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Paleoenvironmental reconstruction and anthropogenic influence in the lagoon of Val Grande of Bibione (NE Italy): from the Roman coastal villa to Medieval saltmarshes and modern reclamations

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Abstract. Human occupation of the northwestern Adriatic coastal plain has intensified since the late Bronze Age and Iron Age, with major centres developing along the inner lagoon margins and later becoming Roman cities. While the geomorphological development of the coastal belt and lagoonal interiors is rather well known from mapping, stratigraphy, and historical cartography, the knowledge of the archaeobotanical aspects remains scarce, leaving the environmental context of many Roman sites poorly understood. This study reconstructs the evolution of the Val Grande lagoon (Bibione, NE Italy), located behind the dune system hosting the Roman villa of Mutteron dei Frati and adjacent to a large tidal inlet that was once the connection to the open sea. Through the combined analyses of manual boreholes, digital terrain models (DTMs), and palynological data from three stratigraphic sequences (VLG3, VLG4, and BEV1A), we documented the ecological and geomorphological history of this transitional area from the Roman period to the modern reclamations. The pollen record from 30 samples documents the evolution of the former lagoon during the Roman and early Medieval periods, marked by brackish–lagoonal communities, halophytes, and extensive wetlands, with weak and localized anthropogenic indicators compared to more urbanized areas. These are linked with occupational phases of the villa and likely reflect small-scale productive activities. Radiocarbon dating and age–depth modelling further constrain ecological changes, including the avulsion of the Tagliamento River in the sixth century CE that reshaped the lagoon into a rather confined brackish environment. Together, these datasets illustrate how lagoonal ecosystems responded to long-term environmental and geomorphological reorganization in a relatively undisturbed setting.

1 Introduction and geological setting

The low-lying coastal floodplain of the northwestern Adriatic has undergone major modern transformations due to anthropogenic activities, which profoundly altered the natural morphology and dynamics of lagoons and coastal sandy systems. Extensive reclamations in the early 20th century drained large portions of the Venice, Caorle, and Grado–Marano lagoons, converting them into farmland and greatly reducing natural environments (Fig. 1; Bondesan and Meneghel, 2004; Bondesan et al., 2004; Fontolan, 2004). Similar effects have resulted from the proliferation of tourist settlements along the beaches since the 1950s, causing rapid and widespread urbanization, as well as levelling and reworking of most coastal dunes. Early interventions like river embankments, stream canalization, and localized reclamations had already been carried out during the Venetian Republic (Bondesan and Furlanetto, 2012); more broadly, the significant presence of human settlements in the coastal plain dates back to the late Bronze Age and Iron Age. In particular, between

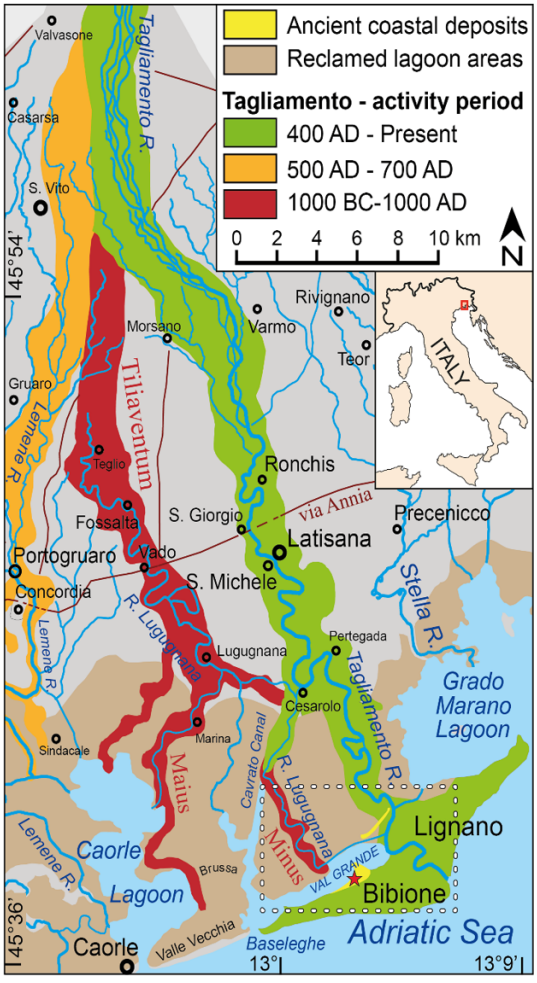

Figure 1. Simplified map of the historical channel belts of the Tagliamento River (modified from Fontana, 2006). The red lines represent the Roman roads, and the dotted rectangle represents the area of Fig. 2, with the star corresponding to the site of Mutteron dei Frati of Bibione.

the end of the second and the beginning of the first millennium BCE (Before Common Era), several centres developed along the inner lagoon margins and later became major Roman cities, such as Adria, Altino, Concordia Sagittaria, and Aquileia (e.g. Peretto, 1986; Croce Da Villa and Di Filippo, 2001; Maselli Scotti and Rottoli, 2007; Mozzi et al., 2016). Roman sites also occurred within the lagoons and along the coastal beaches, although the role of many of them remains debated due to the limited number of stratigraphic investigations conducted to date (e.g. Auriemma et al., 2013; Canal, 2013; Calaon and Cottica, 2020; Primon and Mozzi, 2023; Gaddi et al., 2025; Beltrame, 2026; Busana et al., 2026 and references therein).

Because of the post-abandonment changes and the intense modern transformations, most archaeological sites along the Veneto and Friuli Venezia Giulia coast now lie outside their original environmental context. An exception is the brackish basin of Val Grande (Bibione, municipality of San Michele al Tagliamento; Fig. 2), where a Roman villa, dating from the first century BCE to the late fifth century CE, was built on the flank of the nearby dune named "Mutteron dei Frati" (Battiston and Gobbo, 1992; Steuernagel et al., 2026). Located north of the western Tagliamento delta, the Val Grande remained relatively stable throughout the last centuries thanks to its long-term use as a private hunting reserve and fishery (Casti Moreschi, 1990). The mosaic of lagoonal and marshland environments preserved a continuous sedimentary and paleoenvironmental record that, combined with the archaeological traces documented in this site, allows for a more integral study of human activities and their possible interaction with the natural coastal processes.

Despite the detailed reconstruction of the Holocene geomorphological evolution in the coastal plains and lagoons of NW Adriatic (e.g. Marocco, 1991; Stefani and Vincenzi, 2005; Amorosi et al., 2008; Piovan et al., 2012; Fontana et al., 2017; Ronchi et al., 2021), the vegetation history and ecological dynamics of this sector of the coast remain poorly constrained. Thus, in the framework of a broader project on the Roman villa of Bibione, detailed geomorphological and paleoecological analyses were carried out to reconstruct the environmental conditions before, during, and after the occupation of the settlement. The area also experienced a major paleohydrographic change in the sixth century, when the Tagliamento shifted to its present position (Fontana et al., 2020). Several stratigraphic boreholes were drilled, and cores VLG3 and VLG4 were selected for pollen analysis to document the long-term vegetation development, while core BEV1A was used as a reference for the modern vegetation (Fig. 2). By integrating palynological data from VLG3 and VLG4 with the established geomorphological framework, this study aims to achieve four goals: (i) reconstruct the environmental setting of the Val Grande lagoon before and during the occupation of the Roman villa and highlight the differences recorded in cores VLG4 and VLG3; (ii) investigate the nature and spatial extent of Roman-period human influence on the lagoon and its margins; (iii) understand the response of the lagoon to the early Medieval hydrological reorganization associated with the Tagliamento river avulsion; and (iv) compare the ancient records with the recent land use, as documented by a modern analogue (BEV1A). To achieve these aims, we combined pollen and non-pollen palynomorph analyses with radiocarbon-based age–depth models and pollen-derived indicators of human impact, interpreted within the established geomorphological and archaeological framework.

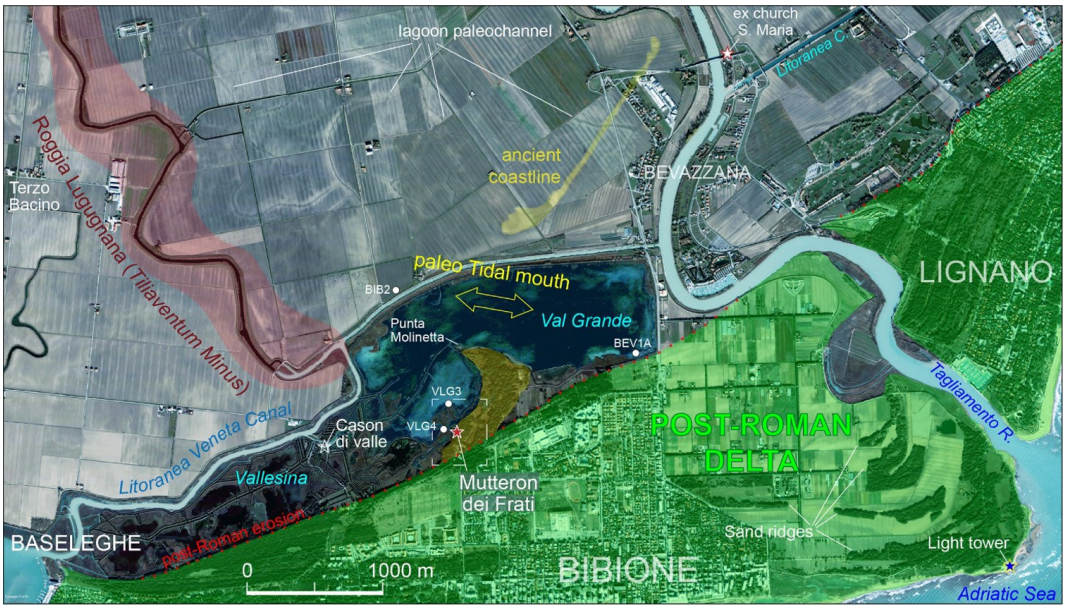

Figure 2. Scheme of the main morphological units of the coastal plain near Bibione. Satellite image of November 2003 as basemap (Image Google Earth © 2026 Maxar Technologies). The dashed rectangle represents the area shown in Fig. 3.

2 Study area

2.1 Depositional setting and regional paleogeographic changes

The Bibione area belongs to the coastal plain of Tagliamento, a major river draining the southeastern Alps, which has been building a Holocene deltaic system since 8000–7000 years ago, when lagoonal and coastal deposits began to onlap over the alluvial plain of the Last Glacial Maximum (LGM: 29 000–19 000 years cal BP; Surian and Fontana, 2017). The study area consists of a Holocene succession of sandy coastal ridges and muddy lagoonal deposits up to 10–12 m thick, thinning landward. Within the system, the SW–NE-oriented Mutteron dei Frati dune ridge stands out as an ancient coastal barrier, morphologically distinct from the younger ridges formed during the Medieval and modern progradation of the Tagliamento delta (Figs. 2 and 3).

Since the beginning of the first millennium BCE, the Tagliamento River flowed along the course described in Roman sources as the *Tiliaventum Maius*, with its mouth near Valle Vecchia (Fig. 1). From this channel belt, a minor branch, the *Tiliaventum Minus*, stemmed off, flowing along the path of the modern Roggia Lugugnana stream (Fontana et al., 2020, 2026, and references therein). A major landscape reorganization occurred in the early Middle Ages when, at the end of the sixth century CE, an avulsion led the Tagliamento to abandon the *Tiliaventum Maius* and adopt its current eastern course (Fontana, 2006; Fontana et al., 2020). This shift triggered coastal erosion that strongly affected the Mutteron dei Frati dune system while later supplying sediments for the construction of the modern delta (Fontolan, 2006; Gordini et al., 2006). Meanwhile, the Val Grande lagoon persisted but gradually evolved into a more enclosed, sediment-filled basin influenced by major Tagliamento floods.

During the Iron Age, the settlement corresponding to Concordia Sagittaria was the main centre in the area. In 181 BCE, however, Aquileia became the principal Roman colony of NE Italy, attracting several thousand new families to the Friulian Plain and prompting the construction of the *centuriatio*, the regular field system defined by a dense network of ditches, canals, and roads (Prenc, 2002, and references therein). A second major phase began around 42–40 BCE, when Concordia became a colony and established its own *centuriatio* between the present Tagliamento and Livenza rivers (Fig. 1; Croce da Villa and Di Filippo, 2001). Even though the coastal strip does not appear to have been included in the *centuriatio* (Busana et al., 2025), the earliest occupation of the Mutteron dei Frati villa likely dates to this very phase as the oldest archaeological evidence from the site belongs to the second half of the first century BCE (Steuernagel et al., 2026). The villa expanded substantially in the second or early third century CE and underwent further renovation in the course of the fourth century CE. The most recent archaeological finds still associated with the villa or its immediate aftermath date from the late fifth century CE (Pandolfo, 2026). The villa was built on the flank of the dune known as Mutteron dei Frati, which currently reaches 11 m a.m.s.l. and is the highest coastal dune of the northern Adriatic. After its abandonment, part of the dune collapsed onto the structures, leading to exceptional preservation of part of the walls and floor mosaics (Steuernagel et al., 2026). Stratigraphic data indicate that the

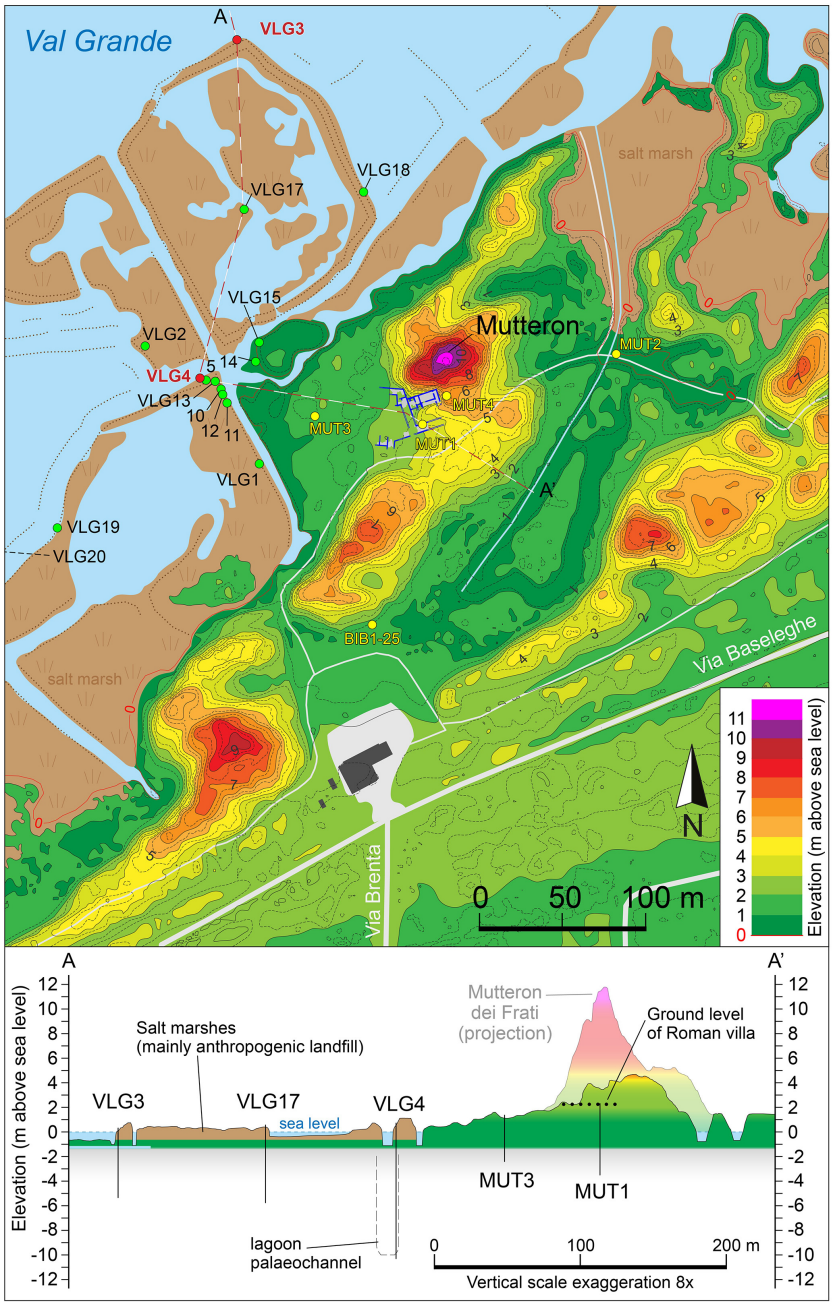

Figure 3. **(A)** Topographic map with contour lines of the area of Mutteron dei Frati, with the plan of the Roman villa and the stratigraphic cores collected in the area; the map was obtained by means of lidar-derived data processing. **(B)** Cross-section of the area between Val Grande and the dune of Mutteron dei Frati; the trace of the section is reported in **(A)**.

dune formed during the first millennium BCE, while, by the Roman period, the coastline had already shifted 250–350 m eastward (Fontana et al., 2026). Sheltered from the direct action of waves and wind by three sandy ridges, the villa did not face the open sea but instead overlooked the Val Grande lagoon, where a tidal channel approximately 10 m deep flowed just a few tens of metres from the building. This channel has been sampled by core VLG4, and it belonged to the lagoon system connected to the sea through the tidal mouth between Mutteron dei Frati and Bonifica Vallesina (Fig. 2), creating a protected yet easily accessible maritime setting that, in addition to the residential and leisure functions, also suggests a possible role in the control of the entrance to the lagoon (Steuernagel et al., 2026). During the Middle Ages and Renaissance, the area was only sporadically frequented for fishing and hunting, as indicated by the temporary huts in the

1527 CE map and limited archaeological evidence (Steuernagel et al., 2026; Fontana et al., 2026). Historical sources document the transformation of Val Grande into a fishery at the end of the 17th century, with some cultivated fields along its southern margin (Casti Moreschi, 1990; Fontana et al., 2026). Its later use as a private hunting reserve prevented reclamation, unlike the rest of the Bibione peninsula, which underwent extensive urban development and land levelling between the 1920s and 1960s (Casti Moreschi, 1990).

2.2 Vegetation

Val Grande of Bibione is a 360 ha brackish basin whose southern margin corresponds to the dunes system of Mutteron dei Frati, characterized by patches of *Quercus ilex* (Oasi Val Grande Bibione, 2026).

Zanetti (2006) provides a detailed description of the floristic assemblage of Val Grande, which hosts several rare species preserved by the exceptional refugial conditions of the relict dune system. Mediterranean taxa include *Quercus ilex*, *Phillyrea angustifolia*, and *Smilax aspera*; Illyrian elements include *Cotinus coggygria*; temperate bog species comprise *Gentiana pneumonanthe* and *Potentilla erecta*; while mountain taxa such as *Primula farinosa*, *Ostrya carpinifolia*, and *Populus tremula* are also present. In the Tagliamento River delta, the original pine woodland has been altered by recent management and urban expansion, as well as by reforestation with *Pinus pinea*. The most intact areas are dominated by nearly monospecific stands of *Pinus nigra* var. *austriaca*, with a dense understorey where *Fraxinus ornus* and marginal *Quercus ilex* also occur. The understorey includes *Juniperus communis*, *Berberis vulgaris*, *Lonicera etrusca*, *Cotinus coggygria*, and *Phillyrea angustifolia*. These woodlands are interspersed with bogs and humid grasslands hosting *Thelypteris palustris, Cladium mariscus, Taraxacum palustris, Gentiana pneumonanthe, Gentianella germanica, Euphrasia marchesettii*, and *Parnassia palustris*. Dry meadows support *Centaurea tommasinii, Globularia punctata*, and 22 orchid species (Zanetti, 2006). The Tagliamento river mouth forms a complex system of active and relict dunes, generating a mosaic of micro-environments and exceptionally high biodiversity. Taxa recorded across these habitats include *Pinus nigra, Neottia nidus-avis, Gymnadenia conopsea, Quercus ilex, Phillyrea angustifolia, Lonicera etrusca, Vitis vinifera, Osyris alba, Ruscus aculeatus, Cistus incanus, Orchis coriophora, Ophrys sphegodes, Stipa veneta, Aster linosyris, Campanula sibirica, Chamaecytisus purpureus, Genista germanica*, and *Rhamnus saxatilis*. Additional species occur in specialized habitats, including halophytes, hygrophilous herbs, psammophilous, and xeric taxa.

The climate is humid–temperate with strong maritime influence, as shown by long-term observations from the Lignano Sabbiadoro station (OSMER-ARPA FVG, 2026). The mean annual temperature is 15.3 °C, with daily average minima in January (5.5 °C) and maxima in July–August (25.1–25.2 °C). Seasonal variability is moderate due to the Adriatic Sea. Precipitation is distributed throughout the year, with a mean annual cumulative value close to 1000 mm, and peaks in spring and autumn; winds are generally mild and are slightly stronger in the same seasons.

3 Materials and methods

Hand coring was carried out at key locations identified through high-resolution digital terrain models derived from the lidar survey of the Italian Ministry of the Environment (PST-A and PST-A Extension 2008), featuring a 1 m^2 cell size and a vertical accuracy of ±0.10 m (Geoportale Nazionale, 2025). All analyses and visualizations were performed using the software QGIS. For the sampling operations through manual coring, an Edelman head was used for sediments above the groundwater table, while a gouge of 1 m of length was employed for the waterlogged units below it. Access to the central basin and more remote coring points was achieved using small boats and kayaks. The two main pollen sequences analysed in this study, VLG3 and VLG4, were extracted from sites that are currently emerged from the waters because of small embankments constructed as part of the fishery structures. BEV1A has been collected in the SW corner of the basin, on a natural saltmarsh formed over one of the oldest sand ridges of the post-Roman delta.

3.1 Pollen sampling and preparation

A total of 30 samples were collected for palynological analysis: 16 samples from core VLG4, 10 from core VLG3 (Fig. 4), and 4 from core BEV1A (see the Supplement for details). Considering the fact that core VLG4 is a continuous and finely laminated sequence from a tidal channel next to the villa, 16 samples were taken with the aim of achieving a reliable detail through the palynological analysis and to document the lagoon transformations before, during, and after the Roman occupation. An additional set of 10 samples was analysed from VLG3, a core sampled in a tidal flat farther from the villa, which was used as a comparison. Moreover, to describe the modern and recent changes in Val Grande, four samples were selected from the upper 35 cm of core BEV1A.

Sample preparation was carried out at the palynology laboratory of the Department of Physical Geography, Utrecht University, following a standard protocol using CH_3COOH 5 %, HCl 5 %, KOH 5 %, acetolysis solution, and heavy-liquid flotation (specific density SD = 2.0). By avoiding hydrofluoric acid, siliceous remains are preserved, allowing recognition of diatoms alongside other non-pollen palynomorphs (NPPs). Pollen concentration (grains cm^{-3}) was estimated by spiking with *Lycopodium* tablets (Stockmarr, 1977) to a measured volume of sediments. Pollen grains were counted using an optical microscope at magnification of ×500 and ×790 and identified following atlases and dichotomic keys (Moore et al., 1991; Reille, 1992, 1998; Beug,

2004; Pini et al., 2016). NPPs were identified following Medeanic (2006), Florenzano et al. (2012), Miola (2012), Dal Corso (2018), Shumilovskikh et al. (2021), and Leal et al. (2021). A minimum number of 300 pollen grains was counted for each sample, excluding aquatic plants. In samples dominated by a single taxon, a minimum of 200 non-dominant pollen grains were counted.

3.2 Pollen grouping

The identified pollen and spore grains were grouped by ecological affinity, and arboreal taxa were assigned to seven groups (Table S2 in the Supplement): (1) conifers, (2) montane, (3) Quercetum, (4) Mediterranean, (5) OJC (*Olea, Juglans, Castanea*; Mercuri et al., 2013b), (6) hygrophytes, and (7) shrubs and lianas (subdivided in three sub-groups: forest edge, open coastal, pioneer- xeric). Herbaceous taxa were assigned to six groups (Table S3): (1) wild herbs, (2) PSIs (potential synanthropic indicators), (3) LDI (lagoon disturbance index), (4) cereals, (5) halophytes, and (6) wetlands. Moreover, the spore group includes spores from mosses and ferns, and the NPP group includes all non-pollen palynomorphs (e.g. diatoms, foraminifera linings, fungi). Spores were assigned to ecological groups for graphical interpretation (e.g. *Dryopteris*-type with forest taxa; *Thelypteris* with wetland taxa), but group percentages were calculated using pollen taxa only. These ecological groupings allow a clearer interpretation of vegetation dynamics and human impact in lagoonal settings. In terms of the relative abundance of the taxa, it is important to note that trees, shrubs, and herbaceous species are included in the Pollensum, whereas wetland and spore species are included in the Supersum. A dedicated Nsum has been created for NPPs, including upland pollen and all non-pollen palynomorphs.

3.3 LDI and PSI

According to Birks and Birks (1980), human disturbance often increases floristic diversity through the creation of secondary habitats where rich herbaceous vegetation can thrive. Many herbaceous pollen grains are used as indicators of past anthropogenic activities and are included in the APIs (anthropogenic pollen indicators, Behre, 1981; Mercuri et al., 2013a) or in the PDI (pollen disturbance index, Kouli, 2015). Changes in their frequency rather than mere presence should be considered to be an indicator of human impact (Behre, 1981). However, interpretation must take into consideration that some synanthropic taxa are spontaneous and cosmopolite, while others are strictly related to agricultural practises or pastoral practices and commonly occur in ruderal, pasture, uncultivated, or meadow areas even in modern environments (Martini et al., 2023). APIs and the PDI are widely applied to detect anthropogenic impacts and natural climatic variabilities; however, a region-specific approach should be used to avoid misinterpretations (Deza-Araujo et al., 2020). For this reason, the lagoon disturbance index (LDI) was developed for this study by adapting those indices and selecting common anthropogenic indicators appropriate for lagoonal pollen records. Several taxa commonly used in anthropogenic assessments (e.g. *Centaurea nigra*, Apiaceae, Cichorieae, *Cirsium*-type, *Plantago* undifferentiated) were excluded from the LDI because they can be native to lagoon marginal settings, and their abundances may be influenced by non-anthropogenic factors such as flooding and relative sea level (RSL) changes and were cautiously grouped as PSIs (potential synanthropic indicators). Taxa assignment was conducted based on ecological preferences documented in floristic lists for northern Italy (Pellegrini et al., 2019; Martini et al., 2023; Acta Plantarum, 2026). Indexes were calculated by summing pollen counts for each taxon and converting them into percentages based on the Pollensum.

3.4 Pollen zonation and diagram construction

The collected data were processed through "Tilia" software v. 3.0.3 (Grimm 1992) for the calculation of relative abundances and concentrations and the plotting of pollen diagrams. Local pollen assemblage zones (LPAZ) within VLG3 and VLG4 were established using stratigraphically constrained cluster analysis, specifically the CONISS (constrained incremental sum of squares) method implemented in the "Tilia" software (Grimm, 1992), based on all of the available pollen grains and spores, excluding NPPs. In VLG4, *Alnus* has also been excluded from the calculation because of its extreme dominance in one sample. A local zonation was adopted to capture ecological changes specific to the Val Grande basin. Wetland and lagoonal taxa were therefore included in the calculation as they sensitively track hydrological and geomorphological shifts, whereas NPPs were excluded because the aim of the zonation is to reconstruct vegetation changes. A square-root transformation was applied, and the dendrogram was scaled to the total sum of squares.

3.5 The land usability probability (LUP) index

To quantify the intensity of human impact, the index of agricultural land usability probability (LUP; Deza-Araujo et al., 2022) was applied to the VLG4 pollen assemblage. The index emphasises the co-occurrence of cultural indicator taxa and weights them according to their anthropogenic indicator value (AIV) within the submediterranean vegetation belt, which best reflects the environmental setting of Val Grande. LUP values were calculated by multiplying the relative abundance of selected taxa (Cerealia, *Castanea*, *Juglans*, *Olea, Plantago lanceolata*, *Urtica dioica*-type) by their AIV and summing the results for each sample. Although the LUP index provides a useful synthetic measure of the co-occurrence of cultural indicator taxa, it does not represent an absolute quantification of land use. As with any pollen-based metric, LUP values are affected by pollen source area, differen-

tial productivity, dispersal properties, and local taphonomic conditions. Therefore, the index was interpreted as a relative indicator of changes in human impact through time, and its trends were assessed in combination with independent proxies (LDI, PSI, PAR) to avoid over-interpretation. LUP values are interpreted here as relative to the range observed within the record: the highest values mark the phases of relatively strongest anthropogenic signal, and the other phases are treated in relation to that.

3.6 Radiocarbon dating, age–depth chronology, and PAR

Radiocarbon dating was performed on botanical macrofossils on three samples of core VLG4, one of core VLG3, and one of core VLG2 to establish chronological control for the pollen sequences and to frame the geomorphological evolution of the area. All samples were submitted to the ETH laboratory in Zurich for accelerator mass spectrometry (AMS) dating, and ages were calibrated using the IntCal20 curve (Reimer et al., 2020). Calibrated age–depth models for VLG4 and VLG3 were produced with the P_Sequence function in OxCal v4.4.4 (see the Supplement for details; Bronk Ramsey, 2021). The models were constrained by the available radiocarbon dates and by brick fragments at 946 cm depth in VLG4 and at 324 cm in VLG3, which provide a maximum age. In fact, such bricks cannot predate the first occupation phase of the nearby Mutteron dei Frati villa (second half of the first century BCE); however, we cannot exclude the fact that the fragments arrived in the sequences in some later phases, following the erosion of the original structures to which they belonged. They were therefore considered to be one-sided constraints, with a uniform prior starting at 50 BCE and no younger limit other than that imposed by the stratigraphic order of the sequence. The sample collected at 1095 cm of depth in VLG4 was found at the base of the lagoon channel passed by the core, and it was radiocarbon dated to 5315–5132 years BCE. It was interpreted as material of the lower and older unit, likely reworked by the erosive action of the channel, and so it was excluded from the model. Pollen accumulation rates (PARs; grains cm^{-2} yr^{-1}) were also calculated for VLG4 by multiplying pollen concentration values by sedimentation rates derived from the age–depth model, following standard procedures described in Davis and Deevey (1964). *Alnus* was excluded from the PAR calculation because of its outlier value in one sample at 365 cm depth.

4 Results

4.1 Stratigraphic description of cores

The sedimentological characteristics of cores VLG3 and VLG4 provide the stratigraphic framework for interpreting the palynological and paleontological records (Fig. 4). The three cores consist mainly of finely laminated clayey–silty to sandy–silty deposits with thin layers of fine sands, scattered plant remains, and lagoonal molluscs (e.g. *Bittium* sp., *Nassarius* sp., *Cerastoderma glaucum*), representing facies typical of protected lagoonal settings. VLG3 includes two peat layers beneath the superficial anthropogenic deposit and terminates at 4 m, where underlying sands could not be recovered with the gauge of the coring equipment. VLG4 sampled a tidal-channel sequence of almost 11 m in thickness, ending where a much tougher unit was encountered, consisting of older lagoon deposits radiocarbon dated to the sixth millennium BCE. Fragments of archaeological material within the sequences demonstrate ancient anthropogenic activity: in VLG4 mortar/plaster at 670 cm depth and $\sim 2 \times 2$ cm brick fragment at 946 cm depth; in VLG3, millimetric brick fragment was found at 324 cm. In both cores, the fine and almost-continuous lamination characterizing the deposits ensures that the original stratification of the layers has been preserved and was not affected by post-depositional reworking, allowing us to consider the sequence as a valuable environmental archive. BEV1A reached a total depth of 260 cm and presents superficial organic-rich sediments overlying the sands corresponding to the northernmost coastal ridge of the early Medieval delta of Tagliamento (Fig. 2). Palynological analysis was restricted to the upper 35 cm of sediments that accumulated in modern times.

4.2 Chronology

The chronological framework of the studied sequences in the Val Grande area is constrained by the radiocarbon ages listed in Table 1. The Bayesian age–depth models constructed for VLG4 and VLG3 indicate variable accumulation rates through the sequences (see the Supplement for details; Figs. S1 and S2, Tables S7 and S8). VLG4 yields an average temporal resolution of approximately 111 years per pollen sample when considering the entire interval between 120 and 1095 cm; however, restricting the calculation to the portion of the core that is effectively constrained by independent chronological information (between 270 and 1095 cm) results in a higher effective temporal resolution of approximately 87 years per pollen sample. The very high sediment accumulation rate of the sequence, consistent with the laminated infill of the lagoonal paleochannel, ensures that even a rather limited number of samples (16 across 10 m) provides a high-resolution record. VLG3 yields an average temporal resolution of 112 years per pollen sample. The age uncertainty of individual samples varies across the sequence and allows us to resolve the Roman-period changes at a centennial scale, whereas, in the Early Medieval period, the ages of single samples are less constrained (Table S7).

Table 1. Radiocarbon dates from the Val Grande area.

Core	Lab name	Depth (cm)	Material	Absolute age (yrs BP)	Calibrated age (1σ), year	Calibrated age (2σ), year
VLG4	ETH-154652	232	Wood fragment	1075 ± 17	902–1017 CE	896–1022 CE
VLG4	ETH-150152	518	Wood fragment	1890 ± 22	125–203 CE	81–220 CE
VLG4	ETH-150153	1095	Wood fragment	6268 ± 25	5301–5215 BCE	5315–5132 BCE
VLG3	ETH-150151	163	Wood fragment	1495 ± 22	565–600 CE	545–639 CE
VLG2	ETH-150150	522	Wood fragment	2034 ± 22	49 BCE–9 CE	100 BCE–60 CE

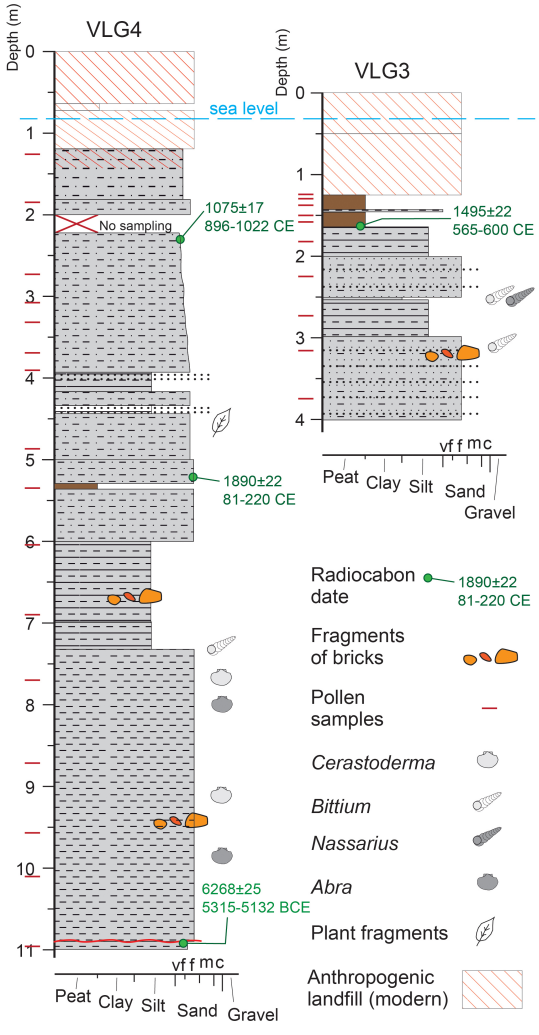

Figure 4. Stratigraphic logs of the cores VLG3 and VLG4.

4.3 Pollen diagram description

4.3.1 CORE VLG4: pollen concentration, most common taxa, and zones

Average pollen concentrations of 14 400 grains cm^{-3} confirm the good preservation conditions of the samples, with the maximum at 365 cm (131 900 grains cm^{-3}) and the minimum at 690 cm (2300 grains cm^{-3}). The floristic list of the site includes 83 taxa, with 30 belonging to arboreal plants (APs), 41 belonging to non-arboreal plants (NAPs), 6 belonging to aquatic plants, and 6 belonging to spore-producing plants, due to both natural and anthropogenic elements. The mean % AP (arboreal pollen), representing the mean forest cover in the site, is 69 % (calculated excluding the sample at 365 cm, whose extreme *Alnus* dominance (97 %) makes it statistically incomparable to the remaining assemblages), ranging from a minimum of 17 % at 335 cm to a maximum of 83 % at 955 cm. The average relative abundance of all pollen groups is reported in Table 2, the LUP values are reported in Table 3, and the pollen diagram is shown in Fig. 5A.

4.3.2 Zone 1 (six samples, 1095-650 cm, ~330 BCE to ~130 CE)

Corylus is the dominant tree taxon, increasing from 15 % to 22 %, followed by *Alnus* (avg. 14 %) and deciduous *Quercus* (13 %); *Pinus* is the main bisaccate pollen (7 %). The Poaceae – wild grass group lead the herbaceous component (11 %, peak 16 % at 865 cm). PSI taxa are low, with Cichorieae around 3 %. Cereal pollen is continuously represented by *Hordeum*-type (0.4 %). LDI taxa are rare, limited to sporadic *Polycarpon tetraphyllum* and *Urtica dioica*-type. Samples at 865 and 1010 cm show co-occurring Amaranthaceae, *Artemisia*, *Armeria maritima*-type A, and *Limonium vulgare*-type A. Cyperaceae dominate the wetland group (6 %), with minor *Sparganium*-type, *Ruppia maritima*, and *Potamogeton/Triglochin*. Among spores, *Dryopteris*-type (5 %) and *Pteridium aquilinum* (4 %) prevail. NPPs include continuous *Pseudoschizaea*; frequent foraminiferal linings; and dinoflagellate cysts, with occasional *Campylodiscus*, *Tryblionella* cf. *compressa* diatoms, and *Cymatiosphaera* in the upper samples. LUP values remain low (mean 5.5), with modest rises at 955 and 865 cm (7.5 and 9.0).

4.3.3 Subzone 2a (five samples, 649–350 cm, ~130 to ~660 CE)

Relative to zone 1, subzone 2a shows a marked rise in *Alnus*, which becomes the dominant arboreal taxon (15 %–23 %). Deciduous *Quercus* remains stable at 17% average, while *Corylus* drops at the base but then increases upward. *Fagus* becomes more relevant, peaking at 540 cm (11 %), and *Pinus* declines to 4 %. The OJC group increases and reaches 2 %,

Table 2. Average abundance of pollen groups for each zone in VLG4 core.

Zone	Subzone	No. of samples	Depth (cm)	AP		NAP		Notes
				Group name	%	Group name	%	
2	2b	5	120–349	Conifers	9	Wild herbs	37	– Quercetum dominant AP, decrease
				Montane	4	PSI	5	– Conifers increase, significant
				Quercetum	22	LDI	0.5	– Hygrophytes decrease
				Mediterran.	2	Cereals	0.5	– Wild herbs dominant NAP, increase
				OJC	2	Halophytes	7	– Cereals and LDI low
				Hygrophytes	9	Wetlands	15	– Halophytes and wetlands peak
				Shrubs and li.	1	Spores	5	
	2a	5	350–649	Conifers	7	Wild herbs	19	– Conifers and Quercetum decrease
				Montane	6	PSI	5	– Hygrophytes, Mediterranean, and OJC increase
				Quercetum	33	LDI	2	– Wild herbs increase
				Mediterran.	3	Cereals	2	– Cereals and LDI peak
				OJC	2	Halophytes	2	– Wetlands increase
				Hygrophytes	20	Wetlands	14	
				Shrubs and li.	0.8	Spores	6	
1	/	6	650–1095	Conifers	17	Wild herbs	15	– Quercetum dominant AP
				Montane	7	PSI	4	– Conifers significant
				Quercetum	37	LDI	0.2	– Hygrophytes consistent
				Mediterran.	2	Cereals	0.4	– Wild herbs dominant NAP
				OJC	0.3	Halophytes	3	– Wetlands well present
				Hygrophytes	15	Wetlands	7	– Cereals and LDI low
				Shrubs and li.	0.9	Spores	9	
Average Pollensum (excluding sample at 365 cm)								348
Average Supersum (excluding sample at 365 cm)								424

Table 3. LUP index values for VLG4 core. Data plot available in Fig. S8.

Depth (cm)	120	180	270	305	335	365	390	480	540	605	690	770	865	955	1010	1095
LUP_Cerealia	0.0	6.0	6.0	7.0	4.0	0.0	30.0	9.0	3.0	19.0	3.0	3.0	6.0	3.0	3.0	6.0
LUP_Castanea	0.2	0.2	0.2	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
LUP_Juglans	2.3	0.0	4.0	4.0	2.3	0.3	3.3	2.5	1.5	3.3	1.8	0.0	0.0	1.5	0.0	0.0
LUP_Olea	6.0	0.0	0.0	3.0	1.0	1.0	7.0	3.0	3.0	3.0	0.0	0.0	3.0	0.0	0.0	0.0
LUP_Plantago_lanceolata	3.0	0.0	3.0	3.0	2.0	0.0	0.0	10.0	3.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0
LUP_Urtica	0.0	6.0	0.0	0.0	1.0	0.0	0.0	3.0	3.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0
LUP_TOT	11.4	12.2	13.2	17.1	10.3	1.3	40.3	27.6	13.7	31.3	4.8	3.0	9.0	7.5	3.0	6.0

with the first appearance of *Castanea*. Herbaceous taxa remain dominated by the Poaceae – wild grass group (14 %), while disturbance indicators intensify: both PSI and LDI show two clear peaks (605 and 480 cm), and the LDIs record the highest diversity of the entire sequence. Cereal pollen increases markedly: *Hordeum*-type reaches its maximum (2 % at 390 cm), and *Avena/Triticum*-type appears, peaking at 1 % at 390 cm. Wetland taxa also intensify, with Cyperaceae rising to 13 %. NPPs include *Trichuris trichiura* cf. *Capillaria* in the upper sample, and Urediniospores, Gelasinospores, and Zygnemataceae in the central part. Dinoflagellate cysts, diatoms (*Campylodiscus*, possibly *Cyclostephanos*), and *Cymatiosphaera* remain represented, except in the top sample; foraminiferal linings occur only at 480 cm. LUP averages 28.2, with peaks at 605 cm (31.2) and 390 cm (40.3).

The uppermost sample of the zone is an outlier dominated by *Alnus*, including clustered pollen that indicates high locally elevated deposition; other tree taxa are represented marginally, overshadowed by the dominant taxon. Therefore, mean values for the zone were calculated using only the lower four samples. LUP drops to 1.25 in this sample.

4.3.4 Subzone 2b (five samples, 349–120 cm, ~660 to ~1440 CE)

The zone marks a clear shift toward higher herbaceous taxa. The lower part is dominated by the Poaceae – wild grass group (peak 76 %) with relative clusters, while arboreal taxa remain low: deciduous *Quercus* – 4 %; *Alnus* – 4 %; and *Pinus* – 0.9 %. Arboreal components recover upward, with *Pinus* showing a steady increase; *Quercus* deciduous and *Alnus* briefly rise after the Poaceae peak and then decline, while *Fagus* remains stable. *Quercus ilex*-type peaks at 3 % at the top. "Poaceae – wild grasses" show strong oscillations,

and cereals decrease markedly compared to in subzone 2a: *Hordeum*-type occurs mid-zone, and *Avena/Triticum*-type only occurs in the upper sample. LDI indicators are poorly represented (0.5 %). Halophytes intensify toward the top as *Artemisia* increases, Amaranthaceae become a major component, and *Limonium vulgare*-type A and B and *Armeria maritima* co-occur. Wetland taxa remain well represented, with Cyperaceae fluctuating strongly and peaking mid-zone, followed by *Potamogeton/Triglochin* and *Sparganium*-type. Among NPPs, *Pseudoschizaea* is recorded continuously, and *Trichuris* and *Sordaria* appear in the lower sample. Dinoflagellate cysts remain common, while foraminiferal linings peak toward the top, together with *Spirogyra* and *Tryblionella* cf. *compressa*. LUP values average 11.8, peaking at 305 cm (17.1) and then declining steadily toward the top.

4.3.5 PARs (pollen accumulation rates) VLG4

PARs in VLG4 show an overall stable background, with the Pollensum averaging 4000 grains cm^{-2} yr^{-1} (excluding *Alnus* because of a sharp peak at 365 cm depth), reaching its minimum at 180 cm (1713 grains cm^{-2} yr^{-1}). PAR_AP broadly mirrors this pattern, with higher values in the lower part of the core and a progressive decline toward the top, whereas PAR_NAP shows the opposite trend, peaking at the base of the upper zone (8184 grains cm^{-2} yr^{-1}).

Among arboreal taxa, *Pinus* displays high PAR values in the lower zone, a marked reduction in the middle section, and a renewed increase in the uppermost samples, culminating in a maximum of 697 grains cm^{-2} yr^{-1}. *Fagus* follows a similar structure, with elevated PAR in the lower zone, a short-lived peak in the middle section, and a moderate increase at the top. Deciduous *Quercus* records oscillating PAR values throughout, with higher overall values in the lower zone. *Corylus* also shows high PAR values in the lower zone and then declines significantly in the rest of the core. *Olea* and *Juglans* are sporadic in the lower zone but become more consistently represented in the middle part of the core, where *Castanea* also appears; *Juglans* reaches its maximum at 335 cm (77 grains cm^{-2} yr^{-1}). Herbaceous taxa show distinct signals. *Hordeum*-type records two marked peaks in the middle zone, coinciding with the first appearance and subsequent maxima of *Plantago lanceolata* and *Avena/Triticum*-type. Both the LDI and Cerealia groups display their highest PAR values in this interval, indicating increased disturbance and agricultural activity. Halophytes, in contrast, show discontinuous and low values in the middle zone but rise sharply in the uppermost samples, peaking at 721 grains cm^{-2} yr^{-1}. Wetland taxa fluctuate considerably, with a minimum at 690 cm (220 grains cm^{-2} yr^{-1}) and a maximum in the top sample (785 grains cm^{-2} yr^{-1}).

4.3.6 Core VLG3: pollen concentration, most common taxa, and zones

The pollen concentration is 29 100 grains cm^{-3} on average, with the maximum at 157 cm (95 000 grains cm^{-3}) and the minimum at 180 cm (5100 grains cm^{-3}). The floristic list of the site includes 86 taxa, with 31 belonging to arboreal plants, 41 belonging to non-arboreal plants, 7 belonging to aquatic plants, and 7 belonging to spore-producing plants. The % AP is 61 %, ranging from a minimum of 34.1 % at 135 cm to a maximum of 74 % at 225 cm. The average relative abundance of pollen groups for each zone is reported in Table 4, and the pollen diagram is shown in Fig. 5B.

4.3.7 Zone 1 (five samples, 375–170 cm, ∼ 240 BCE to 570 CE)

The zone shows a stable arboreal assemblage, dominated by *Alnus* (19 %), becoming increasingly relevant, followed by stable *Quercus* deciduous (15 %) and *Fagus* (5 %), rising *Corylus* (8 %), and oscillating *Carpinus betulus* (2 %). *Pinus* shows a gradual decline. *Juglans* is the most consistent taxon within the OJC group, peaking at 320 cm (6 %) and then declining. *Castanea* also peaks at 320 cm, and *Olea* peaks at 275 cm. Herbaceous taxa remain dominated by the Poaceae – wild grass group (13 %); Cichorieae are the leading PSI taxon (4 %); and LDI taxa remain scarce, with *Plantago lanceolata* occurring sporadically. Several herbaceous taxa appear for the first time in the upper part. Cereal pollen was poorly recorded: *Hordeum*-type is present almost continuously at low abundances (0.5 %), while *Avena/Triticum*-type is restricted to the lower sample. Halophytes are consistently represented, with continuous *Artemisia* and Amaranthaceae, and *Limonium vulgare*-type A and B and *Armeria maritima*-type A appear discontinuously. Wetland taxa are dominated by Cyperaceae, peaking in the uppermost sample (20 %), together with *Potamogeton/Triglochin* and *Ruppia maritima*. Spore-producing plants are dominated by *Dryopteris*-type, peaking at 320 cm (9 %), and *Pteridium aquilinum*, peaking at 275 cm (8 %). Among NPPs, foraminiferal linings and *Pseudoschizaea* occur almost continuously, dinoflagellates and *Campylodiscus* are present at the base and top of the zone, and *Spirogyra* appears in the upper sample.

4.3.8 Zone 2 (five samples, 169–125 cm, ∼ 570 to ∼ 880 CE)

Compared to zone 1, arboreal taxa show an overall decline and stronger fluctuations. *Quercus* deciduous, *Corylus*, and *Fagus* peak in the lower part and drop sharply at 135 cm, before partially recovering upward. *Pinus* reaches its maximum abundance at 135 cm (7 %). *Alnus* decreases markedly from zone 1, averaging 8.4 %. Mediterranean taxa remain sporadic, though the upper sample records the highest value for *Quercus ilex*-type and co-occurrence with other taxa of the group. Herbaceous taxa increase significantly, averaging

Table 4. Average abundance of pollen groups for each zone in VLG3 core.

Zone	Subzone	No. of samples	Depth (cm)	AP		NAP		Notes
				Group name	%	Group name	%	
2	–	5	125–169	Conifers	8	Wild herbs	36	– Quercetum and hygrophytes decrease
				Montane	7	PSI	2	– Conifers and montane increase
				Quercetum	24	LDI	1	– OJC and Mediterranean decrease
				Mediterran.	3	Cereals	1	– Wild herbs increase
				OJC	1	Halophytes	7	– Halophytes increase, significant
				Hygrophytes	9	Wetlands	7	– Wetlands decrease
				Shrubs and li.	1	Spores	3	– Cereals increase
1	–	5	170–375	Conifers	7	Wild herbs	19	– Quercetum dominant AP
				Montane	7	PSI	6	– Hygrophytes significant
				Quercetum	29	LDI	0.8	– OJC peak
				Mediterran.	3	Cereals	0.5	– Wild herbs dominant NAP
				OJC	3	Halophytes	4	– Halophytes and wetlands well represented
				Hygrophytes	19	Wetlands	12	– Cereals and LDI low
				Shrubs and li.	1	Spores	10	
Average Pollensum				332				
Average Supersum				396				

47 %, dominated by the Poaceae – wild grass group, which peaks at the bases of both peat layers. Other herbs remain scarce in the lower part, while Asteroideae increase upward. The PSI group decreases overall but peaks in the upper sample (4 %), and LDI indicators oscillate, reaching 3 % at the top. Cereal signal increases: *Hordeum*-type peaks in the upper sample, while *Avena/Triticum*-type occurs sporadically. Halophytes reach their highest values in this zone (7 %), with two expansion phases: the first is marked by high Amaranthaceae and co-occurrence of *Limonium vulgare*-type A and, B and the second is more pronounced, showing Amaranthaceae maxima, *Limonium vulgare*-type A and B, and *Armeria maritima*-type A and B. The upper sample shows reduced halophytes but includes *Plantago maritima*. Wetland taxa decrease markedly (7 %) and are dominated by Cyperaceae. Spore-producing plants also decline (3 %), mainly represented by *Dryopteris*-type. Among NPPs, foraminiferal linings and *Campylodiscus* occur in all peat samples but are absent in the silty-loam one, while *Diploneis* shows the opposite trend. Other NPPs include Zygnemataceae, *Cyclostephanos*, dinoflagellate cysts (upper sample), *Mougeotia* HdV-134, *Spirogyra*, and *Botryococcus* (upper two samples).

4.3.9 Core BEV1A pollen concentration, most common taxa, and zones

The pollen concentration is 7500 grains cm^{-3} on average, with the maximum at 15 cm (12 600 grains cm^{-3}) and the minimum at 35 cm (3700 grains cm^{-3}). The floristic list of the site includes 73 taxa, with 26 belonging to arboreal plants, 36 belonging to non-arboreal plants, 6 belonging to aquatic plants, and 4 belonging to spore-producing plants. The mean % AP is 65.6 %, ranging from a minimum of 58 % at 5 cm to a maximum of 76.9 % at 35 cm. The average Pollensum for the analysed samples is 310, and the average Supersum is 446. The average relative abundance of all pollen groups for the BEV1A core is reported in Table 5, and the pollen diagram is shown in Fig. 5C.

4.3.10 BEV1A (four samples, 35–5 cm)

The most abundant tree taxon is *Pinus* (28 %), dominating the lower part of the zone and declining upward, while deciduous *Quercus* (16 %) records a moderate increase. *Quercus ilex*-type peaks in the top sample (3 %). Other arboreal taxa, including *Fagus, Juglans,* and Ericaceae are present at low but stable values. Herbaceous taxa are dominated by the Poaceae – wild grass group, which increases toward the top, accompanied by PSI and LDI indicators: Cichorieae peak in the second sample, while *Plantago lanceolata* peaks in the top one. Cereal pollen (2 %) is consistently recorded in the core with *Hordeum*-type grains, while *Avena/Triticum*-type peaks at the top sample (3 %); *Zea mays* appears in the top sample as well, marking its unique recording among the three cores. Halophytes are present in all samples, with *Artemisia*, Amaranthaceae, and *Limonium vulgare*-type B occurring almost continuously and *Armeria maritima*-type A/B and *Plantago maritima* occurring just sporadically. Wetland taxa are well represented and dominated by Cyperaceae (23 %), which shows strong fluctuations; *Ruppia maritima* peaks in the top sample (3 %). Spore-producing plants are mainly represented by *Dryopteris*-type and *Pteridium aquilinum*, both decreasing upward. Among NPPs, *Glomus* and foraminiferal linings occur continuously, while dinoflagellate cysts, *Diploneis* sp. and *Campilodiscus* sp., *Spirogyra*, and *Tecaphora* occur sporadically. *Botrycoccus* follows a decreasing trend.

Table 5. Average abundance of pollen groups for each zone in BEV1A core.

Zone	Subzone	No. of samples	Depth (cm)	AP		NAP		Notes
				Group name	%	Group name	%	
1	–	4	5–35	Conifers	33	Wild herbs	21	– Conifers dominant AP
				Montane	5	PSI	4	– Quercetum significant
				Quercetum	19	LDI	4	– OJC consistent
				Mediterran.	3	Cereals	2	– Hygrophytes poorly represented
				OJC	2	Halophytes	3	– Wetlands and Wild herbs significant
				Hygrophytes	1	Wetlands	25	– PSI, LDI, and cereals consistent
				Shrubs and li.	2	Spores	4	
Average Pollensum				310				
Average Supersum				446				

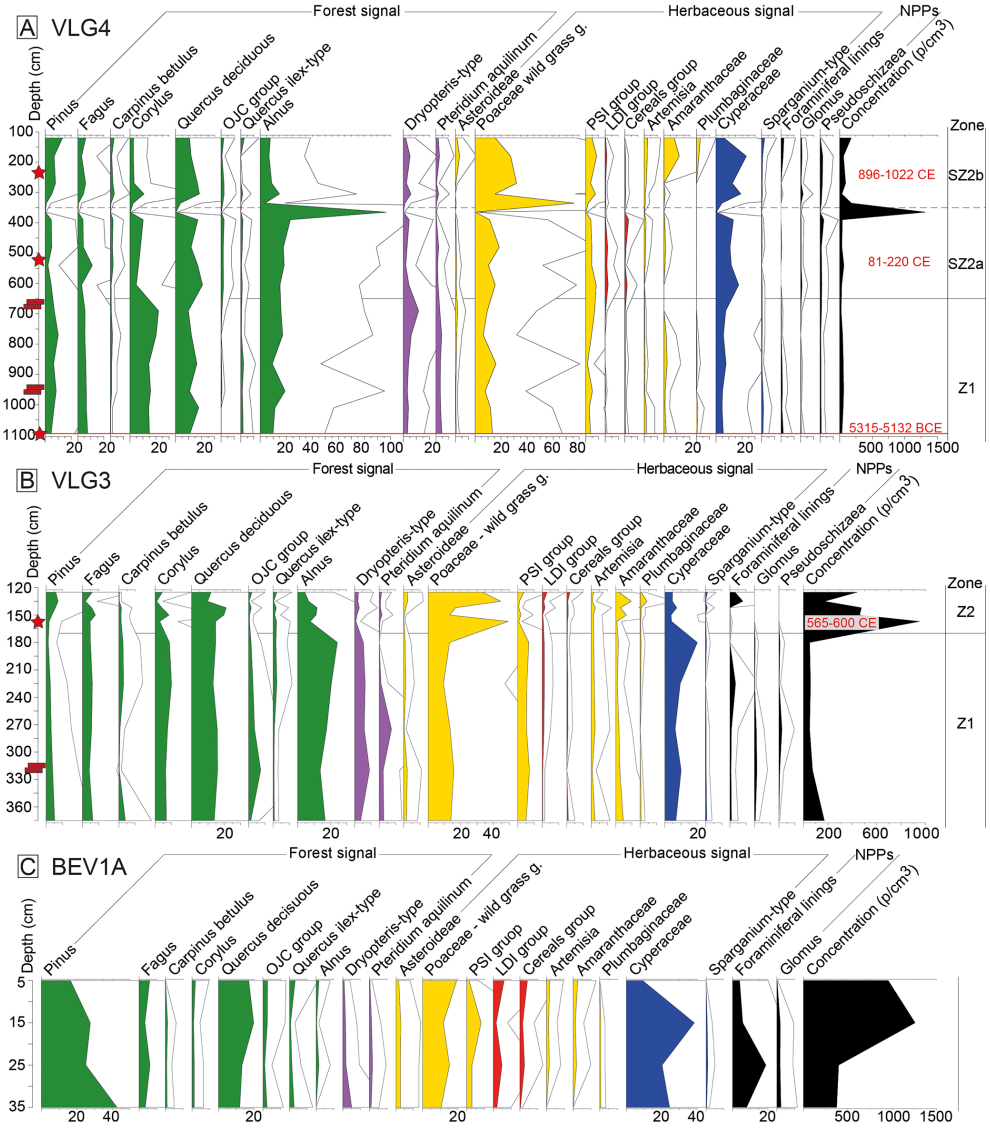

Figure 5. Pollen diagrams with selected taxa: **(A)** VLG4 core; **(B)** VLG3 core; **(C)** BEV1A core. Red stars indicate depths relative to radiocarbon dates, while red bricks indicate the presence of anthropogenic material within the sequences; the red line at the base of the VLG4 diagram represents an erosional surface. The detailed diagrams for each core are present in the Supplement (Figs. S3 and S4).

5 Discussion

5.1 Depositional settings of VLG4 and VLG3 and their implications for the pollen records

The sediment cores VLG3 and VLG4 from Val Grande present complementary information on lagoonal dynamics surrounding the Roman villa of Mutteron dei Frati. Although formed within the same lagoonal system, they sampled different depositional environments, which affect pollen source area, transport, and preservation and must be kept in mind whenever their signals are compared. VLG4 was cored from a tidal channel that reached almost 10 m in depth during its active phase, reflecting a higher-energy system capable of accommodating rapid sediment infill, likely driven by channel lateral migration. The core lies only 110 m from the villa, within the sector most likely connected to the area where the harbour facilities serving the settlement were present: the channel would have allowed vessels to approach the settlement safely, providing a sheltered but navigable route between the open sea and the lagoon interior, as documented by some relicts found in NW Adriatic (see Beltrame, 2001; Beltrame et al., 2019; Capulli, 2020). Brick fragments and mortar remains in the core further support the idea of nearby landing structures. In contrast, VLG3 was cored from a shallower tidal-flat environment 230 m north of the villa, representing a lower-energy environment, more sensitive to local hydrological changes. Thus, VLG3 more strongly records the development of the marsh and internal lagoon processes, as well as a weakly expressed anthropogenic signal. Because the distance from the villa and the depositional setting covary in this pair of cores, their respective effects on the pollen signal cannot be separated within the present data. Nevertheless, this dual perspective is essential for disentangling natural lagoon variability from human activity.

5.2 The lagoon before and during the Roman occupation of the villa

Both VLG4 and VLG3 pollen sequences highlight the environmental imprint of Roman activities around the Mutteron dei Frati villa, although with different intensities and resolutions (Fig. 6).

In VLG4 zone 1 (∼330 BCE to ∼130 CE; Table 2; Fig. 5A), the pollen assemblage documents a largely natural, stable lagoonal saltmarsh fringed by riparian and deciduous woodland. Conifer pollen input probably reflects extra-local sources rather than local pine forests, likely through direct input from the *Tiliaventum Minus* river into the sedimentary basin. Emergent hydrophytes (Cyperaceae, probably *Carex* sp.) and a pronounced hygrophilous tree component point to a well-developed marsh margin and shallow vegetated lagoonal habitats under fresh to brackish conditions (Miola et al., 2006), whereas diverse halophytes at two stratigraphic levels mark well-developed saltmarsh phases (Miola et al., 2010; Heim, 1975) – probably correlated to events of increased salinity and direct marine connectivity – that decreased toward the top of the zone. Foraminiferal linings, diatoms, and *Cymatiosphaera* point to brackish conditions with marine influence (Medeanic, 2006; Shumilovskikh et al., 2021), while *Pseudoschizaea* and *Glomus* suggest shallow, periodically exposed wet surfaces (Traverse, 1994) and phases of soil disturbance and erosion (van Geel, 2003), consistently with fluctuating near-surface hydrology.

In VLG4 subzone 2a (∼130 CE to ∼660 CE; Table 2; Fig. 5A), the arboreal composition shows a shift toward *Alnus*-dominated wet woodlands while bisaccate taxa decline, indicating a reduced regional conifer influence or greater local signal strength from the wetland fringe. Rising hygrophytes and Cyperaceae point to the expansion of marsh and reed bed communities at the lagoon edge (Badino et al., 2026), with sporadic aquatic taxa. The consistent presence of *Pseudoschizaea* and Zygnemataceae, the nearly absent foraminiferal linings, and the absence of *Armeria* and *Limonium* suggest predominantly freshwater conditions at the VLG4 site, without sustained saline waters able to support saltmarsh development.

In VLG3 zone 1 (∼240 BCE to 570 CE; Table 4; Fig. 5B), the assemblage reflects a marsh margin surrounded by riparian and deciduous woodland, with gradually increasing *Alnus* indicating expanding alder stands along wet lowlands. As in VLG4, wetland indicators document an extensive and dynamic marsh system: Cyperaceae, *Sparganium*, *Ruppia*, and *Potamogeton* document vast extents of reed beds and shallow vegetated water (Badino et al., 2026), while continuous and diverse halophytes indicate local saltmarsh influenced by tidal exchange (Miola et al., 2010; Heim, 1975). NPPs confirm persistent brackish conditions and periodically exposed wet surfaces (Medeanic, 2006; Shumilovskikh et al., 2021).

The contrasting brackish conditions recorded in VLG3 and freshwater conditions in VLG4 during the Roman period suggest that VLG3 probably maintained a more open, naturally brackish connection, being relatively close to the mouth of the tidal inlet (Fig. 2), whereas VLG4 appears to have been hydrologically less connected, possibly because of its inner position along the lagoon border and the progressive migration of the tidal channel away from the coring site.

5.3 Evidence of human influence during the Roman period

Anthropogenic indicators in VLG4 zone 1 are weak (Figs. 5A and 6). Nevertheless, several features point to the early construction phases of the villa: brick and mortar fragments within the sequence, likely corresponding to fragments of the pier structures alongside the banks of the channel, produced during their construction or eroded slightly later; a high abundance of *Pteridium aquilinum*, a taxon often associated with soil disturbance (Kouli 2015); and sporadic appearances of *Juglans* and *Olea* in the pollen sequence, al-

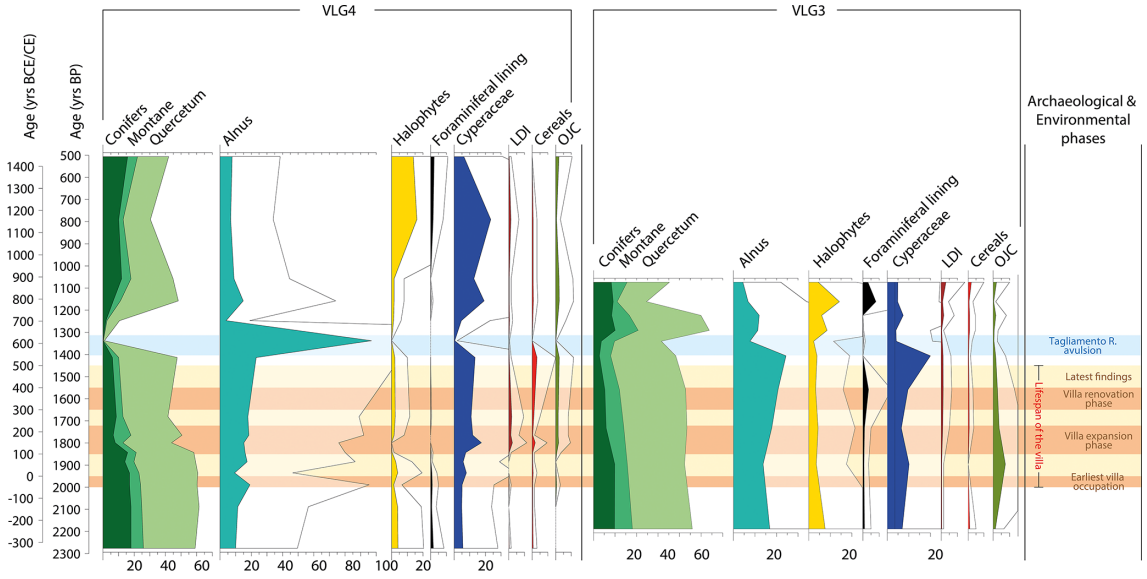

Figure 6. Comparison between VLG4 and VLG3 pollen sequences within a common chronological framework. Archaeological phases are highlighted in yellow and red colours, while the Early Medieval Tagliamento River avulsion is highlighted in blue.

though these are most probably related to background pollen from regionally cultivated trees rather than local planting. Cultivation appears to be minimal to absent at this stage as cereal pollen grains appear continuously but at low abundances and only as *Hordeum*-type, which includes diverse wild taxa, as well as cultivated ones (Mercuri et al., 2013a), in agreement with the low LUP values (Table 3; Fig. S8).

Subzone 2a (∼ 130 CE to ∼ 660 CE) provides the clearest expression of human activity in a period including the phases when the villa was fully established and functioning (Fig. 6). Archaeological data from the excavation of the residential buildings within the villa complex indicate that substantial construction work took place between the second half of the second century and the early third century CE, possibly including an extension of the original complex. Architectural evidence and small finds suggest that the site was in active use throughout the fourth century CE (Steuernagel et al., 2026; Pandolfo, 2026). In the same interval, LDI and PSI groups show two distinct peaks (605 cm, ∼ 150 CE; 480–390 cm, ∼ 270–540 CE). The LUP index and PAR values show the same two pronounced peaks (Table 3; Figs. S6 and S9), providing a complementary representation of the pollen count from which they are derived. The highest cereal presence in the core, marked by the first appearance of *Avena/Triticum*, strongly implies local cultivation (see Mercuri et al., 2013a), especially since cereals are autogamous plants (excluding rye) and their pollen signal is generally weak even close to fields (Behre, 1981; Bower, 1992; Fyfe, 2006). Other indicators co-occur with these peaks: LDI and PSI diversity peaks, the detection of a human parasite (*Trichuris trichiura* cf. *Capillaria*, Florenzano et al., 2012; Dal Corso, 2018) outside of the archaeological setting, and a peak in *Glomus* (see van Geel, 2003) in the lower sample; all of this is consistent with the establishment of local human settlements and soil disturbance and erosion. Moreover, *Castanea* appears at the base of the zone, and *Juglans* and *Olea* become continuous, marking a clear shift from the previous zone and suggesting human management (see Mercuri et al., 2013b). *Corylus* shows a pronounced decline, also marked in the PAR diagram, possibly related to management practices during the Roman occupation.

Taken all together, the interpretation is most robust where cereal pollen, cultivated-tree taxa, disturbance-related NPPs, synanthropic herbaceous taxa, and archaeological material coincide, as in this subzone (Fig. 6). Elsewhere in the record, we refer to possible human disturbance rather than to agricultural activity.

VLG3 records a weaker signal during the same period. Cereal pollen is poorly represented (*Hordeum*-type, almost continuous at low values; *Avena/Triticum*-type, only in the lowest sample of zone 1), and *Plantago lanceolata* occurs only sporadically, suggesting low-intensity disturbance. The brick fragment at 324 cm provides a terminus post quem within the Roman period, and the parallel increases in *Juglans*, *Castanea*, and later *Olea* (Table 4, Fig. 5B), typical markers of Roman cultivation (Mercuri et al., 2013b), further support this interpretation. Anthropogenic disturbance is also supported by contemporary peaks in *Glomus* and *Pteridium aquilinum*, consistently with disturbance and erosion in the catchment (van Geel, 2003; Kouli, 2015). Even during the peak of anthropogenic activity recorded in VLG4, VLG3 does not register a comparable signal (Fig. 6). This could reflect the increased distance from the villa, which limits the input of poorly dispersed pollen such as *Avena/Triticum*-

type (Behre, 1981; Fyfe, 2006; Florenzano et al., 2023) and leaves VLG3 recording mainly the broader environmental consequences of land management (e.g. higher abundances of anemophilous *Juglans*). It may equally reflect the different depositional setting of the core: a low-energy tidal flat with a different pollen source area and hydrological regime may capture local agricultural activity differently from a channel margin. The contrast between the two studied sequences, together with the consistently high AP values, also suggests that cultivation around the villa was spatially limited, likely constrained by the low agricultural potential of the coastal sandy soils and by the lack of evidence of productive structures in the excavated portion of the settlement.

Finally, considering the dimension of the villa and the clear archaeological evidence of its structural complexity, it is likely that some small-scale water management structures were present toward the lagoon (see Busana et al., 2025; Steuernagel et al., 2026). Among the possible anthropogenic features, we can return to the ones found in the Venice Lagoon and Grado-Marano Lagoon as embankments along the lagoon shore, fishing structures, or paths on dikes (see Canal, 2013; Calaon and Cottica, 2020; Beltrame et al., 2023; Gaddi et al., 2025). Overall, the two records suggest that, during the Roman phase, the lagoonal landscape remained largely natural, with human impact being concentrated around the channel margin.

5.4 Integration of the local signal with regional coeval pollen records

The pollen sequences from Val Grande constitute a significant paleoenvironmental archive for the northeastern Italian coast, standing out as one of the rare archaeobotanical case studies documenting the Roman-period landscape along this sector of the Adriatic. Anyhow, a first regional comparison is provided by the pollen record from the paleo-channel named "La Canna", located in the area of Ca' Tron, facing the NE corner of the Venice Lagoon at ∼4 km NE from *Altinum* (Miola et al., 2005; Table S9). The sequence shows an increase in *Juglans* during the Roman period, consistently with the spread of its cultivation, and indicates that the area was already occupied and farmed since the Iron Age. *Avena/Triticum* frequencies are comparable to those found in present-day field ditches of the same area, while the co-occurrence of herbaceous taxa such as Poaceae, Apiaceae, *Plantago*, and *Rumex* suggests the presence of pastures. Anthropogenic indicators rise during the Roman period at Ca' Tron, and a similar trend is recorded by the pollen signal in core VLG4 for cultivated taxa, even if it is less pronounced than at Ca' Tron. The rise in *Juglans* observed in VLG3 probably corresponds to that detected at Ca' Tron. The more isolated position of the Roman villa of Mutteron dei Frati, compared to the proximity of Ca' Tron to the major Roman centre of *Altinum*, may explain the weaker anthropogenic imprint found at Bibione. The Roman-period expansion of *Juglans* across the Italian peninsula is well documented by Mercuri et al. (2013b) and related studies.

At Lago della Costa, near Arquà Petrarca in the Euganean Hills (LPAZ APL-4; Kaltenrieder et al., 2010; Table S9), the Bronze, Iron, and Roman periods are characterized by stable values of the mixed oak forest taxa and persistent meadow and pasture indicators (e.g. *Centaurea jacea*-type, *Ranunculus acris*-type, *Plantago lanceolata*-type), reflecting the presence of open-land habitats. In addition, increases in *Castanea, Juglans, Olea, Cannabis*-type, and Cerealia-type point to phases of intensified land use within the catchment. By comparison, VLG4 shows only modest increases in cultivated and anthropogenic taxa during the Roman period (appearance of *Plantago lanceolata*, *Ranunculus acris*-type, and *Avena/Triticum*-type), and VLG3 records a clear peak in *Juglans*, indicating limited but detectable Roman-period signals within both sequences.

5.5 Early Medieval environmental reorganization of the lagoon

The most pronounced environmental change in both cores occurs in the sixth–seventh centuries CE (Figs. 5A–B and 6). In VLG3 it is expressed by the transition from silty-loam deposition to localized peat accumulation (favoured by anoxic, shallow-water conditions) at the base of zone 2 (∼ 570 to ∼ 880 CE). This is documented by a pollen assemblage dominated by wild Poaceae, signalling an open, highly productive herbaceous surface on freshly exposed alluvial substrates. This configuration is consistent with the sixth-century-CE avulsion of the Tagliamento River (Fig. 1), which flooded and buried Concordia Sagittaria and redirected freshwater into the Val Grande basin. The radiocarbon age at the base of the peat at 163 cm in VLG3 (545–639 CE) overlaps the late-sixth-century window of this event. The calibrated range includes 589 CE, the date of the dramatic flood described by Pope Gregorius Magnus and Paolo the Deacon as "*aquae diluvium*" and probably related to a severe meteo-climatic phase (Fontana et al., 2020).

A significant transition is recorded in VLG4 at the top of subzone 2a, where there is an abrupt change in the presence of a single sample strongly dominated by *Alnus*, framed at ∼ 610 CE (∼ 329–885 CE) in the age–depth model, corresponding to an interval overlapping the base of the VLG3 peat. The very large number of *Alnus* grains, including clusters, suggests either prolific local flowering and direct input from alder stands (Andersen, 1974) or a taphonomic concentration that temporarily overwhelmed the surrounding pollen rain; stable PAR_AP values calculated excluding *Alnus* support a strictly local origin of the spike. The overlap with VLG3 environmental modifications may also suggest a common hydrological trigger; however, since the age of this level is loosely constrained (Sect. 4.2), it does not represent a decisive proof.

The subsequent VLG3 succession captures rapid ecological shifts: an initial rise in halophytes, accompanied by increases in the forest signal, likely reflects enhanced regional and extra-local input into an increasingly open, wind-exposed setting. A short-lived halophyte decline follows, together with recoveries in *Alnus,* Cyperaceae, *Sparganium*, and wild Poaceae, suggesting reduced marine connectivity and a return to fresh–brackish conditions. Renewed and more pronounced halophytic expansion then marks the final development of saltmarsh and open littoral habitats, supported by the highest *Pinus* abundance in the core, *Plantago maritima*, Mediterranean coastal taxa, and declining *Alnus* (Di Rita and Magri, 2009; Miola et al., 2010). Microfossils are dominated by brackish–marine indicators (foraminifera, dinoflagellates, diatoms) with episodic freshwater inputs (Zygnemataceae, *Spirogyra, Mougeotia*; Miola et al., 2010; Medeanic, 2006; Shumilovskikh et al., 2021). The disappearance of *Pseudoschizaea* points to a more stable water supply relative to the earlier phase, while brackish–marine phases (documented by foraminiferal linings and *Campylodiscus* in the peat samples) alternate with fresher, silty sedimentation (*Diploneis*; Diatoms, 2026). This is likely related to Tagliamento river floods that supplied freshwater into the basin, potentially creating a seasonal freshwater lid, as further supported by the brief stasis of halophytes at 142 cm depth.

In VLG4, subzone 2b (∼ 660 CE to ∼ 1440 CE; Table 2; Fig. 5A) opens with a dramatic transition from the previous *Alnus*-dominated wetland to a more open, grass-dominated landscape. Wild Poaceae prevail, and herb diversity increases, while reduced hygrophylous taxa and the limited presence of wetland taxa and *Pseudoschizaea* likely indicate residual marshy patches and fluctuating water levels (Traverse, 1994; Badino et al., 2026). Upward in the subzone, a brief woodland recovery is followed by renewed openness, with increases in *Pinus* and *Fagus* suggesting stronger extra-local input and a wind-exposed environment. Halophytes are initially scarce but increase upward, marking saltmarsh expansion, corroborated by foraminiferal linings and *Artemisia* clusters; in fact, the *Artemisetum* dominates the pioneer phase of saltmarsh formation (Pignatti, 1994). Wild Poaceae and Cyperaceae decrease during the late phase, probably as a result of salinization, while bisaccate pollen rises, reflecting stronger regional input. Mediterranean elements (mainly *Quercus ilex-type*) and Ericaceae indicate the development of coastal Mediterranean vegetation under enhanced marine influence (Di Rita and Magri, 2009). The microfossil assemblage (i.e. foraminiferal linings, *Tryblionella* cf. *compressa,* sporadic *Spirogyra*) points to occasional freshwater input in overall brackish–marine conditions (Miola et al., 2010; Medeanic, 2006; Shumilovskikh et al., 2021).

Anthropogenic indicators remain generally low in both records. In VLG3, *Hordeum*-type, LDI, and PSI values peak toward the top of zone 2 (Table 4; Fig. 5B), and the discontinuous reappearance of *Avena/Triticum*-type, together with a single *Cucumis melo* grain, suggests low-intensity use of marginal land and small-scale cultivation, possibly associated with gardening and/or orchards during the late phase. In VLG4 subzone 2b (Table 2; Fig. 5A), human-associated NPPs (*Trichuris*, *Sordaria*, Florenzano et al., 2012; Dal Corso, 2018) and the reappearance of *Hordeum*-type and *Plantago lanceolata* imply continued human activities in the catchment, but cereals are recorded only sporadically, and LDI and PSI taxa occur discontinuously. LUP values show a modest rise within the subzone, remaining well below the values of subzone 2a (Table 3; Fig. S8) and then declining toward the top. This indicates, in relative terms within the core, renewed but limited human disturbance.

Despite their sedimentological differences, VLG3 and VLG4 pollen sequences display a coherent picture of Early Medieval environmental reorganization, driven primarily by the strong hydrological change and marginal human activities. Both records display the consequences of the sixth-century avulsion of Tagliamento, which triggered widespread landscape opening, expansion of herbaceous communities, and a profound reconfiguration of lagoonal hydrology. Both sequences show renewed saltmarsh development and increased marine influence, whereas human activity remains present but limited.

5.6 Pre-modern versus recent land use

Core BEV1A (Fig. 5C), collected ∼ 1.5 km away in a saltmarsh within the Val Grande basin (Fig. 2), is used as a modern analogue. BEV1A provides sub-modern land use pollen expression that helps in the interpretation of signals from VLG3 and VLG4, and, though not directly dated, its chronological framework rests on two *terminus post quem* constraints and on historical sources and cartography (Fig. 7; Casti Moreschi, 1990; Fontana et al., 2026). The pollen is dominated by *Pinus,* recorded at values well above those of VLG3 and VLG4, which suggests a local pine woodland rather than long-distance input. This is supported by historical cartography (Casti Moreschi, 1990) that documents extensive pine stands in the Val Grande coastal belt since at least 1527 (“PIGNEDA”, AsVE, sEA, Livenza 96, d.1) and again in 1549 (“PINADA”, AsVE, sEA, Diversi, 42; Casti Moreschi, 1990; Battiston and Gobbo, 1992).

Herbaceous taxa are dominated by Poaceae, with Cichorieae, wild herbs, and PSI taxa indicating open, potentially disturbed soils. The LDI group, especially *Plantago lanceolata*, is well represented, and cereals are consistently present, including *Hordeum, Avena/Triticum* and the single occurrence of *Zea mays,* pointing to clear disturbance. *Zea mays* in the uppermost sample provides a first *terminus post quem* as historical and agronomic sources indicate its introduction in northern Italy during the late 16th century and widespread cultivation by the early–mid-17th century. In Friuli Venezia Giulia, documentary evidence shows that corn was already present in rural granaries by 1656 CE, and similar dynamics are documented in Veneto (Fornasin, 1999).

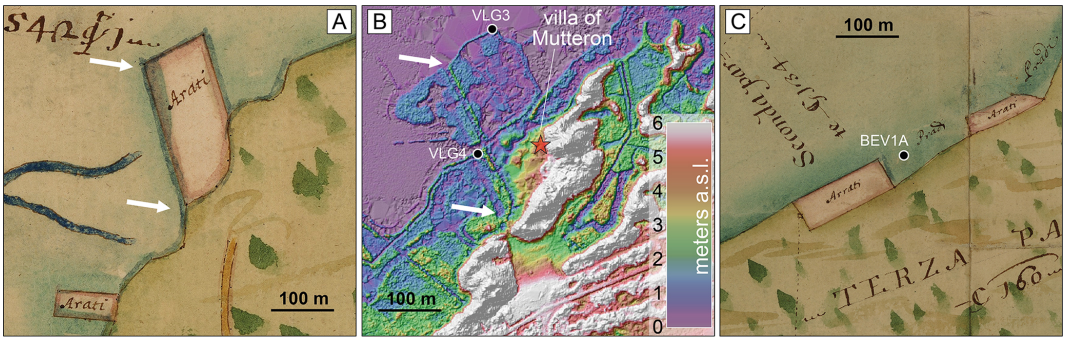

Figure 7. Comparison between the historical map of 1689 (**A**; Archivio di Stato di Venezia, ASVE SEA, Laguna, 60) and the DEM obtained by lidar data **(B)**. The arrows show the evident correspondence between the area of the cultivated field ("Arati" meaning ploughed fields) and the relief still emerging from the water. The location of core BEV1A in the map of 1689 **(C)** was also close to cultivated field (modified from Fontana et al., 2026).

Evidence of cultivation in the Val Grande area is testified to during the 17th century by historical cartography (Fig. 7).

The marked decline in *Pinus* in the upper sequence suggests reduced local pine cover coinciding with rising LDI and cereal group abundances, likely reflecting recent landscape opening and local deforestation. The presence of fluctuating Cyperaceae, *Ruppia*, halophytes, and brackish-water NPPs indicates swampy conditions with lagoonal–brackish influence (Badino et al., 2026). Furthermore, the combination of moderate *Quercus*, scattered mesophilous, and extremely low hygrophilous taxa through the BEV1A sequence reflects a modern forest mosaic, contrasting with the wetter, alder-rich landscapes documented for older periods in VLG3 and VLG4. The reduction in alder stands is likely linked to modern drainage networks, river embankments, and lagoonal reclamation, which lowered or stabilized the water table and permanently reduced waterlogged soils. Reclamation practices in the Bibione area have been carried out extensively between the 1920s and the 1950s (Casti Moreschi, 1990), providing a second *terminus post quem* for the environmental patterns documented in the sequence.

BEV1A shows substantially higher cereal and LDI abundances than VLG3 and VLG4 (peaking at 4.2 % and 6.1 % in the uppermost sample), reflecting intensified agriculture, grazing, and land management practices. Excluding the top sample, however, LDI and cereal signals become roughly comparable to the upper VLG3 sample and VLG4 subzone 2a, indicating that, prior to modern intensification, human impact in Val Grande remained low and spatially discontinuous.

6 Conclusions

The multiproxy analysis of the Val Grande sequences reveals a lagoonal landscape shaped by the interplay of geomorphology, hydrology, and human presence over the last 2 millennia.

Before and during the occupation of the Roman villa, the Val Grande lagoon was a natural lagoon system with the presence of saltmarshes fringed by wetland and riparian vegetation. The sequences of the tidal channel (VLG4) and of the tidal flat (VLG3) recorded different hydrological regimes and different spatial positions within the lagoon system, which affect how strongly each core registers local human activity.

The human influence that affected the area during the Roman period is detectable, but it was of small magnitude and was spatially limited to the zone of the villa and its surrounding, where some harbour facilities were probably established. VLG4 documents this localized signal, with peaks in the LDI (lagoon disturbance index) and cereal pollen, whereas VLG3, in a more isolated setting, records mainly the broader environmental consequences of Roman land use. Although *villae maritimae* are often interpreted primarily as residential or leisure sites, they commonly hosted small-scale productive activities as well. In this context, the construction of the villa and its associated cultivation may have required the levelling or reworking of some portions of the nearby dune ridges, contributing to the localized disturbance signal captured in the pollen records.

A dramatic hydrological reorganization marks the Early Medieval period when, at the end of the sixth century, the river avulsion of Tagliamento resulted in widespread landscape opening, expansion of herbaceous communities, and renewed saltmarsh development. Both VLG3 and VLG4 clearly document this hydrological shift, reflected in landscape openings characterized by limited and discontinuous anthropogenic indicators.

The modern analogue provided by BEV1A highlights the contrast between pre-modern and recent land use. The uppermost sample clearly bears evidence of structured, intensive agriculture, with LDI and cereal abundances exceeding those of VLG3 and VLG4, while the underlying samples are comparable to the most disturbed intervals of the older cores. The marked decline in *Pinus,* alongside increases in anthropogenic indicators, points to human-induced local woodland

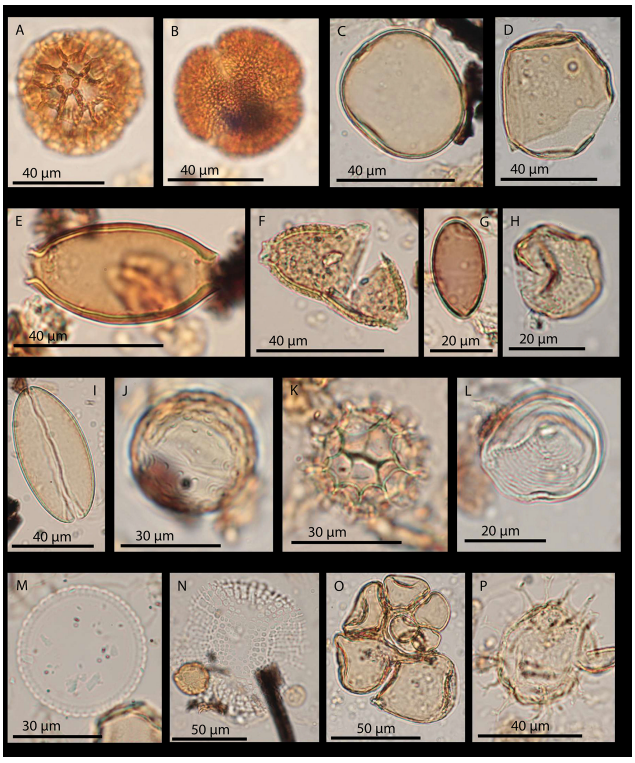

Plate 1. **(A)** *Limonium vulgare*-type A; **(B)** *Limonium vulgare*-type B; **(C)** *Hordeum*-type; **(D)** *Avena/Triticum*-type; **(E)** *Trichuris;* **(F)** *Trichuris trichiura* cf. *Capillaria;* **(G)** *Sordaria;* **(H)** *Cucumis melo;* **(I)** *Spirogyra;* **(J)** Zygnemataceae; **(K)** *Cymatiosphaera;* **(L)** Pseudoschizaea; **(M)** *Cyclostephanos;* **(N)** *Campylodiscus;* **(O)** foraminiferal lining; **(P)** dinoflagellate cyst.

clearance substantially more pronounced than in VLG3 and VLG4.

PSI (potential synanthropic indicators) values fluctuate largely independently of LDI and cereal abundances in all three sequences, indicating that PSI taxa are strongly influenced by local vegetation structure, hydrological disturbance, and taphonomic processes, making them a less reliable standalone indicator of human activity in coastal–lagoonal settings. LDI and cereal abundances therefore provide a more robust basis for assessing anthropogenic pressure in Val Grande, especially when interpreted together with independent archaeological and historical evidence.

A significant result of this research is the documentation that the pine woodland, which appears in the historical maps of the Bibione area and is still present on the dunes of Mutteron dei Frati, is not testified to in the pollen sequences until the modern times. This suggests that its expansion in the area of Tagliamento delta has been favoured artificially in the last millennium, likely during the Venetian domain.

Overall, the Val Grande record depicts a lagoon in motion: a system where the natural hydrological forcing dominated environmental trajectories until very recent times and where human activity, although present since the Roman period, remained marginal, discontinuous, and strongly constrained by the dynamics of the coastal landscape.

Data availability. All pollen count and percentage data from cores VLG4, VLG3, and BEV1A are available in the Research Data Unipd repository at https://doi.org/10.25430/researchdata.cab.unipd.it.00001845 (Azzalin and Fontana, 2026).

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