were in use since the early phases of the Neolithic in Greece.

## 1. Introduction

Mechanical innovations played a fundamental role in agricultural development since prehistoric periods. Chariots, ploughs, and sledges were some of the first machines that, exploiting animal traction, fulfilled agricultural tasks such as ploughing fields, threshing and transporting cereals (Sigaut, 1989). These inventions persisted for millennia, since their first appearance in Pre- and Protohistory, until very recent days. Their initial introduction has been often associated with an increased agricultural productivity and to the emerging of new social and political conditions, such as increasing household inequalities, power centralization and rise of elites (Greenfield, 2010; Price et al., 2021). However, during recent years, several research have suggested that the exploitation of secondary products, such as milking and animal traction, begun earlier than previously thought. The so-called Secondary Products Revolution (Sherratt, 1983) cannot be associated with a single event or millennium, but evidence of changes in animal management and exploitation strategies are given at different times and in different places (Marciniak, 2011).

Dairy products are increasingly detected in ceramic vessels from Mediterranean and European Neolithic, since the earliest Neolithic occupations, despite with varying regional and local importance. Exploitation of dairy products is dated back to the seven-millennium cal BCE in the eastern Mediterranean and in the Balkans and towards the sixth millennium cal BCE in the Western Mediterranean (Salque et al., 2012; Debono Spiteri et al., 2016; Stojanovski et al., 2020; Breu et al., 2021; Naumov et al., 2021).

Zooarchaeological evidence, i.e., pathologies of foot bones, for the exploitation of cattle for traction has been also recently demonstrated for Mediterranean Europe. Pathological conditions attributable to traction have been recognized on materials from the Early Neolithic layers at Knossos (Crete), at least since the ENIc-ENII layers dated ca. 5300–4900 cal BCE (Isaakidou, 2006). According to personal communication with P. Halstead and V. Isaakidou, habitation pit 26 from Revenia Korinos contained cattle bones that shows pathologies compatible with traction-induced stress. One of these bones has been radiocarbon dated to ca. 6370–6220 cal BCE (Maniatis and Adaktylou, 2021). Traction pathologies have been also documented at various sites in the Western Balkans

* Corresponding author.
*E-mail address:* niccolo.mazzucco@unipi.it (N. Mazzucco).

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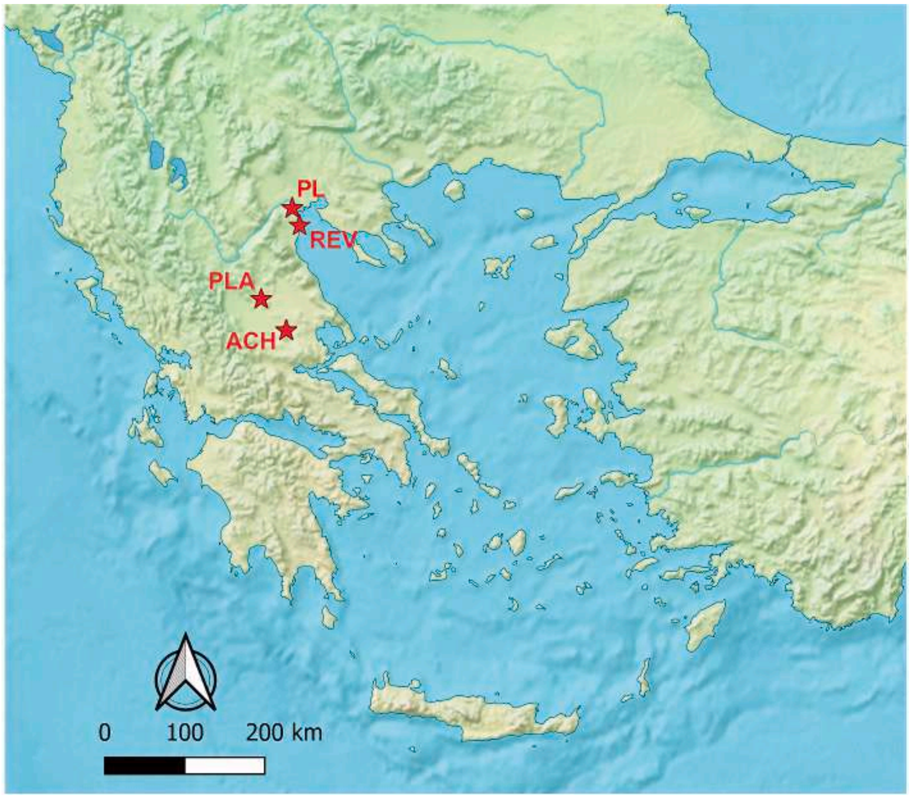


**Fig. 1.** Geographical framework and location of studied sites. ACH: Achilleion; PLA: Platia Magoula Zarkou; PL: Paliambella; REV: Revenia Korinos.

since ca. 6100 cal BCE (Gaastra et al., 2018). At least one specimen was used for traction works at La Draga, in the north-east Iberian Peninsula, dated ca. 5300–4700 cal BCE (Helmer et al., 2018). All this data, suggest that some cattle were used for traction far earlier than previously thought, from the onset of Neolithic in Europe, although most likely for a 'light traction', not such intensively as during the fourth millennium cal BCE (Greenfield, 2010; Galindo-Pellicena et al., 2017).

Concerning the threshing sledges, the study of both experimental and ethnographic *tribula* has shown that we distinguish the stone tools used as inserts for threshing sledges from other flaked tools used for similar tasks like harvesting cereals. This distinction relies on noticing specific wear patterns. These patterns include a kind of shiny surface caused by plants' silica, associated with an intense abrasion of the edge, with fine, parallel scratches all along the used margins (Kardulias & Yerkes, 1996).

The earliest archaeological evidence for the use of threshing sledges comes from Middle/Late Pre-Pottery Neolithic B (PPNB) sites from Syria and Iraq (Tell Magzalia, El Kowm 2, Tell Halula) dated ca. 7800–5700 cal BCE (Anderson, 1992,1994,2003). It is a sample of twenty or so blades, rather thick, showing intense retouching, rounded edges, and residues of adhesive. Nevertheless, many of those tools were first used as harvesting inserts, and later re-used for threshing tasks with a mixing and overlapping of plant- and soil-related polish whose interpretation is not always straight-forward (Gurova, 2014). More reliable and abundant evidence is available for later periods. The use of 'Canaanean' blades as threshing inserts has been proposed for Bronze Age sites from Iraq dated to ca. 3500–2500 cal BCE based on the characteristic use-wear pattern (Anderson & Inizan, 1994; Anderson et al., 2004,2006). This has been further demonstrated by phytoliths analysis (Avner et al., 2003) and by later Sumerian text sources that describe an oxen-drawn threshing instrument (Steinkeller, 1990; Littauer and Crouwel, 1990; Anderson et al., 2004). Evidence of the use of threshing sledge has been provided also for Bulgarian Chalcolithic. N. Skakun (1994) first described tools bearing use-wear traces diagnostic of cereal threshing activities for Chalcolithic sites from Bulgaria. The number of finds has been enlarged thanks to the works of M. Gurova, with a sample of twelve tools recovered from the Bulgarian tell site of Drama-Merdžumekja, dated around 4900 cal BCE (Gurova, 2001,2005,2013,2014).

With this article, we will discuss new evidence concerning the use of threshing sledge from Early to Late Neolithic contexts from Greece. By combining traditional use-wear analysis with quantitative methods (i.e., confocal microscopy and metrological analysis) we will explore the early appearance of threshing sledge and its broader significance within the Neolithic farming systems. The above-mentioned studies have demonstrated that threshing sledges can be discriminated thanks to their characteristic macroscopic and microscopic wear pattern. However, there is a great variability in use-wear traces produced from plant-working and plant-processing activities, and traces derived from working tasks on different contact materials often tends to visually overlap. Quantitative methods, such as confocal microscope and metrological analysis, offer an additional tool to explore such variability, measure and describe it in terms of textural parameters.

## 2. Materials and methods

### 2.1. Archaeological sites

Archaeological materials come from four archaeological sites, two of them located in Thessaly, Achilleion and Platia Magoula Zarkou, and two in Macedonia, Revenia Korinos and Paliambela Kolindros (Fig. 1).

- Achilleion is one of the Thessalian reference archaeological sites. The tell, excavated by M. Gimbutas and collaborators (Gimbutas et al., 1989), is dated to the Early Neolithic/Middle Neolithic transition (6300–5500 cal BCE) (Reingruber and Thissen, 2009).
- Platia Magoula Zarkou is a tell site located in Thessaly, excavated by K. Gallis from 1976 till 1990. The site spans from the earlier phases of the Middle Neolithic to the earlier phases of the Late Neolithic period (ca. 5900–5600 cal BCE) (Alram-Stern et al., 2022).

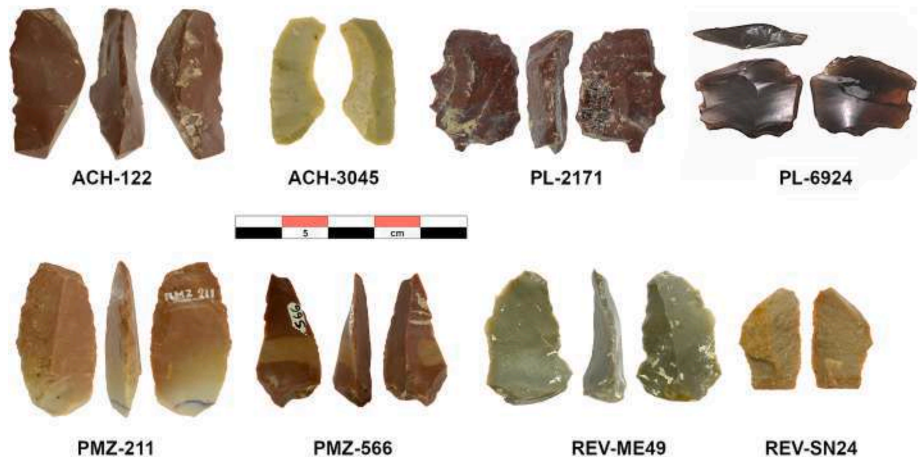


**Fig. 2.** Potential threshing sledges identified based on macroscopic and microscopic wear patterns.


**Fig. 3.** Selection of harvesting inserts used for quantitative analysis through confocal microscopy.

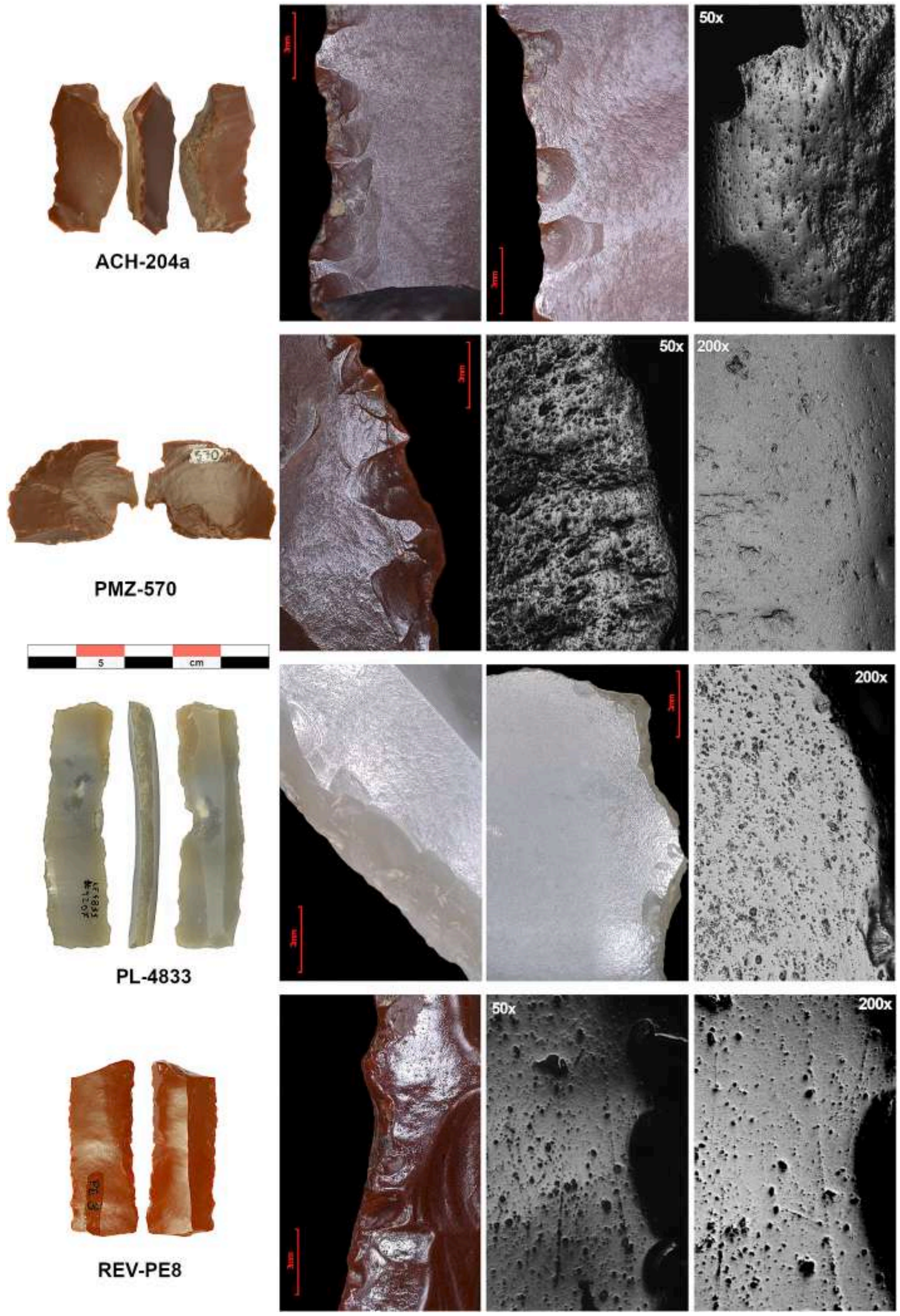


**Fig. 4.** Selection of archaeological harvesting implements from the studied sites, on both flakes and blades. Note the presence of glossy, highly reflective, surfaces. At a microscopic level, smooth and flat polishes, with stria, pits, and comet tails like features are visible.

- Revenia Korinos is an open air, 'flat' site, located in Central Macedonia, North Greece. Dated between 6600/6550 cal BCE and 6200/6100 cal BCE is among the earliest Neolithic settlements of the Aegean (Maniatis and Adaktylou, 2021).
- Paliambela Kolindros is a tell site located in Central Macedonia, North Greece. The site has Initial/Early (6600–6100 cal BCE), Middle (5950–5700 cal BCE), and Late (5300–5000 cal BCE) and Final Neolithic (4450–4350 cal BCE) layers (Mitkidou et al., 2008; Kotsakis, 2014; Maniatis, 2014; Maniatis et al., 2015; Hofmanová et al., 2016).

### 2.2. Archaeological tools

Flaked stone assemblages from each site have been screened completely and all materials observed under stereoscopic observation (Figs. 2-3). The aim of this analysis was to identify all tools potentially used in agricultural activities. Successively, all selected archaeological tools were analysed through stereoscopic and reflected-light microscopy to analyse the macro- and microwear patterns (Figs. 4-6). Edge damage has been documented using a DNT5MP digital microscope, while an Olympus BH2 with magnification between 50X and 400X has been used for the observation of the surface modifications.

#### 2.2.1. Experimental tools

Experimental tools have been selected from both experimental and ethnographic tools to create a reference quantitative framework for the interpretation of the archaeological use-wear traces. A total of 23 tools have been selected: 8 tools used for cutting grasses/reeds; 7 tools used

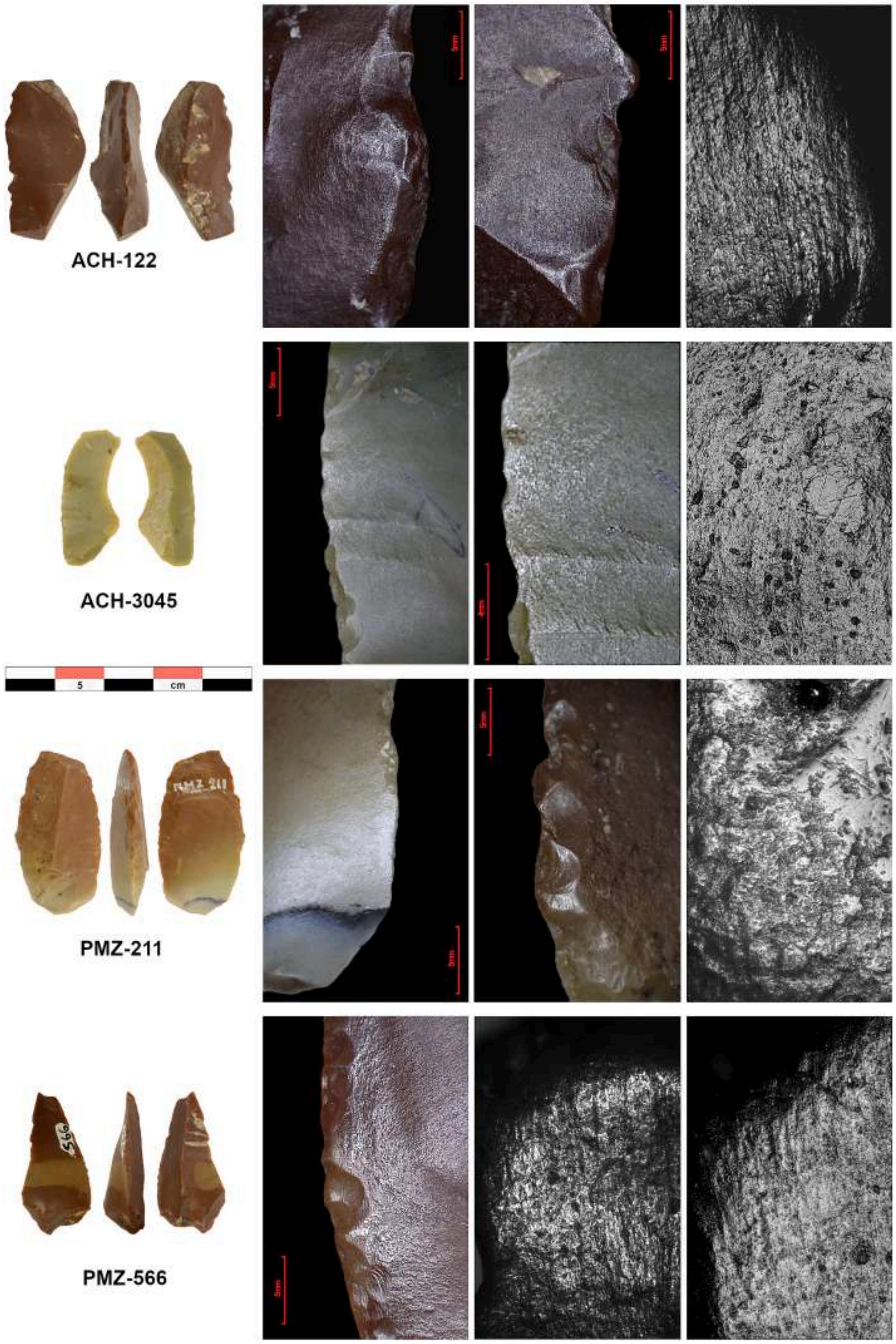


**Fig. 5.** Potential threshing sledges from the analysed sites. Note the presence of heavily rounded edges with matt surfaces. At microscopic level, tools are characterized by heavily abraded surfaces with a mix of plant polish, abrasions, and striations.

for different domesticated cereals (*Hordeum vulgare*, *Triticum monococcum*, *Triticum aestivum*, *Triticum spelta, Triticum turgidum*); 8 tools collected from ethnographic threshing sledges of different provenance (Spain —Asturias, Navarra, Catalonia—, Greece —Continetal Greece, Crete—, Bulgaria, Cyprus, Ukraine) and 2 tools from ethnographic/experimental experiences. More information on the selected experimental tools is available as Supplementary Information (S0).

### 2.2.2. *Confocal and microtexture analysis*

To compare quantitatively the different use-wear traces observed, archaeological and experimental tools were measured under a Sensofar Plu Neox blue light scanning confocal microscope, following a protocol already used by Ibáñez et al. (2019, 2021), Ibáñez and Mazzucco (2021), Mazzucco et al. (2022).

Prior to analysis, all lithic surfaces both archaeological and experimental tools, have been cleaned repeatedly with water, acetone, and alcohol and to remove superficial impurities. For the archaeological tools, silicone impressions of the archaeological materials have been taken directly at the museums using a two-component paste (Provil Novo Light Fast by Heraeus Kulzer GmbH) that is commonly used for this goal in use-wear studies (Banks and Kay, 2003; Mazzucco et al., 2022).

Impressions have been later used to measure polish from a selection both harvesting and potential threshing sledge inserts. Harvesting inserts on both flake and blade implements on a diversity of raw materials have been selected to provide a reference framework and test the

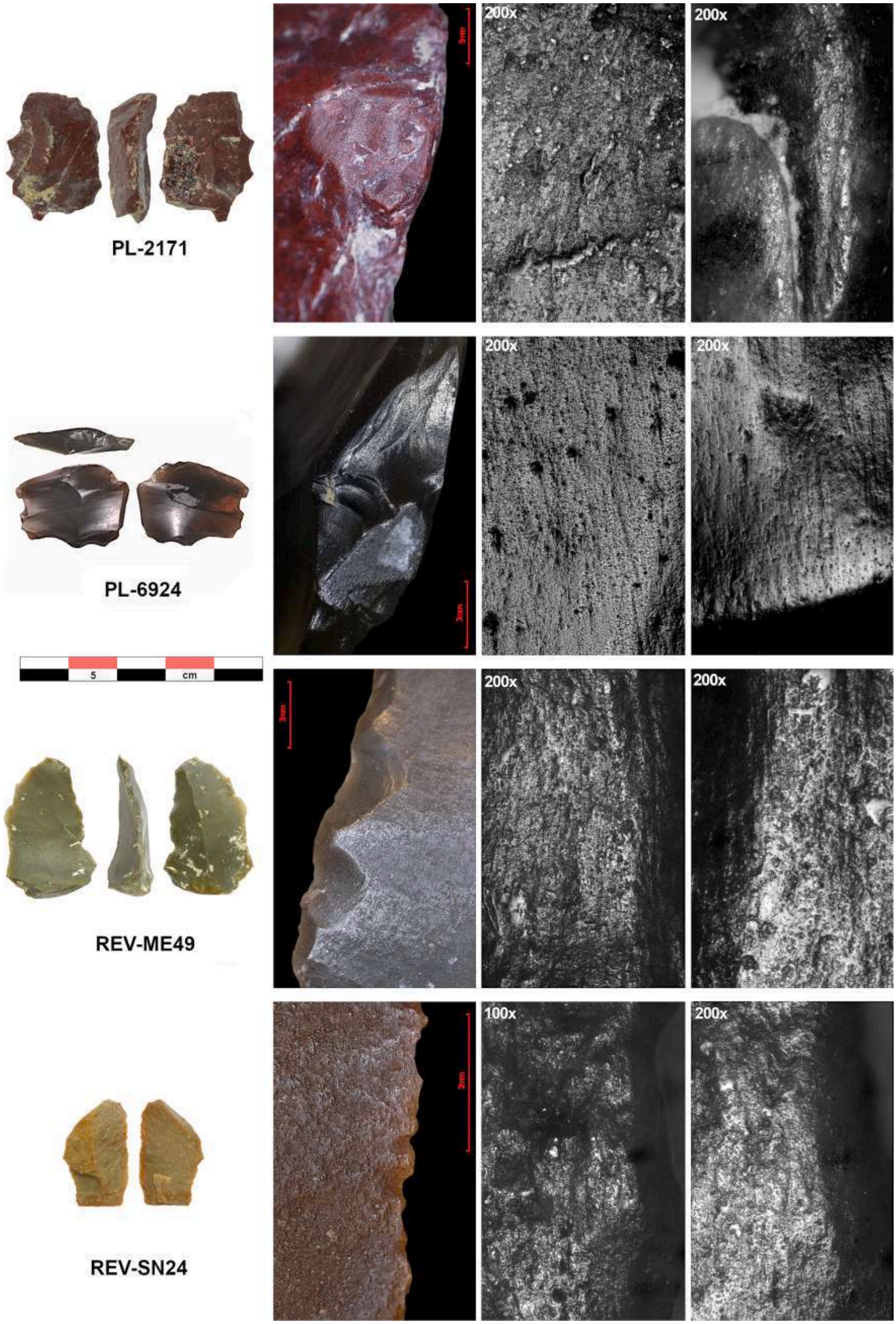


**Fig. 6.** Potential threshing sledges from the analysed sites. Note the presence of heavily rounded edges with matt surfaces. At microscopic level, tools are characterized by heavily abraded surfaces with a mix of plant polish, abrasions, and striations.

**Table 1**
Detailed information of the number of analysed lithics for each site, indicating the No. of glossy blades and of potential threshing sledges.

| Site | Region | Museum/Deposit | Phase/ Phase | Chronology | Analysed sample | No of Glossy blades | No of potential threshing inserts |
|---|---|---|---|---|---|---|---|
| **Paliambella** | Macedonia | University of Thessaloniki | EN | 6600–6100 | 111 | 10 | – |
| | | | MN | 5950–5700 | 45 | 3 | 1 |
| | | | LN/FN | 5300–4350 | 209 | 24 | 1 |
| **Revenia** | Macedonia | Ephorate of Antiquities of Pieria | EN | 6650–6100 | 472 | 81 | 2 |
| **Achilleion** | Thessaly | Diachronic Museum of Larissa | EN | 6280–6070 | 230 | 28 | – |
| | | | MN | 6100–5900 | 412 | 78 | 2 |
| **Platia Magoula Zarkou** | Thessaly | Diachronic Museum of Larissa | MN | 5850–5500 | 271 | 29 | 2 |

validity of the classification procedure. Experimental tools have been measured directly under the confocal microscope at the IMF-CSIC laboratory.

Lithics and impressions were therefore measured with a Sensofar Plu Neox blue light scanning confocal microscope, using a 20 × (0.45NA) objective, with a spatial sampling of 0.83 µm, optical resolution of 0.31 µm, vertical resolution of 20 nm and a z-step interval of 1 µm. Between 5 and 24 areas of 650 × 500 µm were scanned for each lithic insert, depending on the extent of the use-wear polish. Afterwards, subareas of 200 × 200 µm were selected and processed using the SensoMAP Standard v.8 from Digital Surf. Sampled subareas areas were processed using a levelling operator using the least squares (LS) plane method was used to correct the lack of horizontality. Spatial filtering is then applied to isolate the roughness components of the surfaces using a Gaussian filter with a 0.08 mm cut-off. Afterwards, texture parameters have been extracted for each area and data imported into.csv. The Rstudio script TRAC3D (https://github.com/nmazzucco/TRAC3D.git) developed by one of the authors has been used to process data.

## 3. Results

The results of the microscopic observation of the harvesting are detailed in Table 1. 250 harvesting inserts have been recognized and 8 potential threshing sledge inserts (Fig. 2). Despite our sample being numerically limited, threshing sledge inserts share some common features. They are made on thick flakes (N = 7) or laminar flakes (N = 2) with average blank dimensions L: 2.7 × W: 1.5 × Th: 0.62 cm. They have a triangular or quadrangular shape. Vice versa, harvesting inserts are mainly made on regular blades (N = 207) and, in lesser extent, on flakes (N = 43), generally choosing thinner blanks: L: 2.9 × W: 1.4 × Th 0.3 cm (Fig. 3).

From a macroscopic point of view, harvesting and threshing sledge inserts show quite different wear patterns. Harvesting inserts are characterized by a shiny gloss (Fig. 4), while on threshing sledge inserts gloss is less shiny and more matt, with grooves and striations that are often visible at stereoscopic view (Figs. 5-6). In addition, the edges of the threshing sledge inserts tend to be extremely worn out, rounded, almost steep, and poorly adapted for cutting tasks (Figs. 5-6).

To carry out a more detailed comparison of the microwear patterns, a selection of relevant archaeological tools has been made, including a selection of potential threshing sledges (N = 7, one insert —PZM-211— has been excluded because the silicone impression was damaged) and of harvesting tools (N = 19) on both blade and flake blanks. As result, a total of 27 tools on different raw-materials (i.e., radiolarite, different varieties of chert) and blank types (i.e., flakes, laminar flakes, blades) have been selected (Figs. 2-3). Both macroscopic and microscopic features are resumed in Table 2. As can be appreciated by visually comparing the micrographs (Figs. 5-6, 7-8, the complete selection of micrographs can be seen in the Supplementary Materials S15 https://doi.org/10.5281/zenodo.8410024), use-wear traces show a considerable variability, from smooth, flat, and bright surfaces, to rough, domed, abraded/striated, matt surfaces, with intermediate stages between these two extremes. From a visual point of view, flat and bright polish, often with comet-tail striations, are commonly associated with cereal/plant harvesting, domed polish with a varying degree of abrasions with grasses and reeds cutting, while more rough and abraded surfaces with threshing sledge inserts (see also Figs. 5-6).

In order to quantitively explore polish variability texture parameters were extracted using SensoMAP Standard from 837 subzones from archaeological tools (Table 2) and from 731 subzones from experimental ones (Table 3). A total of 47 parameters included in the ISO 25178 standard were selected, and in addition 3 parameters measuring the furrows contained in each surface, measuring their maximum depth, mean depth, and mean density (S1a). The classification variable (CODE_COD) is introduced, at first separating experimental tools in three main categories: “1: Grass_reeds”, “2: Domesticated_cereals”, “3: Threshing_sledges”. The statistical procedure used is available at github.com/nmazzucco/TRAC3D and supplementary materials are provided as outputs of the Rstudio script.

The first step consisted in splitting the datasheet into a training, representing the experimental tools, and a test set, representing the archaeological tools. Successively, we removed rows with missing values if present. After, we proceeded in calculating the variance for each parameter and we removed parameters showing zero variance (S2). To further reduce the number of parameters we proceeded by eliminating parameters with low p-values. This has been made by calculating a correlation matrix (S3) and then calculate p-values for each parameter (S4). At this point we selected the 15 parameters showing the lowest p-values and we removed the other parameters from the dataset (S5). Finally, we used pooled within-groups matrix to remove highly correlated parameters, so to isolate independent variables (S6). Definitive list of selected parameters is presented in Table 4.

At this point the dataset is ready to run a Canonical Discriminant Analysis (CDA) using the MASS package. We thus identify the contribution of the seven parameters for the two first dimensions (S7). As results we obtain a classification for each item in one of the abovementioned categories, “1: Grass_reeds”, “2: Domesticated_cereals”, “3: Threshing_sledges” using the seven predictors previously identified. As result, the 61.6 % of areas from tools used for cutting Grass_reeds are correctly identified (group 1); the 63.1 % of areas from tools used for harvesting Domesticated_cereals are corrected identified (group 2); the 89.1 % of areas from Threshing_sledges are correctly identified (group 3) (S8). Overall, the model is capable of correctly classify the 76.7 % of cases. The error is higher for grasses and reeds cutting, followed by harvesting inserts and rather low for threshing sledges that are correctly classified almost at 90 % of the cases. The distribution of the cases on the two main axes can be observed in the scatter plot (Fig. 9, A).

At this point, to assess the reliability and effectiveness of the developed predictive model, the dataset was split into two halves, employing a random selection approach using nnet R package. One subset was utilized for training a multinomial logistic regression model, while the other subset remained untouched, serving as the testing dataset. The multinomial logistic regression model was trained on the training subset, which involved iterative optimization to best fit the provided

**Table 2**
List of selected tools for the use-wear quantative analysis through confocal microscopy. Interpretation based on optical observation is provided in column "VISUAL INTERPRETATION". Results of the quantitative analysis are provided in the "RESULTS" column, indicating the confidence level (%).

| TOOLS | Period | Chronology (yrs. cal BCE) | Context/ Layer/Phase | Raw-material | Colour | Blank | L | W | T | Macroscopic aspect | Microscopic aspect | VISUAL INTERPRETATION | Sampled areas | Sampled subzones | RESULTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ACH-122 | MN | ca. 5980–5800 | D 1 5 (Phase IV) | Radiolarite | Dark red | Flake | 32.5 | 15.0 | 11.3 | Worn-out, rounded edge | Mixed plant polish and abrasive | Threshing sledge | 8 | 26 | Threshing sledge (80.8 %) |
| ACH-204a | MN | ca. 5980–5800 | B 1 2 (Phase IV) | Radiolarite | Dark red | Flake | 32.8 | 16.0 | 11.4 | Resharpened edge, marginal gloss | Smooth flat polish, no striations | Harvesting insert | 13 | 25 | Harvesting insert (80 %) |
| ACH-226 | EN II | ca. 6300–6070 | B 1 27 (Phase I) | Chert | Black | Blade | 33.3 | 14.9 | 6.5 | Resharpened edge, developed gloss | Smooth domed polish, with abrasions | Doubt (RV2-like polish) | 14 | 22 | Grass_reeds (40.9 %) / Threshing sledge (40.9 %) |
| ACH-2310 | MN | ca. 5980–5800 | D 4 15 (Phase IV) | Radiolarite | Light red/ orange | Flake | 29.1 | 13.5 | 6.1 | Developed gloss | Smooth flat polish, no striations | Harvesting insert | 12 | 29 | Harvesting insert (82.8 %) |
| ACH-2842 | MN | ca. 6070–5980 | D 3 16 (Phase III) | Radiolarite | Dark red | Blade | 25.0 | 14.1 | 4.0 | Marginal gloss | Smooth domed polish, with striations | Harvesting insert | 14 | 26 | Harvesting insert (53.8 %) |
| ACH-3045 | EN/ MN | ca. 5980–5800 | B 4 17 (Phase IV) | Radiolarite | Light green | Blade | 27.0 | 11.5 | 4.9 | Worn-out, rounded edge | Mixed plant polish and abrasive, contact with mineral | Threshing sledge | 9 | 35 | Threshing sledge (100 %) |
| ACH-614 | MN | ca. 5980–5800 | C 4 4 (Phase IV) | Radiolarite | Dark red | Laminar flake | 48.0 | 24.0 | 4.2 | Resharpened edge, developed gloss | Smooth flat polish, no striations | Harvesting insert | 12 | 26 | Harvesting insert (88.5 %) |
| BE-451 | MN | ca. 5900–5600 | Lithic Phase V (building phase V) | Radiolarite | Dark red | Laminar flake | 29.2 | 13.2 | 4.2 | Resharpened edge, developed gloss | Smooth domed polish, few striations | Harvesting insert | 11 | 30 | Harvesting insert (56.7 %) |
| BE-459 | MN | ca. 5900–5600 | Lithic Phase I (building phase Vd) | Radiolarite | Dark red | Blade | 37.2 | 15 | 5.1 | Resharpened edge, developed gloss | Smooth flat polish, no striations | Harvesting insert | 10 | 24 | Harvesting insert (87.5 %) |
| BE-485 | MN | ca. 5900–5600 | Lithic Phase I (building phase Va), sol 29, foyers 29, 30, 31 | Radiolarite | Dark red | Blade | 32.1 | 16.1 | 5.2 | Resharpened edge, developed gloss | Smooth flat polish, no striations | Harvesting insert | 16 | 38 | Harvesting insert (78.9 %) |
| BE-566 | MN | ca. 5900–5600 | Lithic Phase I (building phase IIIb), soil | Radiolarite | Dark red | Laminar flake | 29.2 | 14 | 7 | Worn-out, rounded, edge | Mixed plant polish and abrasive | Threshing sledge | 21 | 69 | Threshing sledge (85.5 %) |
| BE-570 | MN | ca. 5900–5600 | Lithic Phase I (building phase IIIb) | Radiolarite | Dark red | Flake | 21.5 | 28.2 | 7 | Marginal gloss | Smooth domed polish, few striations | Harvesting insert | 15 | 32 | Harvesting insert (62.5 %) |
| BE-595 | MN | ca. 5900–5600 | Lithic Phase I (building phase IIIb) | Radiolarite | Dark red | Blade | 50 | 15 | 6.5 | Resharpened edge, developed gloss | Smooth domed polish, few striations | Harvesting insert | 16 | 30 | Harvesting insert (83.3 %) |
| PL-2171 | LN | ca. 5400–4700 | Trench-13 US-13014 Lay-2 | Radiolarite | Light red | Flake | 24.5 | 20.0 | 7.8 | Worn-out, rounded, edge | Mixed plant polish and abrasive | Threshing sledge | 15 | 30 | Threshing sledge (96.7 %) |
| PL-2774 | LN | ca. 5400–4700 | Trench 9 US-9069 Lay-1 | Chert | Yellow/ honey | Blade | 41 | 21 | 3.9 | Resharpened edge, marginal gloss | Smooth domed polish, few striations | Harvesting insert | 12 | 26 | Harvesting insert (96.2 %) |

(*continued on next page*)

**Table 2** (*continued*)

| TOOLS | Period | Chronology (yrs. cal BCE) | Context/ Layer/Phase | Raw-material | Colour | Blank | L | W | T | Macroscopic aspect | Microscopic aspect | VISUAL INTERPRETATION | Sampled areas | Sampled subzones | RESULTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PL-2870 | LN | ca. 5400–4700 | Trench 6 Ditch US-6181 Lay-17 | Chert | Grey | Blade | 13.5 | 10.5 | 2.5 | Developed gloss | Smooth flat polish, no striations | Harvesting insert | 10 | 24 | Harvesting insert (83.3 %) |
| PL-4023 | LN | ca. 5400–4700 | Trench 9 US-9111 Lay-14 | Chert | Beige | Blade | 27 | 13.5 | 3.5 | Resharpened edge, developed gloss | Smooth domed polish, few striations | Harvesting insert | 16 | 25 | Harvesting insert (84 %) |
| PL-4051 | MN | ca. 5900–5700 | Trench 21 US-21045 Lay-5 | Radiolarite | Dark red | Blade | 20 | 11 | 2.8 | Marginal gloss | Smooth domed polish, few striations | Harvesting insert | 11 | 25 | Harvesting insert (88 %) |
| PL-4833 | LN | ca. 5400–4700 | Trench-9 Us-9207 Lay-29 | Chert | Grey | Blade | 51.5 | 18 | 4.8 | Resharpened edge, developed gloss | Smooth flat polish, no striations | Harvesting insert | 11 | 28 | Harvesting insert (100 %) |
| PL-6924 | MN | ca. 5900–5700 | Trench-6 Ditch US-24163 Lay-28 | Chert | Black | Flake | 17.8 | 13 | 4.5 | Worn-out, rounded edge | Mixed plant polish and abrasive | Threshing sledge | 17 | 32 | Threshing sledge (96.9 %) |
| REV-ME49 | EN | ca. 6550–6100 | Pit 4 | Radiolarite | Green | Laminar flake | 28.5 | 17.0 | 5.0 | Worn-out, rounded and scarred edge | Mixed plant polish and abrasive | Threshing sledge | 16 | 47 | Threshing sledge (97.9 %) |
| REV-ME91 | EN | ca. 6550–6100 | Pit 20 | Radiolarite | Dark red | Blade | 34.0 | 13.2 | 2.9 | Resharpened edge, developed gloss | Smooth domed polish, few post-depositional striations | Harvesting insert | 16 | 38 | Harvesting insert (97.4 %) |
| REV-PE1 | EN | ca. 6550–6100 | Pit 7 | Radiolarite | Dark red | Blade | 59.0 | 21.0 | 2.9 | Marginal gloss | Smooth plant polish with successive abrasion | Reused harvesting insert | 18 | 42 | Grass_reeds (33.3 %) / Threshing sledge (42.9 %) |
| REV-PE373 | EN | ca. 6550–6100 | Pit 6 | Chert | Blonde | Blade | 22.5 | 15.5 | 3.2 | Resharpened edge, developed gloss | Smooth flat polish, few striations | Harvesting insert | 15 | 34 | Harvesting insert (88.2 %) |
| REV-PE8 | EN | ca. 6550–6100 | Pit 2 | Radiolarite | Dark red | Blade | 36.5 | 15.0 | 3.9 | Resharpened edge, developed gloss | Smooth flat polish, few striations | Harvesting insert | 12 | 19 | Harvesting insert (84.2 %) |
| REV-PE92 | EN | ca. 6550–6100 | Pit 4 | Chert/calc | White | Blade | 28.5 | 16.0 | 4.0 | Resharpened edge, developed gloss | Smooth flat polish, striations on the very edge | Harvesting insert | 9 | 19 | Harvesting insert (94.7 %) |
| REV-SN24 | EN | ca. 6550–6100 | Pit 7 | Radiolarite | Dark red | Flake | 21.5 | 14.0 | 4.0 | Rounded edge, matt aspect. | Mixed plant polish and abrasive | Threshing sledge | 25 | 36 | Threshing sledge (97.2 %) |

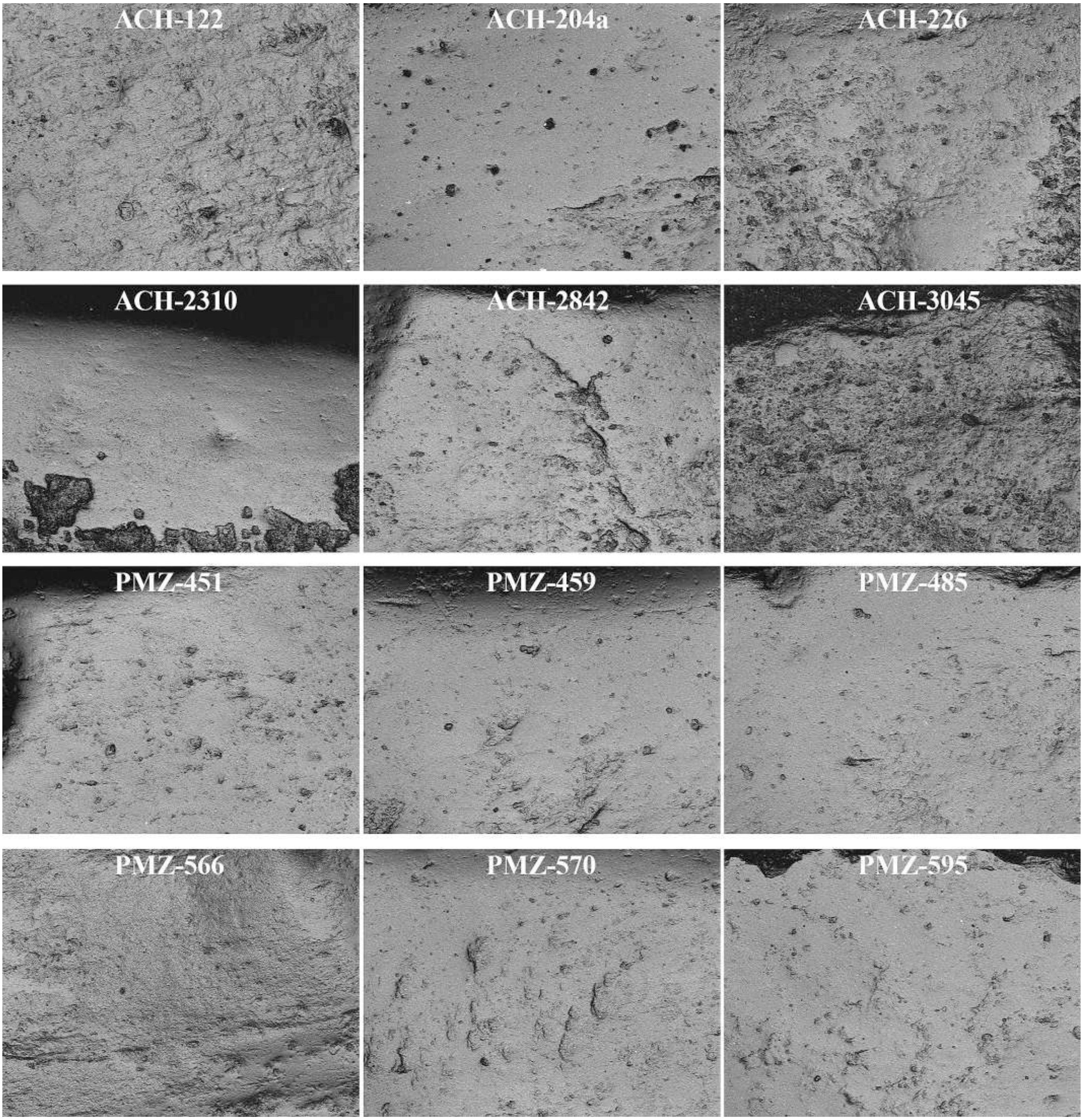


**Fig. 7.** Selection of zones measured with the SensoFar S Neox 3D Profilometer for each selected tool. Note the visual variability of use-wear traces from plant-related working tasks. For both visual interpretation and results of the statistical procedure for each, refer to Table 2.

dataset. Following model training, the testing subset was subjected to prediction using the trained model. This prediction process facilitated the creation of a confusion matrix (S9). The resulting accuracy value obtained is 0.7222. Therefore, the model demonstrated the capability to accurately classify the class of the provided data with a success rate of 72 %.

At this point, subzones from archaeological tools have been introduced into the analysis, undergoing testing against the experimental set. Consequently, a total of 837 archaeological samples have been blindly classified using the trained model, which relies on the seven most influential predictors (Table 4). In the process of classifying archaeological samples, the model employs the discriminant scores derived from CDA. These scores encapsulate the essence of each archaeological item's characteristics in relation to the predictive variables. By utilizing these scores, the model assigns each item to one of three possible classes, signifying its association with a specific category of archaeological tools. For each subzone a confidence value is obtained based on the maximum posterior probability for each classification (S10).

The distribution of the archaeological tools within the experimental set can be observed in the scatter plot (Fig. 9, B). Results are presented in Table 5, indicating the count and percentage of subzones classified in

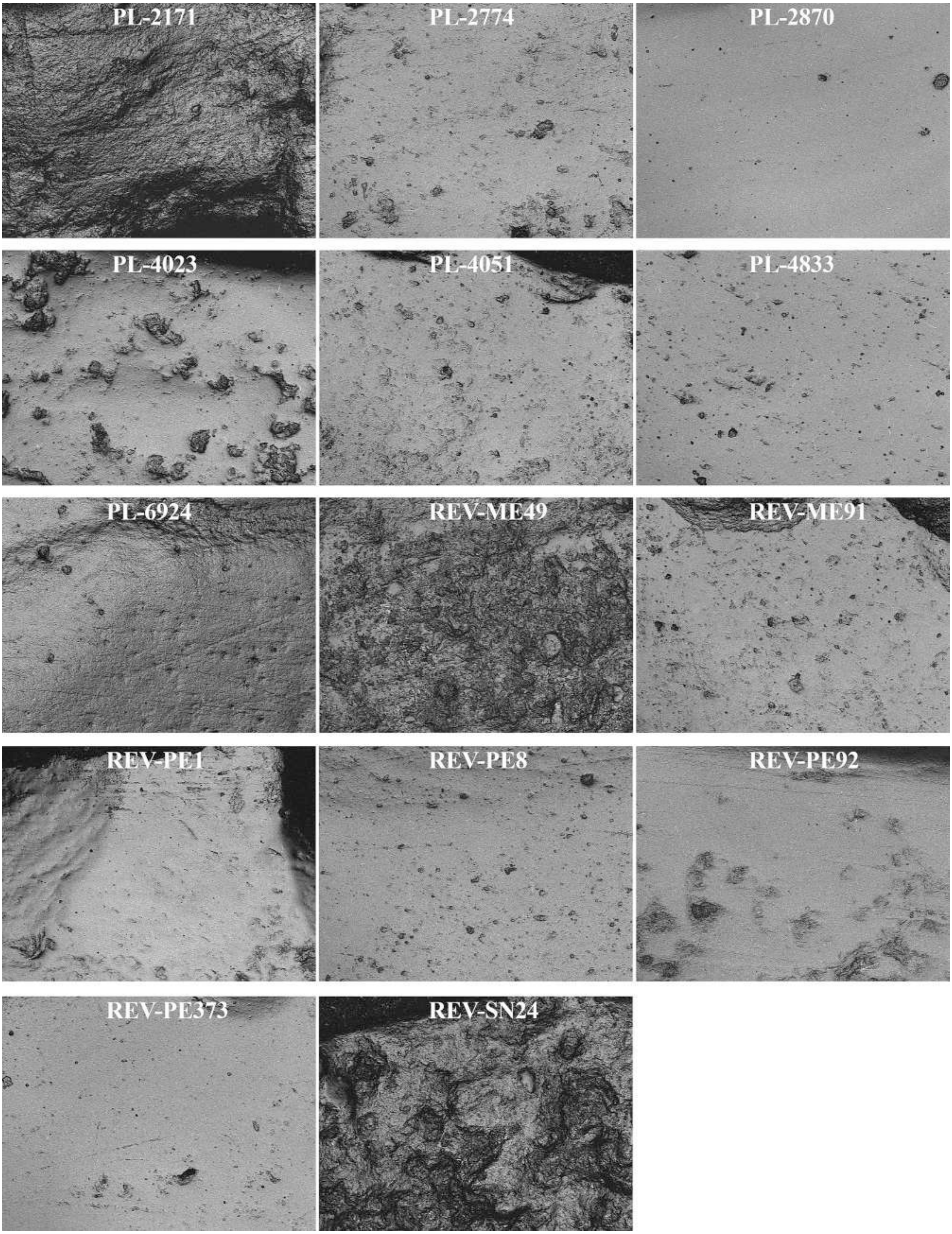


**Fig. 8.** Selection of zones measured with the SensoFar S Neox 3D Profilometer for each selected tool. Note the visual variability of use-wear traces from plant-related working tasks. For both visual interpretation and results of the statistical procedure for each, refer to Table 2.

**Table 3**
List of experiments and selected subareas.

| Type | Experiments | Sampled areas | Sampled subzones |
|---|---|---|---|
| Cutting Grasses | Wild Grass – EXP1 | 17 | 31 |
| Cutting Grasses | Wild Grass – EXP2 | 15 | 15 |
| Cutting Grasses | Wild Grass – EXP3 | 17 | 15 |
| Cutting Reeds | Reeds – EXP4 | 12 | 15 |
| Cutting Reeds | Reeds – EXP5 | 14 | 15 |
| Cutting Reeds | Reeds – EXP6 | 14 | 21 |
| Cutting Reeds | Reeds – EXP7 | 12 | 14 |
| Cutting Reeds | Reeds – EXP8 | 14 | 24 |
| Harvesting insert | Several Cereals – EXP9 | 16 | 22 |
| Harvesting insert | Wheat – Domestic T. aestivum – EXP10 | 24 | 25 |
| Harvesting insert | Wheat – Domestic T. monococcum – EXP11 | 15 | 33 |
| Harvesting insert | Wheat – Domestic T. monococcum – EXP12 | 7 | 24 |
| Harvesting insert | Barley – Domestic Hordeum v. – EXP13 | 14 | 25 |
| Harvesting insert | Wheat – Domestic T. spelta – EXP14 | 16 | 28 |
| Harvesting insert | Wheat – Domestic T. turgidum – EXP15 | 22 | 25 |
| Threshing sledge insert | Asturias Ethnographic Tribulum – EXP16 | 19 | 20 |
| Threshing sledge insert | Catalonia Ethnographic Tribulum – EXP17 | 14 | 32 |
| Threshing sledge insert | Navarra Ethnographic Tribulum – EXP18 | 16 | 32 |
| Threshing sledge insert | Bulgaria Ethnographic Tribulum – EXP19 | 13 | 34 |
| Threshing sledge insert | Crete Ethnographic Tribulum – EXP20 | 14 | 32 |
| Threshing sledge insert | Cyprus Ethnographic Tribulum – EXP21 | 11 | 26 |
| Threshing sledge insert | Greece Ethnographic Tribulum – EXP22 | 17 | 62 |
| Threshing sledge insert | Ukraine Ethnographic Tribulum – EXP23 | 18 | 31 |
| Threshing sledge insert | Ethnogrpahic Experience – EXP24 | 13 | 32 |
| Threshing sledge insert | Experimental Tribulum – EXP25 | 17 | 98 |
| Total | | 418 | 731 |

each of the three groups for each of the three experimental categories. Most of the tested subzones exhibit a clear preference towards at least one of the three class categories, with one category garnering over 50 % representation. This most frequently represented category can legitimately be considered the correct classification for a given archaeological tool (S11). As a result, all tools classified as 'harvesting inserts' by means of traditional microscopy are effectively classified as such by means of quantitative use-wear data. Remarkably, the only two tools for which classification remains less decisive, ACH-266 and REV-PE1, were respectively classified as 'Doubt (RV2-like polish)' and 'Reused harvesting insert' (S11, Table 2), confirming the mixed nature of their polish. All the seven potential threshing sledge inserts tested (see also Table 2) have been classified together with the experimental *tribulum* implements. Therefore, surface metrology confirms interpretation based on macro and microscopic visual examination.

A second test was conducted to further verify the robustness of the obtained classification. As can be seen from the scatter plot (Fig. 9), a series of subzones obtained from experimental sickles that harvested domestic cereals mixes with the subzones obtained from the sledge inserts. This is particularly about a series of areas measured on a sickle used to harvest *Triticum turgidum* (EXP15) (S0). The climatic conditions of the area (i.e., the northern sector of the Ebro valley), notably arid, and the harvesting carried out in a particularly late phase, with a very dry wheat, produced extremely abrasive traces. At the macroscopic level, the sickle inserts do not have rounded edges like the threshing sledge inserts, but at the microscopic level, the use-wear traces are very abrasive and resemble the wears produced by the tribulum. To ensure that this group does not impact the previously obtained classification, we performed an additional Canonical Discriminant Analysis (CDA), adding EXP15 as a fourth group (dataset S1b). We utilized the same predictors previously identified (Spd, Sk, Smr1, Sci, Svi, Mean depth of furrows, Mean density of furrows) (S13-S20). From the results, we obtained a scatter plot (Fig. 10, A), in which we can see that EXP15 is classified at the extreme end of the plot, suggesting that harvesting traces from EXP15 are even more abrasive than those from the experimental threshing sledges. However, when archaeological areas are tested across these four categories ("1: Grass_reeds", "2: Domesticated_cereals", "3: Threshing_sledges", "4: EXP15"), the seven potential threshing sledges are classified as threshing sledge inserts with similar percentages as in the previous test (S21), exhibiting less abrasive use-wear traces, as is also visible from the scatter plot (Fig. 10, B).

**Table 4**
List of selected parameters.

| Selected parameters | Description |
|---|---|
| Spd | Area roughness parameter. *Spd* represents the number of peaks per unit area. A large number indicates more points of contact with other objects. |
| Sk | Area roughness parameter. *Sk or* Core height is calculated by subtracting the minimum height from the maximum height of the core surface. |
| Smr1 | Area roughness parameter. *Smr1* represents the areal material ratio that divides the reduced peaks from the core surface. |
| Sci | Functional parameter. *Sci* surface core fluid retention index characterizes the main void volume acting as a lubricant reserve. |
| Svi | Functional parameter. *Svi* surface valley fluid retention index characterizes, as Svk does, the void volume of the deepest valleys. |
| Mean depth of furrows | Furrows network parameters. Mean depth. |
| Mean density of furrows | Furrows network parameters. Mean density. |

A further step can be made by analysing archaeological tools classified as threshing sledge inserts by taking as reference only tools from ethnographic and experimental threshing sledges, and including EXP15, but excluding the rest of harvesting inserts and tools used for cutting grasses and reeds. As results, a new dataset is provided (S12). The same procedure used above is repeated: first, dataset is filtered by removing row with missing values and variables with constant variance; secondly, significant parameters are selected using p-values from correlation tests, then highly correlated variables are removed. Classification is thus carried out using Canonical Discriminant Analysis (CDA), using 11 categories, corresponding to the different experimental or ethnographic threshing sledges (S0) (i.e., Bulgaria, Catalonia, Creta, Cyprus, EthnoPA, ExpPA, Greece, Navarra, Ukraine, Asturias) and to EXP15. A scatter plot is obtained (Fig. 11, A). As can be saw from the diagram, the tools that are well discriminated and isolated are the ones from the experimental "Sumerian" threshing sledge realized by P. Anderson (Anderson, 1994,2003) (S0). This threshing sledge is characterized by a raft-like structure, slightly elevated above the threshing ground due to the presence of two wooden axles, placed between the sledge and the ground. The lithic inserts, therefore, do not rest directly on the ground. As a result, the use-wear traces have a smoothed appearance, with the typical micropolish resulting from cutting cereals, and a much-reduced abrasive component compared to ethnographic *tribula*, where the flint inserts rest directly on the ground. That is why, this group tend to be clearly differentiated from the others ethnographic inserts. As for the latter, it is difficult to distinguish subgroups within the scatter plot, as all the points are rather mixed.

At this point, the seven archaeological threshing inserts are tested using the trained CDA model and a predicted class is given for each

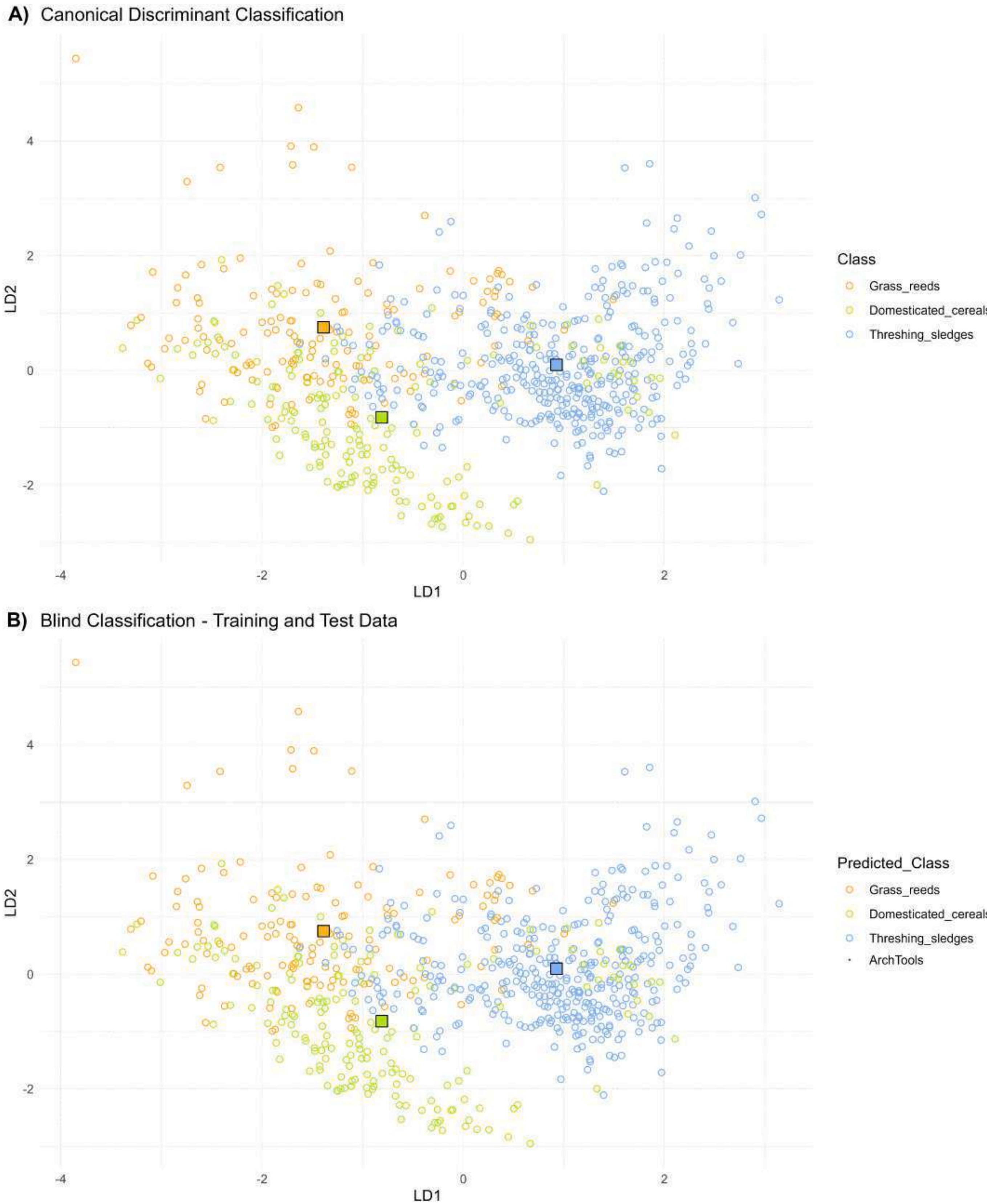


**Fig. 9.** A) Scatter plot (LD1 and LD2) with the subzones (points) and the centroids for each experimental group (Grass_reeds; Domesticated_cereals and Threshing_sledges) in the analysis. B) Same Scatter plot with the addition of the archaeological specimens, blindly classified on the training set.

**Table 5**
Classification results of archaeological tools. In red is highlighted the class summing > 50 % of tested subzones.

| Tool. No. | Grass_reeds | | Domesticated_cereals | | Threshing_sledges | |
|---|---|---|---|---|---|---|
| | Σ | % | Σ | % | Σ | % |
| ACH-122 | 4 | 15.4 | 1 | 3.8 | 21 | **80.8** |
| ACH-204a | 2 | 8.0 | 20 | **80.0** | 3 | 12.0 |
| ACH-226 | 9 | 40.9 | 4 | 18.2 | 9 | 40.9 |
| ACH-2310 | 0 | 0.0 | 24 | **82.8** | 5 | 17.2 |
| ACH-2842 | 5 | 19.2 | 14 | **53.8** | 7 | 26.9 |
| ACH-3045 | 0 | 0.0 | 0 | 0.0 | 35 | **100.0** |
| ACH-614 | 3 | 11.5 | 23 | **88.5** | 0 | 0.0 |
| BE-451 | 13 | 43.3 | 17 | **56.7** | 0 | 0.0 |
| BE-459 | 3 | 12.5 | 21 | **87.5** | 0 | 0.0 |
| BE-485 | 0 | 0.0 | 30 | **78.9** | 8 | 21.1 |
| BE-566 | 5 | 7.2 | 5 | 7.2 | 59 | **85.5** |
| BE-570 | 4 | 12.5 | 20 | **62.5** | 8 | 25.0 |
| BE-595 | 5 | 16.7 | 25 | **83.3** | 0 | 0.0 |
| PL-2171 | 0 | 0.0 | 1 | 3.3 | 29 | **96.7** |
| PL-2774 | 0 | 0.0 | 25 | **96.2** | 1 | 3.8 |
| PL-2870 | 0 | 0.0 | 20 | **83.3** | 4 | 16.7 |
| PL-4023 | 0 | 0.0 | 21 | **84.0** | 4 | 16.0 |
| PL-4051 | 1 | 4.0 | 22 | **88.0** | 2 | 8.0 |
| PL-4833 | 0 | 0.0 | 28 | **100.0** | 0 | 0.0 |
| PL-6924 | 0 | 0.0 | 1 | 3.1 | 31 | **96.9** |
| REV-ME49 | 1 | 2.1 | 0 | 0.0 | 46 | **97.9** |
| REV-ME91 | 1 | 2.6 | 37 | **97.4** | 0 | 0.0 |
| REV-PE1 | 14 | 33.3 | 10 | 23.8 | 18 | 42.9 |
| REV-PE373 | 1 | 2.9 | 30 | **88.2** | 3 | 8.8 |
| REV-PE8 | 0 | 0.0 | 16 | **84.2** | 3 | 15.8 |
| REV-PE92 | 1 | 5.3 | 18 | **94.7** | 0 | 0.0 |
| REV-SN24 | 1 | 2.8 | 0 | 0.0 | 35 | **97.2** |

subzone (S22). The classification result is evaluated through a cross-table (S23). Five tools out of seven are classified as Cyprus ethnographic inserts with percentages between 57.7 % and 88.6 %; two tools are classified with the Greek inserts (75 % and 100 % of the subzones) (Fig. 11, B). None of them is classified within the range of the experimental "Sumerian" threshing sledge, or as EXP15.

## 4. Discussion & conclusions

Threshing sledge, often called by its Roman name *tribulum*, represents one of the first farming machinery that, exploiting animal traction, fulfilled and improved agricultural tasks. They have widely used around the Mediterranean and in the Near East and survived until very recently in several places throughout this broad area. In respect to other threshing methods —such as hand threshing, beating grains, treading, or utilizing simpler tools like a wooden stick or a flint knife (the latter of which has been posited for the Western Mediterranean Neolithic, according to Clemente and Gibaja, 1998; Antolín et al., 2014)— the use of the sledge would have contributed to increased productivity, allowing for the more rapid accumulation of surplus crops. Furthermore, the use of threshing sledges not only facilitates the processing of more grain but also yields more shredded straw. This straw can be repurposed in construction, such as in the creation of adobe houses and as feed for livestock.

That is why the introduction of animal-drawn sledges has been traditionally associated with later phases of Neolithic, from the fourth millennium cal BCE onward, with the so-called Secondary Product Revolution, next to the plough and the chariot (Sherratt, 1981; Avner et al., 2003).

The evidence presented in this study suggests that threshing sledges may have been in use in Greece earlier than previously thought, since the early phases of Neolithic period, ca. 6500 cal BCE onward. This data holds significant importance in understanding the diffusion and evolution of Neolithic farming systems from the Near East to Europe. If we accept evidence suggesting the introduction of threshing sledges already during Middle and Late PPNB and pre-Halaf (ca. 8000–6500 cal BCE) in the Upper Euphrates (Anderson, 2003), our study indicates that threshing sledges were introduced in Europe from the Near East since the earliest phases of Neolithic expansion, as part of a larger set of farming technologies, including domesticated species and animal traction, ground stone technology, sickles, storage facilities, etc.

It is true that the data upon which we can base this interpretation are still quite limited. For the Near East, the findings are sporadic, comprising a few pieces that were often previously used as sickle elements. Given the visual overlap between traces produced by grain harvesting and those produced by threshing with sledges, interpreting tools with dual functionality—first for cutting grain and later as a sledge component—can be extremely complex. In the case of Greece, the number of sledge elements we've identified remains extremely low. We found 8 pieces, compared to 250 sickle elements identified across the four sites analysed. The low number of threshing sledge inserts is a characteristic that extends to other contexts as well. In Bulgaria, the sample of sledge teeth identified is also around a dozen elements, thus numerically low (Gurova, 2014,2018). There can be multiple reasons for this scarcity of findings. First, it relates to how the sledges are managed. Sickle elements are usually found within villages because they need periodic resharpening, requiring the replacement of stone elements. Using worn-out sickle inserts negatively impacts harvesting efficiency (Astruc et al., 2012; Mazzucco et al., 2018). This is not the case for threshing sledges. They are not cutting tools, so maintaining the edge sharp is not so essential. Sledges serve to separate the grain from the husk by applying pressure through complex rotational movements, while also breaking down the straw. This can be done even with blunt flint inserts. Some types of ethnographic sledges even use squared blocks of basalt or other volcanic/metamorphic rocks instead of flaked flint. Consequently, there is no need to periodically bring the sledge back to the village for replacing the stone inserts; it can remain at the threshing site, and the inserts may never need to be replaced. The recovery of these sledge inserts from Early Neolithic sites is likely due to pieces that were accidentally lost or detached from the sledge. This could partially explain their scarcity at the investigated contexts. It is also possible that in this early phase, the use of animal traction and associated machine is not still intense, but sporadic, tied to specific times in the agricultural calendar or specific events. Therefore, the use of sledges may be less frequent than in later periods.

Another aspect to consider is the production context within which the use of sledges is employed. Our data suggest their use between the eighth and seventh millennia in the Near East and the eastern Mediterranean; however, the spread of threshing sledges seems to then halt and is excluded from the Neolithic package as it spreads westward. In the central and western Mediterranean, there is no evidence of the use of threshing sledges until at least the third millennium. The oldest archaeological evidence for the use of the threshing sledge in the western Mediterranean dates it between approximately 3000 and 2500 cal BCE in the Spanish Meseta (Gibaja et al., 2012) and between approximately 2900–2300 cal BCE in Portuguese Estremadura (Clemente et al., 2014). For earlier phases, threshing would be done employing 'low scale' methods, by hand or with simpler tools (Clemente and Gibaja, 1998). This delineates a phase of long interruption in the spread of sledges; although they quickly move from the Near East to the eastern Mediterranean, they would not spread to the rest of the Mediterranean for another three millennia. In this regard, it is interesting to note that this divide between the eastern and western Mediterranean is also documented on a more general level. The study of the spread of grain harvesting tools has shown that between the Balkan area and the western Mediterranean, there is a sharp change in the number and intensity of use of the first sickle elements. While in Greece they are one of the most widely used tools, making up to 40 % of the retouched tool assemblage, in Italy and Spain sickle teeth are much rarer (comprising 3–4 % of lithic industries) and less intensively used (Mazzucco et al., 2020).

All of this seems to indicate that the scale of agricultural production

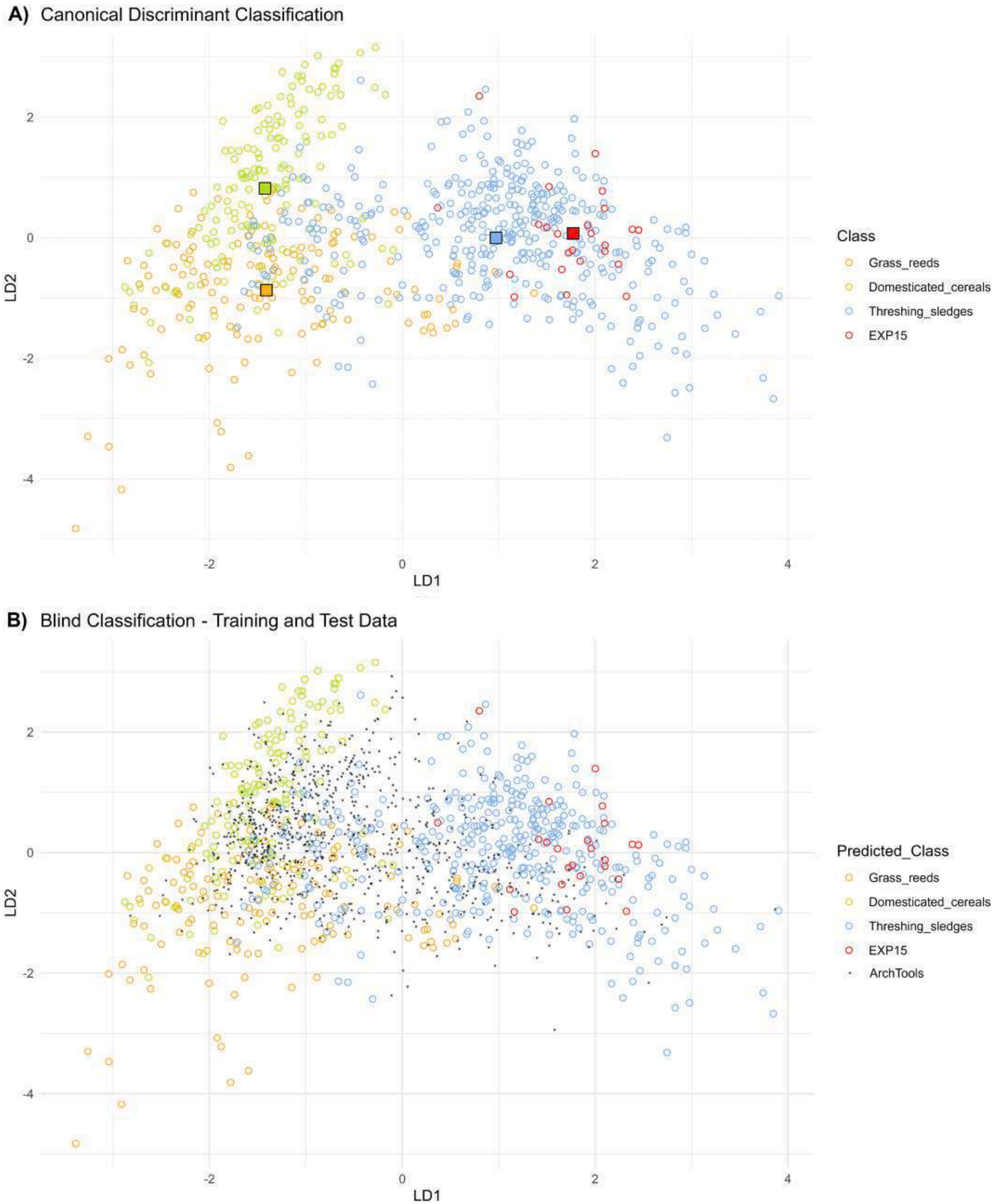


**Fig. 10.** A) Scatter plot (LD1 and LD2) with the subzones (points) and the centroids for each experimental group (Grass_reeds; Domesticated_cereals, Threshing_sledges, EXP15) in the analysis. B) Same Scatter plot with the addition of the archaeological specimens, blindly classified on the training set.

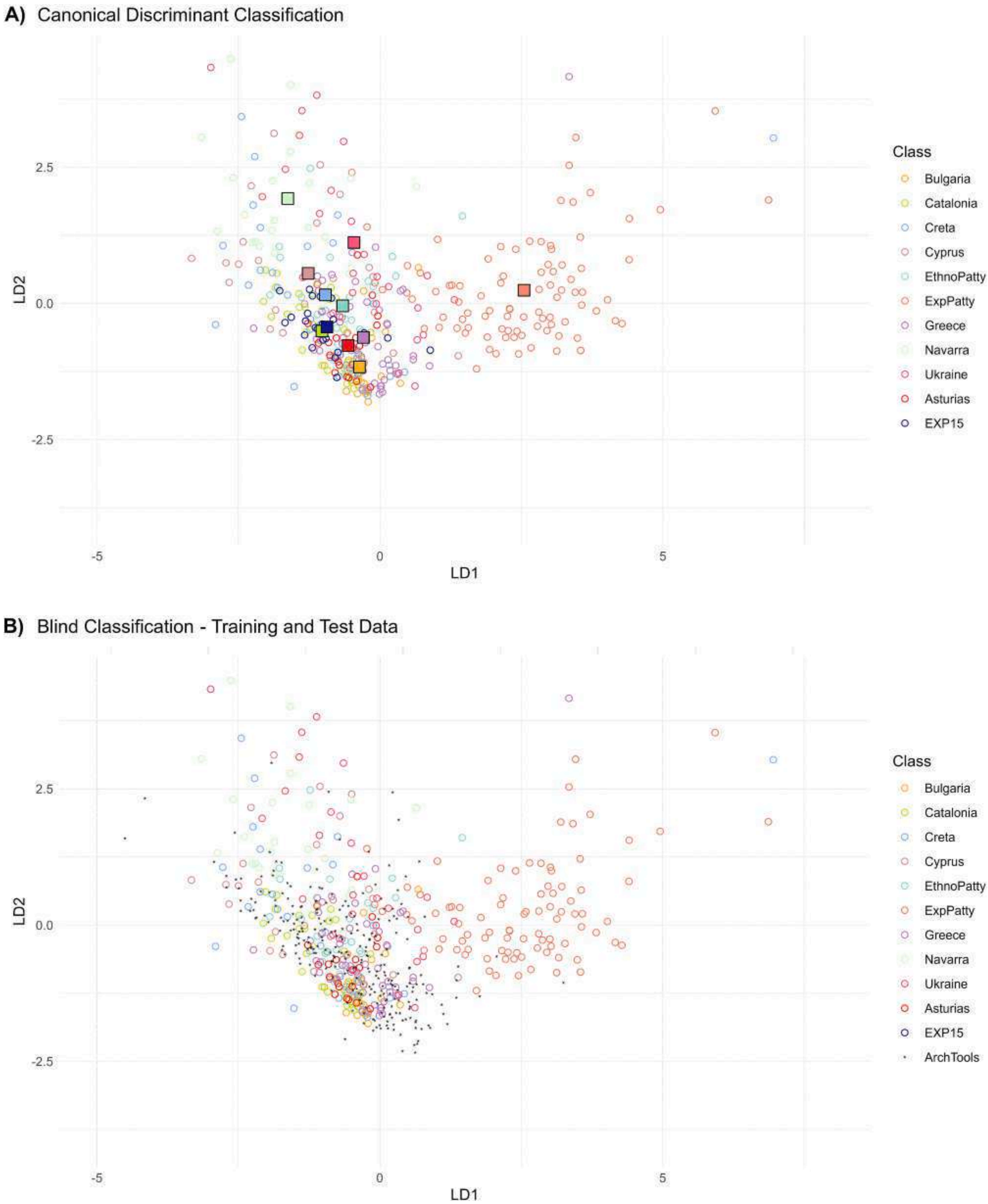


**Fig. 11.** A) Scatter plot (LD1 and LD2) with the subzones (points) and the centroids for each experimental threshing group in the analysis. B) Same Scatter plot with the addition of the archaeological specimens, blindly classified on the training set.

between the two areas is substantially different. While in the Balkans, agriculture would have an immediately high economic weight, with a level of production that would justify the more or less occasional, more or less frequent use of sledges, in the western Mediterranean, the earliest Neolithic agriculture would likely be oriented toward 'low scale' production. A considerable intensification and increase in agricultural production would only date to the later phases of the Neolithic and the Chalcolithic.

In conclusion, the data we have obtained appears to confirm the existing framework on the spread of the Neolithic and agricultural technologies in the Mediterranean. A first phase of expansion of the Near Eastern farming technologies into the southern Balkans is observed, although with an initial reshaping of its components (Perlès, 2005; Milić 2019). Subsequently, in the westward expansion, a further reconfiguration is seen at the level of technologies and exported domestic species, along with adaptation to new environmental contexts (Ivanova et al., 2018; Krauß et al., 2018), and to new social and demographic conditions (Mazzucco et al., 2020).

The use of threshing sledges in Greece well reflects the first phase of Neolithic expansion, and although the data at our disposal is still limited, it seems legitimate to envision the introduction of this technology in an early phase of the Neolithic. Furthermore, the use of this technology appears to fit into a broader context that involves the use of animal traction from the early phases of the Neolithic to perform a variety of tasks ranging from transportation and towing to the processing of agricultural products.

The integration of traditional use-wear analysis with quantitative methods, such as confocal microscopy and metrological analysis, has enabled a more precise and reproducible understanding of the observed use-wear traces. The high variability in use-wear traces, produced from different plant-working and plant-processing tasks, poses challenges in visually distinguishing them (Ibáñez et al., 2021; Ibáñez and Mazzucco, 2021; Mazzucco et al., 2022). This is why the application of quantitative methods provides a valuable tool to explore, measure, and describe this variability in terms of textural parameters. Our study demonstrates that the characteristic wear patterns associated with threshing sledges—including plant polish, intense edge abrasion, and fine striations—can be distinguished from those of other tools used for different plant-processing tasks. Use-wear traces from threshing sledges can even be differentiated from those resulting from harvesting in arid climatic conditions on very dry cereals. Indeed, our study demonstrates that visual differences within harvesting traces can be highlighted and characterized quantitatively.

## CRediT authorship contribution statement

**N. Mazzucco:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visulation, Writing - original draft. **J.J. Ibáñez:** Data curation, Formal analysis, Methodology, Resources, Validation, Writing - review & editing. **P. Anderson:** Investigation, Methodology, Resources, Validation, Writing - review & editing. **K. Kotsakis:** Investigation, Resources, Validation, Writing - review & editing. **A. Kita:** Investigation, Resources, Validation, Writing - review & editing. **F. Adaktylou:** Investigation, Resources, Validation, Writing - review & editing. **J.F. Gibaja:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

I have shared the link to my data

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104579.

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