

Legacy effects of selective coppicing on forest regeneration in Bronze Age Italy

Received: 13 February 2026

Accepted: 8 September 2026

Published online: 27 October 2026

 Check for updates

Anna Maria Mercuri ¹✉, Assunta Florenzano ¹✉, Eleonora Clò¹,
Jessica Zappa¹, Giovanna Bosi¹, Mauro Rottoli², Andrea Zerboni ³,
Andrea Cardarelli⁴ & Mauro Cremaschi³

Unambiguous evidence of sophisticated woodland and land-use management in Bronze Age southern Europe is presented from the Terramare culture in northern Italy. Archaeological layers dated to ~3,600 years ago reveal a society whose economy was structurally dependent on wood, used as both building material and fuel, defining what we term here a ‘Wood Age’ culture. High-resolution pollen sequences and stratigraphic data from key sites indicate that oak-dominated woodlands regenerated through long-term recurrent cycles of selective coppicing targeting specific broad-leaved trees (*Quercus* species, *Carpinus betulus*, *Corylus avellana* and *Ostrya carpinifolia*) and that these practices followed repeated cycles of cutting and regrowth under sustained human disturbance. The Terramare economy relied on a multifunctional agro-silvopastoral system integrating woodland management, crop rotation, animal husbandry and water control. Yet, selected woodland patches were maintained for fruit gathering and boundary marking, highlighting a conscious balance between exploitation and ecological awareness. This land-use strategy sustained the Terramare communities for centuries but also drove profound and partly irreversible transformations of soils and water systems, at times exceeding local sustainability thresholds. By revealing long-term, regeneration-driven forest management, our results challenge the assumption that many temperate lowland forests represent natural baselines, highlighting instead the deep ecological legacies of past human intervention.

Intensive land use and associated human impacts on the environment are among the main drivers of today’s loss of biodiversity, soil degradation, resource depletion and threats to human health. Natural habitats are increasingly endangered by urbanization and industrial expansion¹, and urgent changes are required to reshape societies towards sustainable development². However, the current ecological disequilibrium has deep historical roots. When and how land management began, and the extent to which it interfered with plant communities and ecosystem processes, remain debated, as long-term anthropogenic

drivers of environmental change are often overlooked in favour of short-term dynamics.

Some authors argue that only recent economic intensification has drastically altered ecosystems³, while others trace irreversible transformations back to the introduction of agriculture and pastoralism^{4–6}. Early prehistoric societies maintained a relatively balanced interaction with their environment, but this gradually shifted towards increasingly controlled landscapes characteristic of the Pro-Anthropocene⁷. Complex land-use systems shaping vegetation structure and

¹Laboratorio di Palinologia e Paleobotanica, Dipartimento di Scienze della Vita, Università degli Studi di Modena e Reggio Emilia, Modena, Italy.

²Laboratorio di Archeobiologia, Musei Civici di Como, Como, Italy. ³Dipartimento di Scienze della Terra ‘A. Desio’, Università degli Studi di Milano, Milan, Italy.

⁴Dipartimento di Scienze dell’Antichità, Università degli Studi di Roma ‘La Sapienza’, Rome, Italy. ✉e-mail: annamaria.mercuri@unimore.it; assunta.florenzano@unimore.it

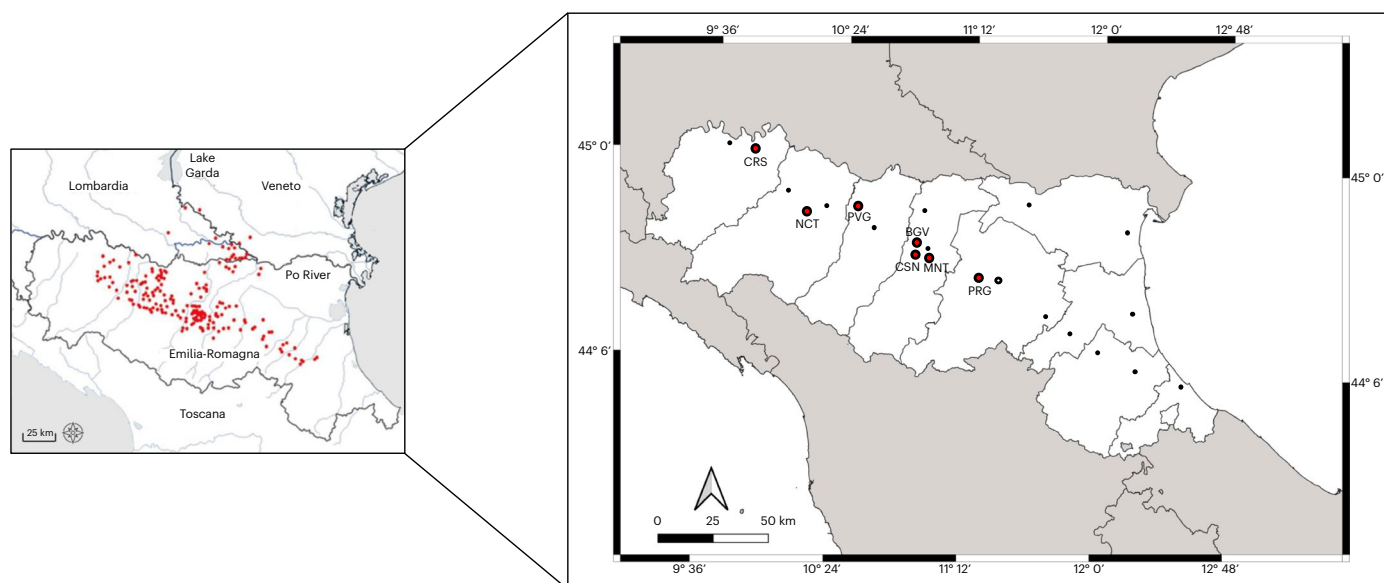


Fig. 1 | Distribution of Terramare culture sites. Left: distribution of known Terramare sites across northern Italy. Right: locations of the study sites in Emilia-Romagna. CRS, Caorso; NCT, Noceto; PVG, Poviglio; CSN, Casinalbo; BGV, Baggiovara; MNT, Montale; PRG, Pragatto. Left: map from d-maps.com

(<https://www.d-maps.com>) (map number 8065). Right: map generated using QGIS v.3.42 (WGS84/UTM zone 32N) with administrative boundaries from the Italian National Institute of Statistics under a Creative Commons license CC BY 4.0.

Table 1 | Chrono-typological phases of the Terramare culture and their corresponding dates, based on archaeological evidence and radiocarbon dating

Cultural period	Phase	Dates (BC)
MBA	MBA1	1650–1550
	MBA2	1550–1450
	MBA3	1450–1325/1300
RBA	RBA1	1325/1300–1225
	RBA2	1225–1150

ecosystem functioning have been documented in several Mediterranean regions since prehistory, with many examples from the Near East and southern Europe^{8,9}.

With their high site density and advanced technologies^{10–14}, the Terramare system represents a highly specialized Bronze Age landscape management strategy based on agropastoral multifunctional land use¹⁵. During the Middle Bronze Age (MBA), Recent Bronze Age (RBA) and Final Bronze Age, between 1650 and 1150 BC (Table 1), this culture developed increasing social complexity across the broad plains of southern Europe^{16–18} (Fig. 1). In the absence of written sources documenting economy and social organization, archaeology provides exceptional reconstructive power, and plant archives from high-resolution stratigraphic sequences offer invaluable insights into vegetation dynamics and forest regeneration under sustained human disturbance in the fertile wetlands of the Po River plain.

Here we combine archaeological and palaeoenvironmental evidence to show that Terramare land-use and vegetation management practices left a strong imprint on pre-existing lowland landscapes, generating substantial and persistent ecological transformations in territories continuously occupied for about five centuries. We selected case studies for their well-preserved archaeological deposits and interdisciplinary datasets: the settlements of Terramara Santa Rosa di Poviglio¹⁹ and Terramara di Montale²⁰ (with high-resolution pollen records; Methods), together with the necropolis of Casinalbo²¹ and the artificial basin of the Noceto ‘Vasca Votiva’ (votive tank)²², were compared with other Terramare settlements (Baggiovara²¹, Pragatto²³ and Caorso²⁴)

and nearby Bronze Age settlements in northern Italy. The comparison of 218 pollen spectra highlights marked variability in woodland use and provides evidence of both shared and site-specific forest regeneration pathways within the same cultural system.

This study documents recurrent coppicing cycles using high-resolution pollen records, providing strong evidence of forest regeneration under sustained human disturbance in the Terramare system. The research supports earlier interpretations, based on archaeological and environmental evidence, that the Terramare economy was grounded in trade and agropastoral production. Within this framework, woody biomass and forest regeneration processes played a central role, serving as the equivalent of modern petroleum in terms of energy and resource value.

Results

Impact of Bronze Age cultures on woodlands

Bronze Age societies, heavily dependent on the exploitation of natural resources, are considered among the first to have caused widespread and regionally detectable reductions in forest cover^{17,25}, a phenomenon often recorded in pollen diagrams²⁶ and thought to have influenced European climate dynamics²⁷. Within the Terramare culture, pollen records document the extent and biological dynamics of woodland transformation (the baseline forest conditions in the Po Plain before the Terramare are provided in Box 1). At Santa Rosa di Poviglio, sedimentary near-site cores record a marked decline in arboreal pollen (AP < 30%)²⁸, representing the lowest forest cover of the Holocene sequence. A broad regional signal of forest reduction coinciding with the expansion of Terramare settlements is also evident in the Adriatic core RF93-30, which contains Po River sediments transported several hundred kilometres downstream from the Terramare area, demonstrating a basin-scale impact of woodland loss²⁹.

After deciduous oaks and other broad-leaved taxa reached peak values (~80%) around 1950 BC, the off-site record shows a progressive opening of the landscape, with oak pollen declining to ~60% by ~1650 BC. This phase coincides with increased fire activity³⁰ and rising human-related pollen indicators, reflecting intensified land clearance for construction, agriculture, pastures and fuelwood³¹. In managed woodlands, coppicing is known to influence pollen production and

BOX 1

Baseline forest conditions and wood availability in the Po Plain before the Terramare

In the Po Plain, palaeoenvironmental evidence points to a relatively open and cool environment since the onset of the Holocene, characterized by a high proportion of *Pinus* pollen. This signal is interpreted either as the result of long-distance transport from upland forests or as a marker of alluvial deposits associated with flooding events^{28,93–95} (see also the alluvial layers in the deposits of Baggiovara²¹ and Fondo Paviani⁵³). Moreover, reconstructions of Po Plain vegetation should be interpreted in the light of the known taphonomic characteristics of fluvial pollen archives, including the potential over-representation of highly dispersive taxa such as *Pinus* and the under-representation of some broad-leaved trees⁹⁶.

In this context, a strong *Pinus* signal does not necessarily imply closed-canopy forests but is fully compatible with open woodlands and sparse pine stands embedded within a mosaic of fluvial and palustrine environments.

During the Preboreal, the dominance of *Pinus*—representing roughly half of the AP signal (AP=64%, including ~12% of deciduous broad-leaved taxa on average across five sites)⁹⁷—points to open conifer woodlands or a heterogeneous lowland mosaic rather than to closed-canopy forests. This interpretation is consistent with early Holocene deltaic records showing variable tree cover shaped by fluvial and palustrine dynamics and vegetation turnover (EM2 terrestrial core)⁹⁸.

Even when temperatures increased and mixed broad-leaved forests expanded during the Boreal⁹⁹, there is no clear indication of particularly dense lowland woodlands (AP=53%)^{93,95}. Forest cover remained sparse across most of the Po Plain, in the central sector (<20% in 1-MRZ, correlated to the Neolithic)¹⁰⁰, in the northwestern sector (<38% in Pra' Marci peat)¹⁰¹ and in the eastern plain at the transition between the Po and Apennine river systems (<30% in MAL sequences, ~1400–1300 BC)¹⁰². Near the Po delta, similar patterns are recorded in the EM2 core (~1600–1300 BC), where AP ranges around 30–50%⁹⁸. Later in the Mincio Valley, in the north-central Po Plain, forest cover at ~1200 BC does not exceed 60%¹⁰³, further confirming that Holocene pollen spectra typically reflect relatively

open or sparse woodlands and forest-clearing-grassland mosaics, reflecting constrained forest regeneration under fluvial dynamics and the widespread presence of flooded or flood-prone areas, rather than dense, closed-canopy forests that would have reduced habitat availability for herbaceous plants¹⁰⁴.

These long-term conditions of relatively sparse woodland and readily available resources help explain why the area became increasingly attractive for humans. The development of human settlement systems is known to benefit from the interplay of social and environmental factors, including moderate forest cover, fertile soils, suitable topography, favourable climatic conditions, abundant sunlight, a relatively low risk of natural hazards at low to medium elevations¹⁰⁵ and proximity to water sources that also provided potential routes of communication¹⁰². By the fourth millennium BC, the Po Plain offered nearly all these conditions, supporting its occupation and colonization.

During the pre-Terramare phase at Montale, the on-site forest cover (42%) was more than three times higher than during the occupation levels (Bronze Age layers, 12%)²⁰, a pattern comparable to that of the pre-Terramare phase at Baggiovara (30%; Bronze Age layers, 19%)²¹ and at the near-site core N-S3-Poviglio (46%; Bronze Age layers, 22%)²⁸. This trend is not so evident approximately 150 m to the southwest, away from the village centre and about 50 m from the Montale ditch (Profile 3; Methods), where forest cover remains steady, suggesting that the impact of the settlement was concentrated primarily in the inhabited area. Across different types of Terramare sites, including Pragatto, Casinalbo and Noceto, AP values consistently range between 20% and 30%, indicative of open-canopy or managed woodland conditions. At Santa Rosa di Poviglio, forest cover in the moat declined from ~45% in the MBA to ~20% in the RBA, with deforested zones expanding from ~500 m to nearly 4 km around the village^{19,106}.

Together, the baseline conditions explain why long-term woodland management could develop without immediate resource exhaustion, providing the ecological context for the forest regeneration dynamics documented in this study.

the representation of woody taxa in pollen assemblages, reflecting differences in regeneration and flowering dynamics among species³².

Radiocarbon dates on charcoal reveal a consistent pattern: in MBA contexts, dates are systematically older due to the “old wood effect”³³, whereas in the RBA, dates on charcoal and collagen coincide, confirming the archaeological stratigraphy (Fig. 2 and Supplementary Table 1)^{34,35}. This indicates that during the MBA, lowland forests still contained centuries-old trees, while by the RBA these had disappeared, replaced by younger, regenerating secondary woodland. The establishment of settlements, with their vast demand for timber for construction and fortifications, is thus strongly supported by palaeoecological evidence. Intensive and repeated exploitation of woodland resources, together with the expansion of fields and grazing areas, altered forest regeneration trajectories and contributed to the long-term reorganization of the surrounding agro-silvopastoral system.

Availability of wood as a resource for sustainability

The Terramare settlements developed in a lowland landscape characterized by naturally open forest mosaics and abundant water resources, providing favourable conditions for long-term woodland management

(Box 1). As noted above, the construction of Terramare villages relied on extensive wood cutting, and the limited woodland extent recorded in pollen sequences may therefore partly reflect active woodland management and repeated disturbance of tree populations, rather than solely natural landscape openness. However, woodland resources differed among settlement territories in both density and floristic composition (Fig. 3).

Settlements were established in open but heterogeneous forest-grassland mosaics (clearing space required little effort), with woodlands located at short distances (easy access to resources). Although woodlands were generally discontinuous across the region, pollen data reveal local variability in resource availability: woodlands were thinner or more distant at Baggiovara and Casinalbo, whereas they were denser or located closer to the settlements at Montale and Poviglio.

At Poviglio, the moat sequence¹⁹ records the highest AP values, with two peaks during MBA3/early RBA1 largely attributable to locally persistent hygrophilous woodland regeneration (~30%, while other AP values are around ~43%; Fig. 3). A contrasting pattern has been reported for the Terramara di Parma (AP around ~40%), where deciduous oak woodland remains dominant and hygrophilous taxa are less prominent,

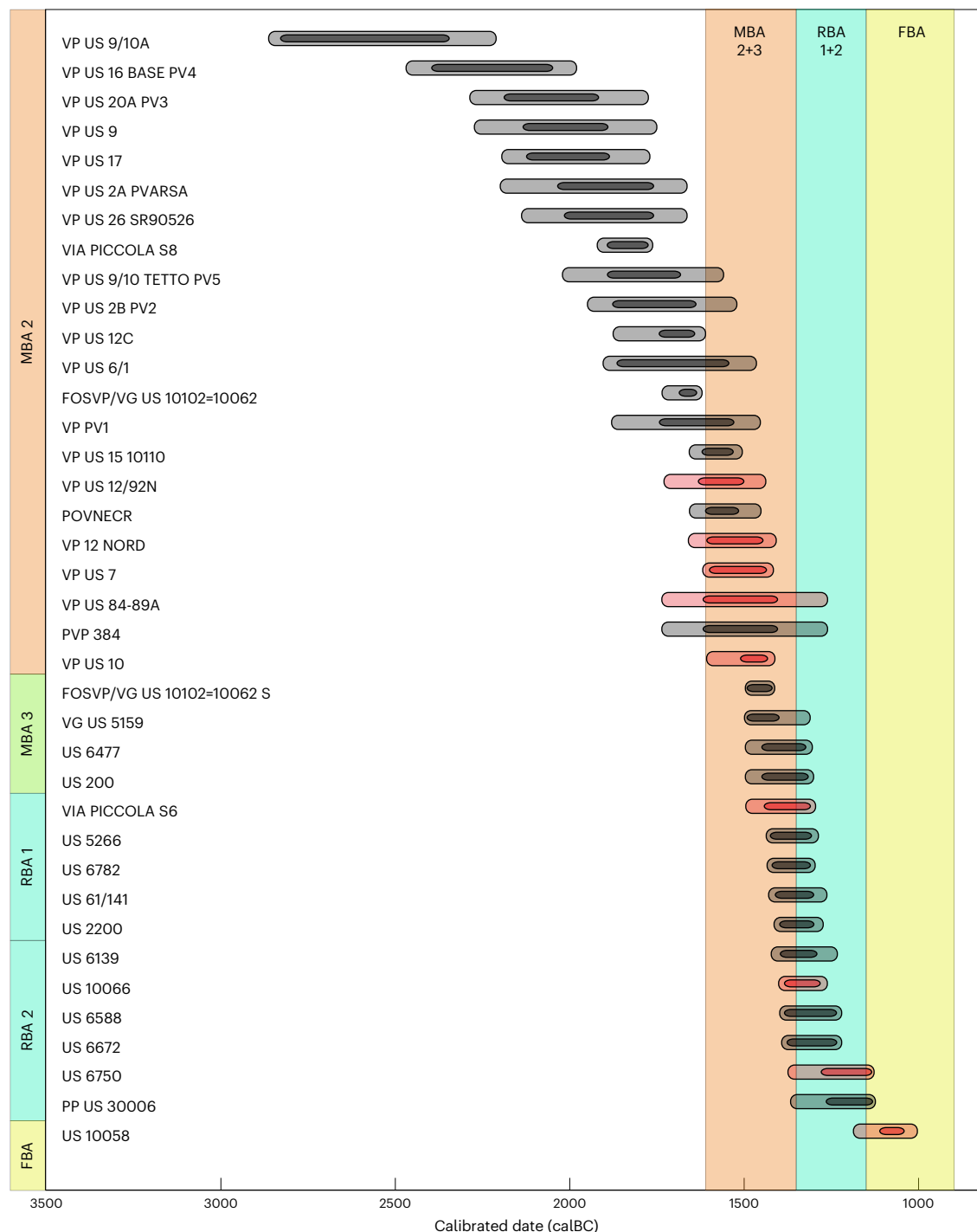


Fig. 2 | Distribution of radiocarbon dates in comparison with archaeological ages at the Terramara Santa Rosa (Poviglio). Charcoal-derived dates are shown in grey, while collagen-derived dates are shown in red. The inner and outer horizontal bars represent the 68.2% (1 σ) and 95.4% (2 σ) calibration intervals, respectively. The coloured bands indicate the reference archaeological periods and their chronological boundaries. FBA, Final Bronze Age. The dates refer to the

stratigraphic units of the Terramara Santa Rosa and are arranged from the oldest (top) to the youngest (bottom). The left column indicates the archaeological attribution of each stratigraphic unit, determined on the basis of the associated archaeological assemblages. Radiocarbon dates obtained from charcoal in the oldest stratigraphic units predate their expected archaeological age as a consequence of the old wood effect. Radiocarbon dates from refs. 34,35.

while *Corylus avellana* and *Carpinus betulus* contribute substantially to the arboreal assemblage³⁶.

Forest composition also varied considerably across sites. Deciduous oaks—high pollen producers—dominate all records, but *Carpinus betulus* often reaches higher values at Montale, a pattern that may partly reflect earlier Neolithic–Eneolithic forest disturbance through cutting and burning³⁷. At Noceto, *Corylus avellana* is particularly abundant (24% on average), and it has been hypothesized that hazel may

have been deliberately cultivated near the votive tank³⁸. *Alnus* and *C. avellana* prevail in some samples from Baggiovara, while at both Baggiovara and Casinalbo the high percentages of *Pinus* are interpreted as alluvial indicators²¹.

Besides pollen evidence (Fig. 3), hygrophilous taxa such as *Alnus*, *Salix* and *Populus/Salix* are recurrently represented in the xylo-anthracological records from these sites^{20,21}, indicating that wetland woodland resources were available and exploited within the

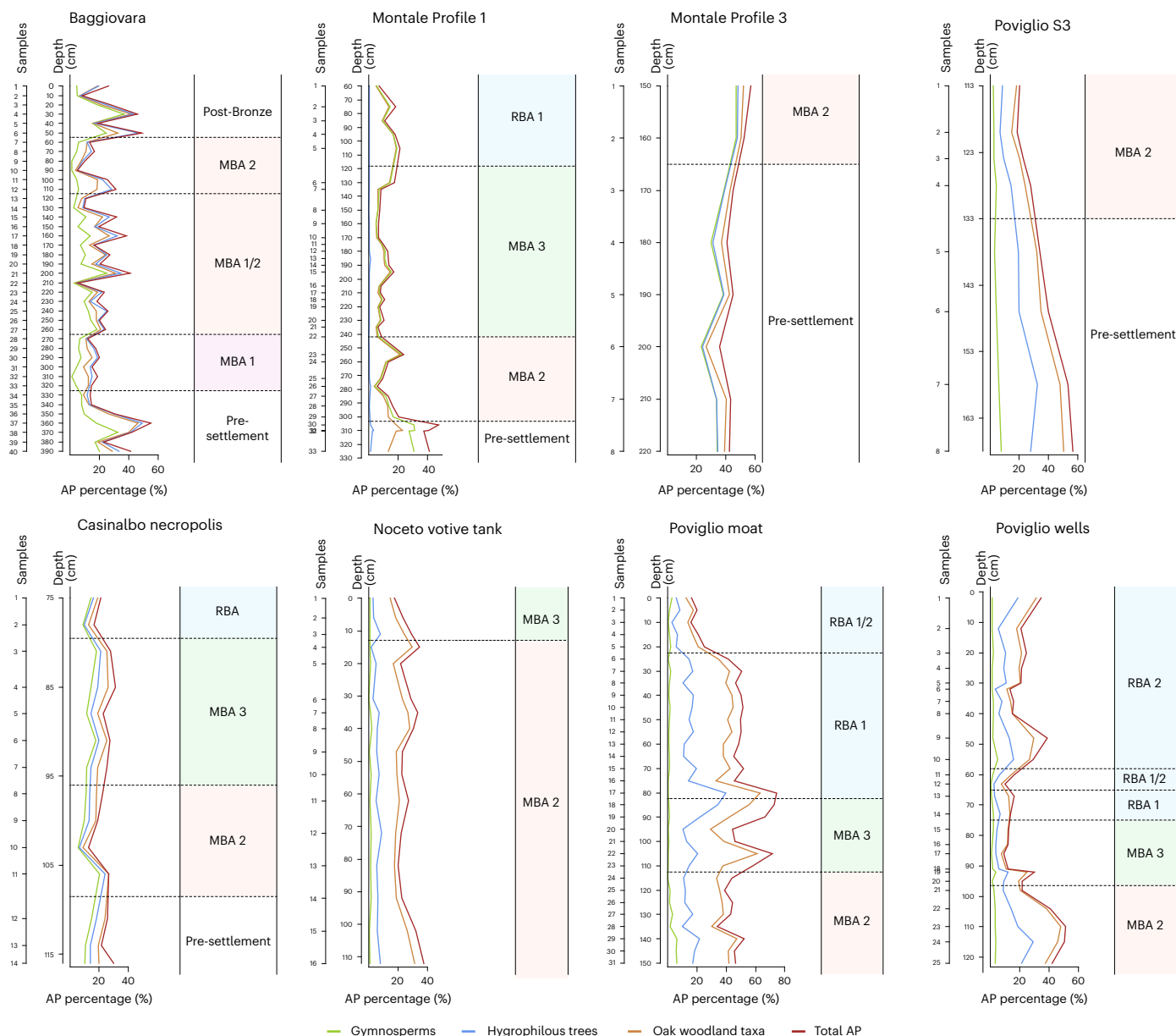


Fig. 3 | Comparison of AP trends and woodland vegetation trajectories across the main occupational phases of the Terramare settlements investigated in this study (Montale, Santa Rosa di Poviglio, Noceto and Casinalbo). Each diagram represents changes in AP percentages through the main occupational phases of the Bronze Age (MBA2–RBA2). Background colours indicate chrono-cultural phases. Depth scales represent archaeological stratigraphy and therefore differ among sites; comparisons are based on the independently

dated chrono-cultural phases rather than on absolute depth values. Coloured curves represent cumulative AP groups contributing to the total AP signal and their trends through time. The dominant tree taxa contributing to each peak (deciduous *Quercus*; *Fraxinus excelsior* type; *Carpinus betulus*; *Corylus avellana*, and *Alnus*) represent the principal components of woodland vegetation. Their variable peaks among sites reflect local woodland composition and human use of woodland resources.

settlement territories. At Poviglio, hygrophilous woodland appears to have provided resources more frequently (Fig. 3), probably because it extended close to the settlement and receded only towards the end of the sequence. Riparian stands of *Alnus* and *Salix* developed near the site, where *Vitis vinifera* also grew well³⁹.

Woodlands also supplied fruits and a wide range of edible resources, such as acorns, berries and other nuts, with carpological evidence indicating that *Cornus mas* played a particularly important role during the earlier phases of the Bronze Age, thereby contributing to the food economy. In many archaeological layers, grape pips have also been recovered alongside pollen evidence (for example, at the terramaras of Montale²⁰ and of Parma¹⁸). At Poviglio, high values of *V. vinifera* subsp. *sylvestris* in the pollen spectra indicate that the

plant was used and probably protected near the settlement. As wild grapevines produce edible grapes⁴⁰, these plants were probably valued as a food source and may have been subject to early forms of management influencing regeneration and persistence. Increasing evidence shows that the Bronze Age was a key period in the development of human interaction with this species⁴¹. Morphobiometric analyses using linear discriminant analysis suggest that about 70% of the grape pips recovered at Montale can be attributed to the domesticated subspecies *V. vinifera* subsp. *vinifera*⁴². This may indicate early wine production or the fermentation of grape juice from both wild and domesticated vines. Lipid and organic acid residues of wine and its derivatives have been extracted from ceramic vessels, demonstrating that the grape-based products were already widely consumed in Bronze

Age Italy (Pilastris and Canale Anfora-Aquileia in the northeastern peninsula; Sa Osa and other sites in Sardinia)⁴³.

Taken together, this broader interdisciplinary framework provides the socio-ecological context within which the pollen evidence for woodland regeneration and coppicing can be interpreted. Palynological, archaeobotanical and biomolecular evidence show that access to diverse and abundant woodland resources—timber, fuel, fruits, nuts and grapevines—played a central role in sustaining Terramare communities: the greater the capacity for woodland regeneration, the higher the long-term resilience of plant–human systems.

Coppicing for the preservation of the wood resource

The excavation of Terramare sites has revealed extraordinary wooden structures, including poles and palisades^{44,45}, charred tree trunks at the base of the village of Montale, wooden planks in Pragatto, the recurrent occurrence of deciduous *Quercus* and other woodland taxa in wood and charcoal assemblages, and the spectacular votive tank in Noceto²². In addition, traces of deliberate management of arboreal resources have been identified at Poviglio, where *Fraxinus* and *Ulmus* charcoals preserve short ring sequences showing repeated formation of earlywood without corresponding latewood, a growth anomaly interpreted as the result of defoliation, probably associated with foddering practices.

Altogether, these sites provide clear evidence of systematic and extensive use of timber for the construction, expansion and defence of the villages. Nevertheless, it remains unclear whether this intensive exploitation radically transformed the structure of forest cover in the surrounding lowlands. In light of the widespread use of woodland resources documented across the Terramare system, macrobotanical evidence suggests that active woodland management and regeneration-based strategies were developed to ensure the renewal and long-term availability of timber (Methods).

On the basis of these considerations, the most effective way to exploit a forest without severely reducing or depleting it is through coppicing—the practice of cutting trees near the ground to stimulate vegetative regeneration from stumps or roots.

Pollen-based evidence of coppicing in the Terramare culture

The pollen evidence (Fig. 4) presented here provides robust support for woodland management practices during the Bronze Age, offering a spatially integrated signal of coppice-type exploitation that extends beyond the scale accessible through wood-anatomical analyses. Given the chronological structure of archaeological sequences, the patterns observed are best interpreted as recurrent decadal-scale cycles of woodland exploitation and regeneration rather than as individual management events (Fig. 4 and concentration diagrams in Supplementary Fig. 1).

The independent yet alternating behaviour of *Quercus* and other broad-leaved taxa during specific phases of the pollen records points to cyclical fluctuations that cannot be explained solely by intrinsic variations in pollen productivity associated with mast-seeding dynamics. If driven primarily by masting, similar oscillations would be expected throughout the record; instead, such reciprocal trends are confined to phases associated with Terramare occupation and involve multiple taxa known to respond to coppicing through species-specific regeneration strategies.

The temporary reduction of one woodland component, balanced by the expansion of another, is therefore more plausibly explained by selective cutting followed by regrowth. This pattern further suggests that coppicing was selectively applied to specific tree species, probably chosen on the basis of functional traits related to wood properties and rapid resprouting capacity, rather than uniformly across the woodland. Such dynamics probably reflect an early, experimental form of coppicing, which may not fully correspond to later or modern coppice systems. Rather than seeking modern coppice systems in the past,

the pollen record reveals forms of management acting on pre-existing woodland communities, reflecting regeneration dynamics that may only partially overlap with modern silvicultural traditions.

The alternating patterns are consistent with managed disturbance–regeneration dynamics—alternating cut and uncut trees—and provide palynological evidence of coppicing as a deliberate and structured woodland management practice in the Terramare Bronze Age system. Comparison among sites further reveals a regionally coherent signal of coppice-type exploitation, supporting a landscape-scale pattern of forest regeneration rather than isolated, individual growth responses typically captured by anatomical data. Although pollen data are not generally regarded as direct evidence of woodland management practices, the repeated cyclic patterns observed across multiple independent sequences, together with their archaeological context and ecological coherence, are most parsimoniously explained by selective coppicing as a recurrent management strategy. The pollen record should be read as recording the cumulative expression of recurrent selective management in woodland composition and regeneration dynamics over decadal to sub-centennial timescales.

The rapid fluctuations in the curves of mixed oak and hygrophilous forests (Fig. 4) show that peaks in *Quercus* often coincide with independent, synchronous declines in *Carpinus betulus*, *Corylus avellana*, *Ostrya carpinifolia*, *Ulmus* and *Fraxinus excelsior*, and vice versa. This pattern is interpreted as evidence that coppicing involved the cutting of oaks and other deciduous trees with contrasting regeneration dynamics. At Santa Rosa di Poviglio (Fig. 4a), this trend is less visible in the lower part of the diagram (where only *Ostrya* peaks alternate with deciduous oaks) but becomes clearly expressed in the central portion, where oscillations of oaks, hazel and hornbeam—typical components of mixed oak woods—are mirrored by those of hygrophilous/riparian taxa such as *Alnus* and *Ulmus*. These signals weaken or disappear towards the top of the sequence.

This pattern indicates that during the MBA phases, woodland resources were initially exploited mainly for oak construction timber and were subsequently managed through coppicing as a subsistence strategy supporting the expansion and cultural development of the Terramare settlements. In the late RBA, however, the regular rhythm of this practice declined, suggesting that coppicing could no longer be maintained under the combined pressure of resource depletion and environmental–climatic stress.

Inverse oscillations between *Quercus* and trees such as *Corylus*, *Carpinus* and *Fraxinus* are characteristic of coppiced woodlands⁴⁶. *Quercus robur* and *Q. petraea* produce slower and light-demanding regrowth, whereas *Carpinus betulus* and *Fraxinus excelsior* rapidly occupy canopy gaps after cutting, and *Corylus avellana* responds almost immediately with vigorous shoot production. This functional pattern corresponds to a three-stage cycle: a post-cutting phase dominated by fast-growing shrubs and light-tolerant trees (*Corylus*, *Fraxinus*, *Rubus*), a mid-cycle phase with increasing competition and canopy closure (*Carpinus*, *Acer*, *Tilia*) and a late-cycle phase in which oaks gradually regain dominance⁴⁷.

Such rise-and-fall dynamics in species abundances are well described for modern coppiced woodlands⁴⁶ and closely match the inverse fluctuations observed in parts of the MBA–RBA sequences, suggesting that woodland exploitation in the Terramare area followed a recurrent coppicing cycle structured by forest regeneration dynamics. These regeneration patterns—expressed by the cyclic alternation of *Quercus* dominance with faster-resprouting taxa such as *Corylus*, *Carpinus* and *Fraxinus*, and by site-specific shifts in forest composition detected through pollen records—indicate that past management practices left ecological legacies in forest structure and composition. These legacies are expressed in the establishment of regeneration pathways and species relationships that challenge the assumption of wholly natural forest baselines and may continue to influence the composition and dynamics of temperate woodlands today⁷.

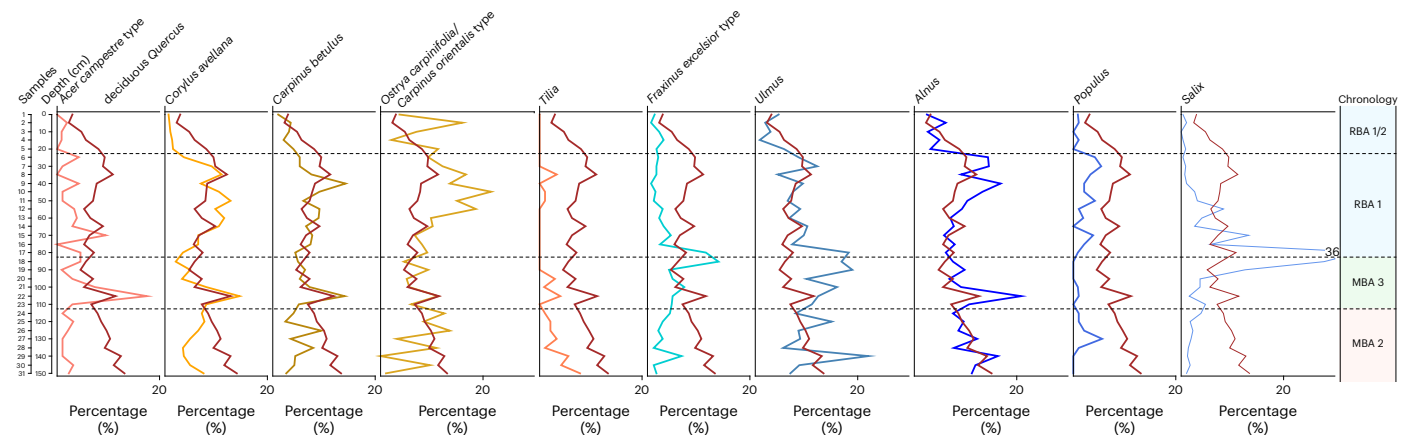
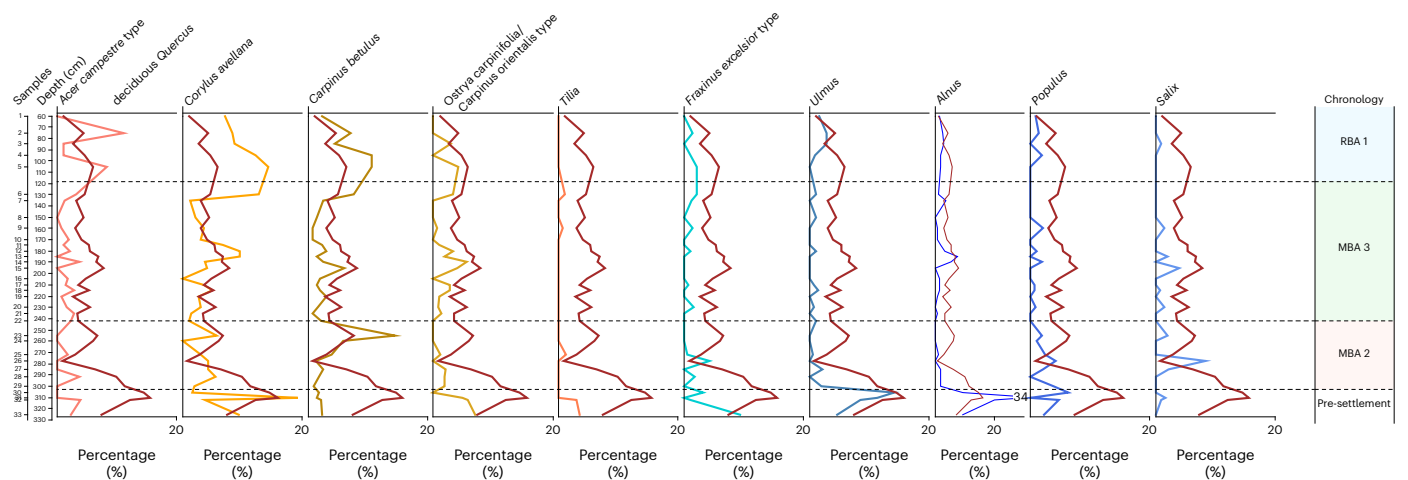
a Poviglio moat**b** Montale Profile 1

Fig. 4 | The gentle but rapid oscillations of the curve of deciduous oaks, sometimes mirrored by other woody plants such as hornbeam, highlights recurrent fluctuations in AP representation. All AP curves were calculated using alternative pollen sums excluding *Quercus*, to enhance the visibility of short-term fluctuations in subordinate taxa. **a, Terramara Santa Rosa di Poviglio (PV/PG moat sequence). In MBA2, an alternation between *Quercus* (the brown curve) and *Ostrya carpinifolia*/*Carpinus orientalis* type is evident, later also involving *Carpinus betulus*. In MBA3, all curves increase simultaneously, with only *Salix* declining; however, this phase is followed by oscillations of *Corylus*,**

Carpinus and *Ostrya*, and partly *Ulmus*, *Alnus* and *Salix*, alternating with *Quercus*. To enhance visual comparison, some curves are multiplied by a factor of 2 (*Carpinus betulus* and *Fraxinus excelsior* type) or 5 (*Acer campestre* type, *Ostrya carpinifolia*/*Carpinus orientalis* type, *Tilia*, *Ulmus* and *Populus*). **b**, Terramara of Montale (Profile 1). Here, the oscillatory pattern is less clear but still evident in the *Carpinus*–*Quercus* alternation during phase MBA2. In the subsequent phases, the oscillating trends of the curves show a generally coherent pattern. For visual comparison, all taxa except *Quercus* and *Carpinus betulus* are plotted at $\times 10$.

Agro-silvopastoral systems and landscape-scale resilience

Beyond woodland management, crop–pasture dynamics and agricultural practices contributed to the overall resilience of the Terramare system (the Terramare agro-silvopastoral system is summarized in Box 2). Against this broader background of long-term socio-ecological resilience and increasing environmental stress^{18,19}, multivariate analysis helps disentangle the relative roles of chronology and local context in shaping plant resource use and vegetation dynamics. Principal component analysis (PCA) (Fig. 5) reveals a clear separation of samples by site rather than by chronology, supporting the interpretation that local environmental and ecological conditions played a stronger role than temporal variation in structuring land-use practices. The main components of the Terramare economy are distributed across the PCA quadrants: cereals cluster in quadrant III, whereas Cichorieae and legumes are positioned in quadrants II and I. Legumes plot closer to hygrophilous woodland taxa, while Cichorieae occupy more open-land positions, suggesting differential relationships with soil moisture, vegetation structure and plant species in wetland versus pasture environments. Across quadrants I and IV, the ordination also suggests an

ecological gradient from drier alluvial terrace woodlands dominated by oak–hornbeam communities to more humid environments, indicating that human activity may have locally modulated forest composition and regeneration trajectories, favouring oak–hornbeam stands during phases of reduced water availability. Among the sites, Poviglio shows the strongest association with tree taxa identified as suitable for coppicing—particularly in the moat sequence—which is consistent with the archaeological and palynological evidence indicating the most pronounced signals of coppice-driven forest regeneration.

Discussion

Selective coppicing and regeneration-driven forest management

The data emerging from this research suggest that what we have traditionally called the ‘Bronze Age’ was, in many respects, also a ‘Wood Age’. Knowledge, practices and behaviour should be viewed along a continuum within a Pro-Anthropocene trajectory that led to long-term and partly irreversible land transformations in western societies, beginning in northern Italy with the Terramare culture. A holistic approach

BOX 2

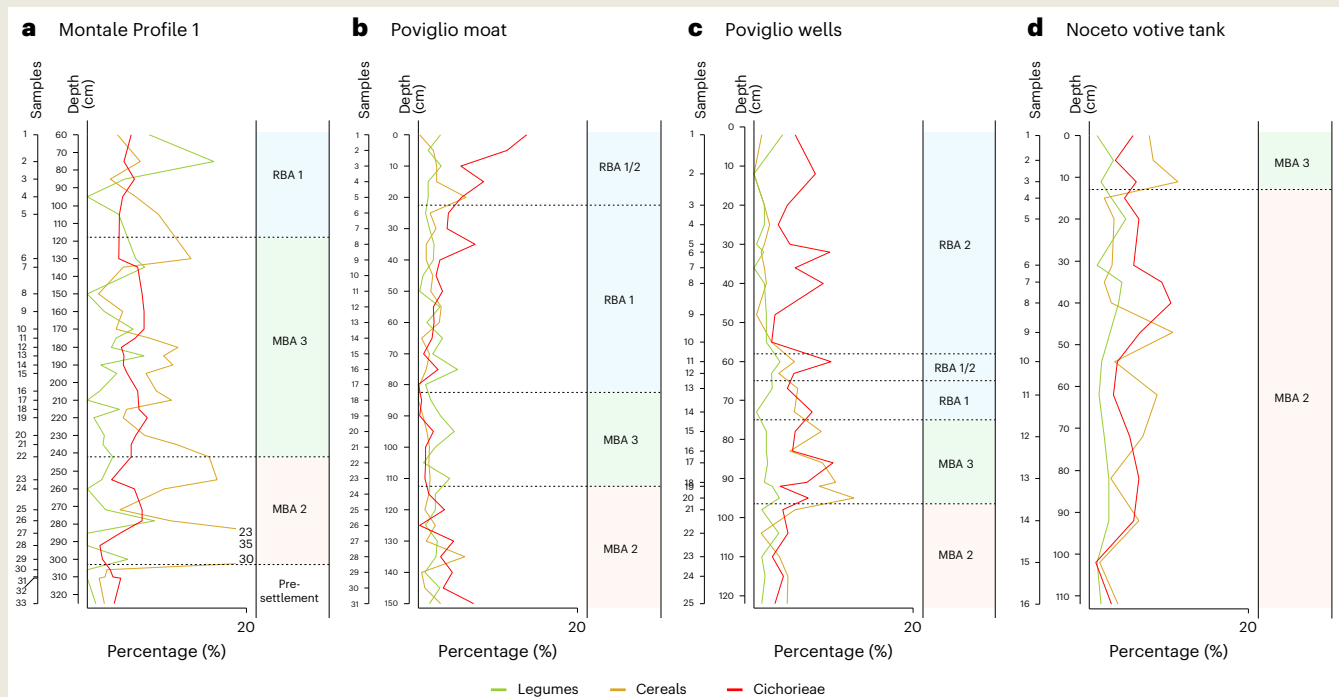
Fields, pastures and agroecosystem dynamics in a managed landscape

Beyond woodland management, the Terramare economy relied on a complementary organization of arable fields and pastures. Crop rotation, seasonal alternation between cultivated and fallow land, and the integration of grazing areas ensured the resilience of the agro-silvopastoral system that sustained Bronze Age communities in the Po Plain by regulating plant productivity and soils.

High numbers of cereal remains, both pollen and charred grains, have been identified in the archaeobotanical record of Terramara di Montale²⁰. This evidence points to the continuous introduction of crops into the settlement, through voluntary or unintentional human transport, leading to the accumulation of plant material on the floors as food or fodder residues. Interdisciplinary data further indicate that Terramare settlements functioned primarily as producer sites. Among the macroremains, common/durum wheat (*Triticum aestivum/durum*), emmer (*T. dicoccum*) and einkorn (*T. monococcum*) prevailed, followed by hulled barley (*Hordeum vulgare*), broomcorn millet (*Panicum miliaceum*), spelt (*Triticum spelta*), oat (*Avena* sp.) and rye (*Secale cereale*). Villages were located at the centre of an ‘area of influence’ that was actively cultivated, while water and woodland resources were managed by the same communities. Pollen data indicate that cereal fields were cultivated within this

area of influence (~14 km²; radius, ~2,110 m; after Cardarelli¹⁰⁷), where demographic reconstructions and the probable pollen source area (RSA, corresponding to the area of influence of each site) suggest that approximately 25–35% of the land was open and largely free of woody vegetation. A comparable agrarian landscape configuration is observed at Santa Rosa di Poviglio, where pollen and plant macroremain evidence indicate that cereal cultivation developed within a similar area of influence, characterized by sparse woodland and open spaces suitable for both agriculture and grazing^{19,106}. For both the Terramara sites of Poviglio and Montale, an RSA of ~1,000 m was therefore adopted to reconstruct pollen-based local vegetation structure^{20,106,108,109}. This value is consistent with estimates from modern analogues in traditional open agricultural and semi-open forested landscapes, where the RSA derived from off-site pollen records is estimated at ~1,000 m (ref. 110). However, this estimate may be more uncertain in archaeological contexts, where humans could collect plants over larger distances and cultivation or gathering activities may have extended beyond this range.

In archaeological sites, human transport of plant material generally prevails over airborne deposition¹¹¹, as was certainly the case for cereals found within the Terramara villages. Although



Pollen diagrams showing the relative abundance of cereals, legumes and Cichorieae in the Terramare sites of Poviglio, Montale and Noceto. a–d. At Montale, the legumes and Cichorieae curves were rescaled ($\times 10$ and $\times 0.1$, respectively) to facilitate visual comparison among taxa. The profiles highlight fluctuations in the relative abundance of cultivated crops and pasture-related indicators through time. In the Montale sequence, legumes (fodder plants) and Cichorieae often display synchronous peaks that sometimes

alternate with cereals, suggesting shifts between pastures and fields (a); whereas in the Poviglio moat, legumes and cereals often show opposite trends, suggesting recurrent changes in the relative importance of cultivation and pasture indicators (b). In the records from the wells (c) and the Noceto votive tank (d), comparable fluctuations among these anthropogenic indicators, suggesting changes in the local agropastoral environment, are evident.

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detecting short-term oscillations in land use would require very high sampling resolution, the available data suggest that a range of agricultural practices were already in use during the Bronze Age, including crop–pasture alternation (cultivating a plot for a few years and then leaving it fallow for grazing), fire farming (burning vegetation to release ashes that fertilize the soil), crop rotation (alternating cultivated and fallow fields over multi-year cycles) and field manuring¹¹². Within this framework, the successful introduction of broomcorn millet added a short-cycle cereal with partially distinct agronomic requirements from those of traditional cereals, enhancing crop diversification and flexibility¹¹³.

Maintaining cereal productivity over the roughly 450–500 years of Terramare occupation required the adoption of specific agricultural strategies to sustain soil fertility and crop yields. Pollen diagrams allow us to identify some of these practices in the Terramara system. At Montale (panel a), alternating fluctuations of cereals and Cichorieae (indicative of pasture areas¹¹⁴) suggests recurrent shifts in the relative importance of cultivated and pasture-related environments. Previous analyses of the same sequence identified peaks in microcharcoal interpreted as evidence of fire use in land management²⁰. In some phases, the largely synchronous trends of cereals and legumes suggest a close association between food and fodder crops, with cereals potentially cultivated either in association (such as intercropping¹¹⁵) or in rotation with legumes in small fields.

At Santa Rosa di Poviglio, Cichorieae show low frequencies and nearly disappear during the central part of the sequence, when crop cultivation and coppicing appear to have been the dominant activities near the settlement. A comparison of the diagrams shows that land management at the Terramara of Poviglio evolved from the MBA phases, characterized by a mixed landscape of woodland and pasture, to the RBA phases, when the environment became more open and intensively cultivated, with an increasing importance of cereal cultivation and evidence of coppiced woodland. In the upper part of the sequence, both crop and woodland indicators decline, while Cichorieae increase, suggesting a shift towards more pasture-dominated landscapes¹⁹. This trend is particularly evident in the moat profile (panel b), whereas in the wells, located within the settlement, the indicators

of crop fields do not decrease, probably reflecting the transport and storage of harvested crops inside the site (panel c).

In general, pollen data show largely synchronous trends in cereals and legumes, suggesting their cultivation as rotation or intercropping of food–fodder plants. By contrast, grassland indicators sometimes alternate with those of crop fields, although this pattern is not consistently expressed across all sequences. The clearest and most coherent trends are observed in the Noceto lower tank¹¹⁶ (panel d), where the particular archaeological context produces a predominantly anthropogenic rather than environmental pollen signal.

Overall, these patterns reflect a resilient agro-silvopastoral system in which crop cultivation, animal grazing and woodland management were closely integrated. This repeated set of practices ensured sustainability for most of the lifetime of the villages, throughout the MBA and early RBA phases. In the later stages, however, the system appears unable to maintain adequate resource levels to support demographic growth. This decline may also reflect limitations in agronomic practices required to sustain long-term soil fertility, particularly the reduced cultivation of legumes, which are nitrogen-enriching crops, and the resulting constraints on effective crop rotation and long-term plant–soil nutrient feedbacks.

Among the factors proposed to explain the collapse of woodlands and cultivated fields are overexploitation and climatic instability, whose combined effects probably pushed the system beyond its resilience threshold^{51,117,118}. In this context, palaeoclimate archives from northern Italy provide an essential framework for assessing the role of external environmental stressors. These records document a sequence of alternating dry and relatively wetter intervals throughout the Bronze Age^{118,119}. After a relatively warm phase during the sixteenth to fifteenth centuries BC—coinciding with the establishment of the Terramare culture—a cooling phase developed in the fourteenth to thirteenth centuries BC, followed by renewed warming and increasing aridity, culminating in a pronounced drought peak around ~1200 BC. This latter phase corresponds to the 3.2 ka event¹²⁰, during which aridity proxies indicate drier conditions between 1200 and 1150 BC, which impacted societies across Europe and the Mediterranean.

helps elucidate the enduring relationships between culture and nature that shaped these permanent changes with particularly strong feedbacks between environmental and cultural dynamics in this system²¹. The progressive reduction of forest cover and the profound alteration of soils marked a long-term trend, as documented by numerous pollen diagrams of the period, and resulted from multiple interconnected causes. The nearly synchronous activity of several settlements, combined with high demographic pressure, also produced important regional consequences^{18,48}.

Within this environmental context, the combination of relatively sparse woodland cover, forest–clearing–grassland mosaics across the alluvial lowlands and abundant water resources probably favoured the establishment of Bronze Age settlements, as already proposed for the Neolithic⁴⁹, across the Po Plain. Palynological and stratigraphic data provide key indicators of woodland management, demonstrating how forest regeneration processes were actively shaped through repeated human disturbance and clarifying how woodland management practices contributed to the preservation and controlled regeneration of wood resources. The Po Plain region was rich in water and characterized by open woodlands or forest–clearing–grassland mosaics. On the one hand, Terramare communities may have deliberately chosen areas with naturally thinner woodland; on the other hand, they may have felled large numbers of trees for building purposes^{16,45}. Pollen

data comparing samples from inside the villages with those from the moats, located along the settlement edges, offer a plausible answer: although forests were cut down to supply timber, nearby woodlands were at least partially maintained, preventing a complete depletion of this essential resource.

Rapid oscillations in the pollen curves provide the clear evidence that woodland management in the Terramare system involved repeated cutting of oaks and other deciduous trees, consistent with coppice-type practices. Importantly, coppicing was not applied uniformly but selectively targeted tree species—probably in an early or emerging form—on the basis of their anatomo-ecological characteristics and regeneration capacity. These oscillations also show that cereals were intercropped or rotated with legumes in small, cultivated plots (Box 2), revealing a structured and multi-year organization of arable land. Together with indicators of grazing and water management, these signals depict a fully integrated agro-silvopastoral system characterized by a low forest canopy, alternating crop and pasture areas, and an artificial hydrological network that sustained the economic landscape of the Terramare. While studies based on tree rings and plant macroremains can only suggest coppice-like practices at the scale of individual trees or assemblages, the palynological evidence presented here identifies recurrent regeneration dynamics consistent with selective coppicing at the scale of the managed landscape. This represents an important

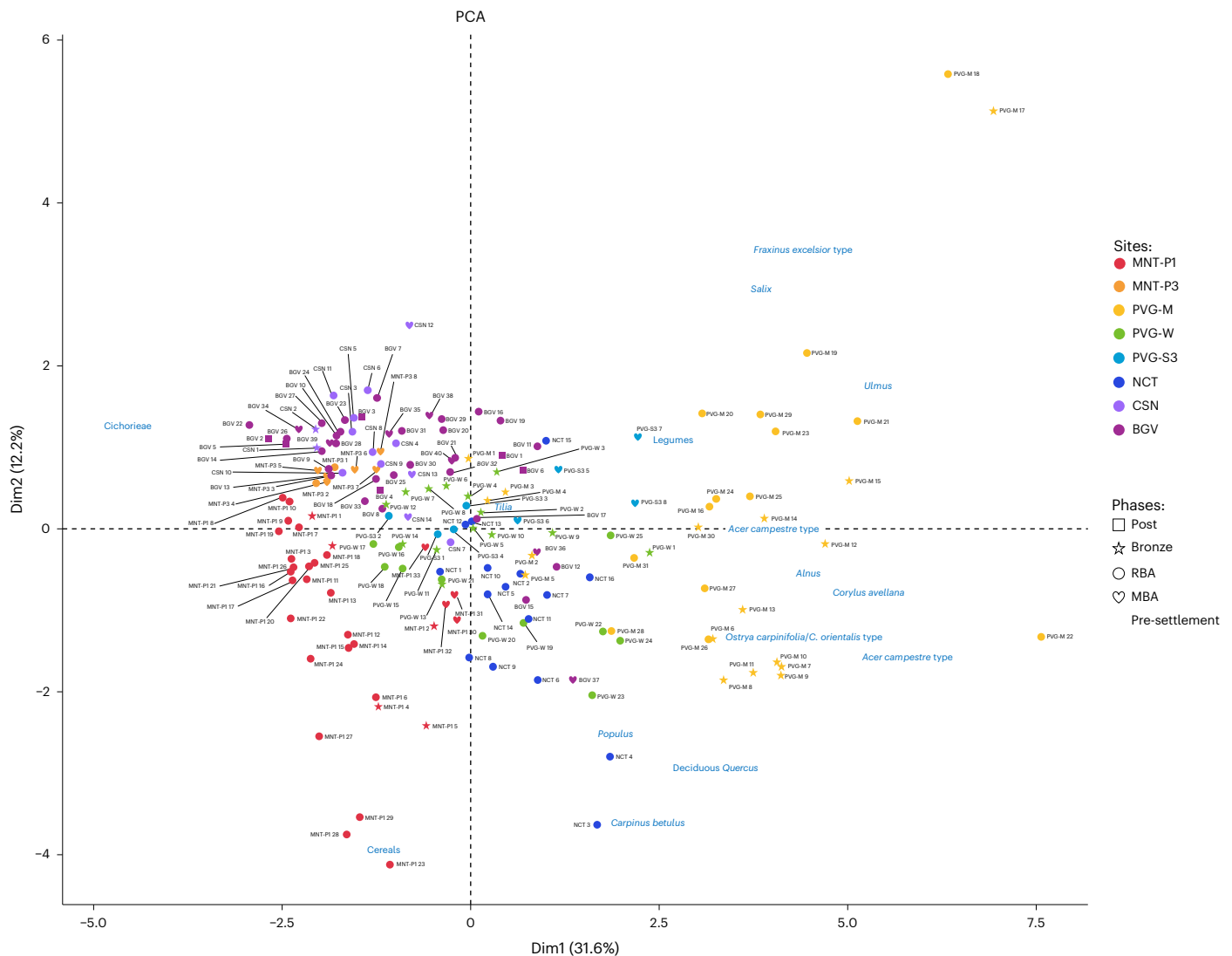


Fig. 5 | PCA of pollen samples from the Terramare sites analysed in this study. The PCA was performed on selected pollen taxa used to reconstruct the agro-silvopastoral system. Sample scores are projected onto the plane defined by the

first two principal components, which explain 31.6% (PC1) and 12.2% (PC2) of the total variance. Sites are distinguished by colours, whereas chronological phases are indicated by different symbols.

step forwards in the reconstruction of Bronze Age woodland exploitation and regeneration.

Rethinking forest naturalness through long-term ecological legacies

These findings challenge the widespread assumption that many temperate lowland forests represent natural baselines, demonstrating instead that their structure, composition and regeneration dynamics are the product of millennia of biologically mediated human management. While a growing body of literature has demonstrated that many ecosystems have been shaped by millennia of human activity (for example, refs. 6,50), our results provide robust evidence of how such long-term management operated in lowland temperate forests, by revealing recurrent, regeneration-driven dynamics that structured forest composition and function over time.

Depending on technological development and local environmental conditions, the Terramare system reflected a multifunctional land-use strategy integrating economic, social and ecological dimensions of landscape management. The Terramare communities were fully aware of the value of natural resources and maintained oak woodlands through coppicing for several centuries, until increasing

environmental stress limited the persistence of this management system on the Po Plain. The collapse of woodland and arable productivity in the late RBA, after centuries of sustainable integration of coppiced woods, fields and pastures, represents a turning point in the Terramare system, revealing how even the most finely tuned land-use strategies can falter when pressure on woodlands surpasses the regenerative limits of the landscape⁵¹. The trajectory of a 'Wood Age' society—characterized by highly specialized and selective forest management yet ultimately facing ecological limits—further indicates that sustainability arises not from improved exploitation of a single resource alone but from diversified management strategies grounded in deep functional knowledge of plant species and vegetation assemblages.

Overall, this case thus illustrates how socio-ecological resilience can be exceeded when resource demand and environmental stress converge, marking the breakdown of a long-maintained equilibrium between people and the wooded landscape. The perspective developed in this paper reframes the Terramare as an early example of sustained landscape management, highlighting how long-term human intervention has shaped present-day ecosystem trajectories and how these enduring legacies continue to inform our understanding of human–environment interactions.

Methods

This study integrates high-resolution pollen records with archaeological, stratigraphic and environmental data to reconstruct woodland management, forest regeneration and land-use dynamics in the Terramare area.

Archaeological and interdisciplinary framework

Scientific investigation of the Terramare began in the mid-nineteenth century and has progressively developed into a strongly interdisciplinary field. Over time, research has integrated archaeology and geoarchaeology, with a range of bioarchaeological and palaeoecological approaches aimed at reconstructing settlement organization, land use and environmental framework^{44,52}. Within this framework, archaeobotanical studies have included systematic sampling for carpology (seeds and fruits) and anthracology/xylology (charcoal and wood remains). Additional proxies have been applied at selected sites, including phytolith analysis (for example, Fondo Paviani⁵³) and plant chemical residue analyses, such as molecular biomarkers from ceramic vessels at Pilastrì⁴³ and lipid miliacine identification in sediments at Poviglio⁵⁴.

Qualitative and taxonomic xylological and anthracological remains, reflecting woody species composition, were recovered from all Terramare sites. Across the investigated contexts, deciduous *Quercus* was consistently represented; at Montale, *Carpinus betulus*, *Fraxinus*, *Acer*, *Tilia* and hygrophilous *Populus/Salix* and *Alnus* were also identified, while *Ulmus* was additionally recorded at Poviglio. The Terramara di Montale macroremain dataset is provided in Supplementary Table 2.

The Terramare settlements were established in the central sector of the alluvial plain of the Po River. These wooden villages were enclosed by palisades, sometimes reinforced with embankments and moats, which ensured protection and regulated local hydrological conditions. In most sites, the moats were probably connected to nearby rivers, enabling water collection and redistribution through canals for the irrigation of surrounding fields^{55,56}. The settlements thus acted as nodes in a broader hydro-ecological network, with moats serving both defensive and agricultural purposes. They also separated the residential area from the productive ‘zone of influence’ maintained for cultivation, animal husbandry and the managed use of surrounding vegetation and wild plant resources^{14,44}.

During the early phases (~1650–1350 BC), villages covered about 1–2 ha and usually consisted of pile dwellings arranged in rows. In later phases (~1350–1150 BC), some settlements were abandoned while others expanded, reaching up to 20 ha. Settlement density and population peaked during the late MBA and RBA^{14,48}. Continuous human presence and intensive activity over a confined area inevitably affected local plant communities and ecosystem functioning²¹, triggering both resource depletion and innovation in land-use practices.

Climate context

The development of the Terramare culture occurred within a phase of generally cooler and more humid conditions in northern Italy, consistent with Alpine cooling associated with the Lobben glacier advance^{57,58}. Regional palaeoclimate records also indicate subsequent variability during the Bronze Age, including episodes of warming and increasing aridity. Speleothem sequences from northern Italy document a shift towards warmer and drier conditions between ~1600 and ~1100 BC, with a pronounced dry phase around ~1200–1100 BC^{59–62}. This climatic framework provides the environmental background that modulated plant growth, forest regeneration dynamics and water availability, against which Terramare land-use practices and woodland management strategies are interpreted in this study¹⁰.

Biological basis of coppicing and criteria for its identification

Many tree species resprout naturally, allowing people to manage forest regeneration cycles between repeated cuts, typically at intervals of

5–30 years⁶³. Today, the interval between cuts within the same coppice compartment is generally 20–25 years for deciduous oaks and 30–35 years for *Ostrya carpinifolia*⁶⁴, whereas *Alnus* can reach rotation periods of up to 60 years⁶³. After each cutting cycle, regrowth occurs through the activation of dormant vegetative buds at the tree base⁶⁵. Although coppicing is frequently proposed as an established practice of woodland management in Europe since the Neolithic^{66,67}, unequivocal archaeological evidence of individual events remains rare, and most arguments for identifying the origin of wood remains are still somewhat speculative. Even so, coppicing appears to have been a key strategy for sustaining supplies of fuelwood and construction materials in a progressively disturbance-driven forest system.

The possibility of recognizing coppicing depends partly on site-specific conditions and is commonly based on comparisons with the structural and growth characteristics of living trees. In prehistoric contexts, such assessments rely primarily on wood-anatomical and tree-ring analyses^{68,69}. However, these indicators provide indirect rather than unequivocal evidence of coppicing, as similar growth patterns may also result from natural regeneration or ecological stress. Direct evidence—such as the preservation of stumps bearing multiple shoots or clearly defined age cohorts—is rarely available in archaeological contexts. Accordingly, Bleicher and Staub⁷⁰ argue that anatomical and dendro-archaeological criteria alone are insufficient to demonstrate coppicing, whereas Out et al.⁷¹ suggest that the combination of dendrochronological, anthracological and contextual archaeological data may allow the identification of managed regeneration cycles, offering a pragmatic framework for recognizing early coppicing practices.

The interpretation of coppicing signals from pollen data presents additional challenges because pollen percentages are compositional and may be affected by closed-sum effects. To minimize this problem, we evaluated short-term fluctuations in arboreal taxa using pollen sums excluding *Quercus* (Fig. 4), thereby reducing the influence of oak pollen variability on the representation of subordinate woody taxa. The interpretation is therefore based not on fluctuations in individual taxa alone but on the recurrent relationships between the *Quercus* curve and multiple subordinate woody taxa observed across different records.

Archaeological inferences of coppicing

In Europe, the earliest possible evidence of woodland management dates to the Mesolithic⁷², whereas evidence or interpretations of coppice-type woodland management have been proposed from the Neolithic⁷³ onwards, with examples from both northern and central regions. The straight, small-diameter wood used for the Sweet Track in the Somerset Levels (England, ~3807 BC)⁷⁴—one of the earliest known Neolithic timber trackways—was constructed from oak planks and small roundwood of hazel, alder and birch, showing features consistent with repeated cutting of young shoots. Although the excavators did not explicitly refer to coppicing, later dendro-anatomical studies of associated trackways in the same wetland complex suggest the use of managed or coppiced woodland^{74,75}. For the Linearbandkeramik culture of western Germany and Austria (Early Neolithic, ~5500–4900 BC), Kreuz⁷⁶ proposed that woodland clearance often involved cutting trees at about man’s height (pollarding) and allowing stumps to resprout. However, management practices such as pollarding, coppicing and shredding remain difficult to demonstrate directly without preserved wooden remains from waterlogged contexts. A possible case comes from the Eneolithic pile dwellings of Ljubljansko Barje in Slovenia (3700–2400 BC), where dendrochronological series of small-diameter timbers with uniform age cohorts have been interpreted as possible results of controlled vegetative regrowth or controlled pruning⁷⁷. Woodland management during the Bronze Age has also been documented through xylological analyses in Poland (Bruszczewo site, 2100–1650 BC; tree rings and wood anatomy)⁷⁸, and further direct indications of coppicing are known from the site of

Holme-next-the-Sea (Norfolk, England; ~2050 BC), where preserved stumps and timbers display clear signs of deliberate exploitation of resprouting tree populations for construction and fuel⁷⁹.

Archaeobotanical evidence from Late Neolithic and Early Bronze Age sites in northern Greece indicates the exploitation of local woodland resources, mainly for fuel and domestic activities, although Valamoti⁸⁰ reports no direct indication of coppicing or organized selective cutting.

In northern Italy, evidence of *scalvatura* (pruning for shoot removal) is known since the Neolithic, identified through small branches (2–10 cm) retaining bark and leaf-scar traces. At Genoa, ash branches show growth anomalies consistent with this practice, and similar indications have been proposed for Arene Candide on the basis of plant remains and soil micromorphology⁸¹. Coppicing inferred from dendrochronological and dendro-typological evidence has also been proposed at Isolino di Varese during Eneolithic and Bronze Age occupations^{82,83}.

Site selection

Numerous sites in the distribution area of the Terramare civilization have been investigated through archaeobotanical studies, and ten of them also include palynological analyses. For this study, we selected sites for which both analytical data and archaeological context are well constrained. All records are included in the BRAIN database⁸⁴ and correspond to the following sites (ID BRAIN): Poviglio (NER92), Montale (NER68), Noceto (NER79), Casinalbo (NER67), Baggiovvara (NER64), Pragatto (NER163) and Caorso (NER161). Some sites include more than one analysed pollen sequence.

Samples derive from archaeological and associated sedimentary archives and were selected to ensure robust palaeoenvironmental reconstructions and plant biodiversity assessment at local scale. On-site sampling consisted of vertical, high-resolution sequences obtained from archaeological trenches. In particular, the Montale and Poviglio on-site sequences derive from vertically exposed archaeological deposits formed during successive phases of settlement occupation, maintenance and associated activities.

Because the on-site sequences derive from stratified archaeological deposits rather than from continuously accumulating natural archives, chronological resolution is established primarily through archaeological stratigraphy, radiocarbon chronology and occupation phases. Geoarchaeological investigations of the studied sequences indicate that depositional discontinuities can be identified through stratigraphic observations and archaeological evidence, while substantial post-depositional reworking is absent or negligible.

A total of 33 samples across 325 cm were collected from a stratified archaeological trench at Montale, spanning approximately 350 years of occupation (~1600–1250 BC), while 31 samples across 150 cm were collected from the Poviglio moat, covering about 380 years (~1550–1170 BC). This corresponds to an average temporal resolution of approximately 10–12 years between consecutive samples, although the actual duration represented by each sample may vary according to the archaeological stratigraphy. This temporal resolution is supported by the detailed archaeological chronology available for both sites and allows the detection of decadal-scale changes in land use and vegetation dynamics. The interpretation of vegetation dynamics is based on stratigraphically ordered pollen assemblages and their relationships to independently dated occupation phases. Comparisons among sites rely on shared chrono-cultural frameworks rather than on continuous age-depth models (Figs. 3 and 5).

Additional on-site samples derive from the ditch at Montale (6 samples), two wells at Poviglio (25 samples), five short profiles at Baggiovvara spanning the pre- and post-settlement phases (50 samples), vertical profiles adjacent to the settlements of Pragatto (18 samples) and Caorso (8 samples), the necropolis of Casinalbo (14 samples) and the Noceto votive tank, a unique, well-preserved wooden structure

dated to ~1600–1300 BC (16 samples). To provide local environmental and vegetation baselines, we also considered stratified sedimentary archives located in the settlement surroundings, including a trench situated approximately 150 m from the Montale settlement (Profile 3) and a sediment core drilled at approximately 150 m from the Poviglio site (S3 core). The spatial scale represented by these archaeological and sedimentary archives differs from that of typical off-site lake, mire or peat records, as they primarily document local vegetation and resource-use dynamics associated with the settlements rather than regional landscape patterns.

Chronology

The chronological framework adopted in this study follows a detailed chrono-typological scheme based on archaeological evidence and radiocarbon dating (Table 1)¹⁴. This framework integrates ceramic typology, stratigraphic descriptions and archaeological correlations, allowing the definition of precise settlement phases and occupation durations for each site and providing a robust temporal structure for the interpretation of vegetation dynamics and forest regeneration processes. Accordingly, the following occupation phases were identified: Poviglio (MBA2–3; RBA1–2), Montale (MBA2–3; RBA1), Noceto (MBA2–3), Casinalbo (MBA2–3; RBA; Roman), Pragatto and Baggiovvara (MBA2–3) and Caorso (MBA2–3; RBA).

Of particular interest is the presence, at Montale, at Casinalbo and in the near-site core of Poviglio, of pre-settlement levels. These provide a baseline for comparing local environmental conditions prior to the village construction with the impacts generated by subsequent occupation, allowing changes in plant communities and regeneration trajectories to be assessed through time.

Pollen analysis

Palynological sequences were collected during archaeological excavations by sampling vertical sections within trenches, using site-specific sampling intervals (for details, see ref. 19 for Poviglio, refs. 20,85 for Montale and ref. 21 for Casinalbo).

Pollen samples were processed following standard laboratory protocols at the Laboratory of Palynology and Palaeobotany of Modena and analysed under an optical microscope using reference atlases, identification keys and the reference pollen collection^{86,87}.

Percentage pollen diagrams were calculated using a standard pollen sum including all identified pollen taxa; where required by specific analytical objectives, alternative pollen sums were applied, as described in the following section. Diagram construction and visualization were performed using Tilia (v.2.1.1) (ref. 88). All data analysed in this study are available in the figshare repository⁸⁹.

Coppicing signal extraction

To isolate pollen signals potentially linked to coppicing, we applied a targeted analysis of taxon-specific regeneration dynamics rather than relying on overall arboreal pollen–non-arboreal pollen patterns, which are insufficient to distinguish short-term woodland management from broader vegetation dynamics. Coppicing-related signals were evaluated using taxa representative of mixed oak woodland (*Quercus* spp., *Corylus*, *Carpinus*, *Ostrya*, *Fraxinus* and *Ulmus*) and hygrophilous woods (*Alnus*, *Populus* and *Salix*).

Two working hypotheses guided this analysis: (A) small but recurrent reciprocal fluctuations were expected in taxa susceptible to coppicing, reflecting temporary reduction in pollen production following the cutting of catkin-bearing branches, followed by recovery during regrowth; and (B) cutting was assumed to have been applied more frequently to oaks, the prevalent anemophilous trees in mixed oak woods, which therefore provide the most continuous and informative pollen signal.

In mixed oak woodlands, the dynamics of woody taxa are shaped by competition, ecological succession and micro-environmental

conditions. Selective cutting modifies these dynamics by removing branches or individuals and promoting rapid resprouting, generating short-term fluctuations detectable in high-resolution pollen curves. To enhance the visibility of these short-term regeneration-driven oscillations, the pollen curves presented in Fig. 4 were calculated using pollen sums excluding *Quercus*, so that each plotted taxon reflects its own relative variability rather than being masked by the dominant oak signal.

Land-use signal extraction

Land-use practices were evaluated using pollen curves of cereals (*Avena/Triticum* and *Hordeum* groups, *Secale cereale* and *Cerealia undiff.*), legumes (representing both food plants and fodder crops) and Cichorieae as indicators of pasture development and grassland vegetation dynamics. These proxies were also included in the multivariate analysis (see the next section). To enable comparison among sites within the same time intervals, pollen samples from each sequence were assigned to chrono-typological phases (Table 1) on the basis of archaeological stratigraphy and available radiocarbon dating. These assignments were applied consistently across all pollen diagrams to track changes in plant community composition and land use through time.

PCA

A dataset comprising 175 samples (observations) and 14 variables was used to explore patterns in vegetation composition across the studied sites. The variables include arboreal taxa representative of mixed oak and hygrophilous woodlands (*Acer campestre* type, *Carpinus betulus*, *Corylus avellana*, *Fraxinus excelsior* type, *Ostrya carpinifolia*/*Carpinus orientalis* type, deciduous *Quercus*, *Tilia* and *Ulmus*, and *Alnus*, *Populus* and *Salix*, respectively), as well as indicators of land use (cereals, legumes and Cichorieae). Each observation corresponds to a pollen sample collected from one of the following sites: Montale Profile 1 (MNT-P1; 33 samples) and Profile 3 (MNT-P3; 8 samples); Poggio moat (PVG-M; 31 samples), wells (PVG-W; 25 samples) and near-site core S3 (PVG-S3; 8 samples); Noceto votive tank (NCT; 16 samples); Casalballo necropolis (CSN; 14 samples); and Baggiovara settlement area (BGV; 40 samples).

All analyses were performed using R (v.4.5.2)⁹⁰. PCA was applied on percentage data of the selected variables, with scaling enabled to standardize variable variance and to allow comparison among taxa with contrasting pollen production. Graphical outputs were produced using the factoextra package (v.1.0.7) (ref. 91) and ggplot2 (v.4.0.1) (ref. 92), generating biplots illustrating sample distribution and the ecological contribution of individual plant taxa.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The pollen datasets analysed in this study are archived in the Botanical Records of Archaeobotany Italian Network database at <https://brainplants.successoterra.net>. Processed data and analytical outputs supporting the conclusions of this study are available via figshare at <https://doi.org/10.6084/m9.figshare.32837054> (ref. 89). Source data are provided with this paper.

Code availability

No custom code was developed for this study.

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Acknowledgements

We thank the Soprintendenza Archeologia, Belle Arti e Paesaggio per la città metropolitana di Bologna e le province di Modena, Reggio Emilia e Ferrara and the Soprintendenza Archeologia, Belle Arti e Paesaggio per le province di Parma e Piacenza for granting access to archaeological sites and materials, and for their continuous support during fieldwork and research activities. We are grateful to the archaeologists M. Miari, G. Pellacani, F. Scacchetti and C. Cavazzuti for their collaboration, availability and invaluable support throughout the study. We thank G. Piovesan for insightful comments on forest dynamics.

Author contributions

A.M.M. and M.C. conceived the study. A.M.M. and A.F. designed the methodology. A.M.M., M.C. and A.C. interpreted the data. A.M.M. wrote the original draft. A.F., A.Z. and E.C. contributed to writing. A.M.M., A.F., E.C. and J.Z. conducted the pollen analyses. G.B. and M.R. conducted the macroremains analyses. A.F., E.C. and J.Z. harmonized and elaborated the data. E.C. and J.Z. prepared the figures. A.M.M., A.F., E.C., J.Z., M.C., A.C., G.B. and M.R. reviewed and edited the paper.

Funding

Part of this work was conducted within the framework of the project 'National Biodiversity Future Center-NBFC' under the National Recovery and Resilience Plan, Mission 4 Component 2 Investment 1.4 of the Italian Ministry of University and Research funded by the European Union—Next Generation EU. We acknowledge the financial contribution from the PRD2026 from the Department of Life Sciences, University of Modena and Reggio Emilia, Italy. Open access funding provided by Università degli Studi di Modena e Reggio Emilia within the CRUI-CARE Agreement.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41477-026-02425-2>.

Correspondence and requests for materials should be addressed to Anna Maria Mercuri or Assunta Florenzano.

Peer review information *Nature Plants* thanks José Sebastián Carrión, Ralph M. Fyfe and Chris Hunt for their contribution to the peer review of this work.

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Software and code

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Data collection No custom code, algorithms or software were developed for this study.

Data analysis Tilia v. 2.1.1 (Grimm, 2004) was used for pollen diagram construction, visualization and data analysis.
R v. 4.5.2 (R Core Team, 2023) was used for statistical analyses.
QGIS v.3.42 was used to generate the regional map in Fig. 1 (right panel).

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The pollen datasets analysed in this study are archived in the BRAIN (Botanical Records of Archaeobotany Italian Network - <https://brainplants.successoterra.net/>)

database. Processed data and analytical outputs supporting the conclusions of this study are available from Figshare (<https://doi.org/10.6084/m9.figshare.32837054>).

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Study description

This study investigates the long-term ecological legacy of early forest management in Bronze Age northern Italy using pollen records from multiple archaeological sites. By identifying recurring cyclic patterns in high-resolution pollen sequences, we provide a novel approach to detecting selective coppicing practices in the palaeoecological record. These data are used to reconstruct forest dynamics and human-environment interactions, and to assess how sustained management influenced forest regeneration over centennial timescales. No additional experimentation has been included in the revised manuscript during the revision process.

Research sample

Sediment samples were collected from seven sites associated with Bronze Age terramare settlements in northern Italy, including Poviglio and Montale. Samples for pollen analysis were taken at regular depth intervals or according to stratigraphic units, in order to obtain high-resolution records spanning the phases of Bronze Age occupation. Chronologies were established using radiocarbon dating, archaeological evidence, and stratigraphic correlation. The use of multiple sites allows assessment of the reproducibility of the observed pollen patterns.

Sampling strategy

Sampling was designed to capture vegetation dynamics in direct association with well-characterised archaeological contexts. Sites were selected based on the presence of Bronze Age terramare settlements with well-defined stratigraphy and continuous occupation phases. Sampling resolution was adapted to stratigraphic units and key archaeological phases to ensure temporal alignment between pollen data and human activity. The integration of palaeoecological, archaeological and geoarchaeological information guided both site selection and sampling design.

Data collection

Sediment cores were collected from sites associated with Bronze Age terramare settlements in the Po Plain (northern Italy). Sampling was conducted in close integration with archaeological and geoarchaeological investigations to ensure accurate contextualisation of the sequences. Samples for pollen analysis were taken at regular depth intervals or according to stratigraphic units, with multiple samples per unit or chronological phase to achieve high temporal resolution. Chronological control was established through radiocarbon dating, detailed archaeological stratigraphy, and correlation with well-characterised archaeological sequences. Standard pollen preparation techniques were applied, including sieving through a nylon mesh and density separation using heavy

liquid. A minimum of 280 and up to 1000 pollen grains per sample were counted to ensure statistical robustness. Pollen identification and counting were conducted independently by at least two analysts per sample to ensure consistency and reduce observer bias. Modern ecological data on forest dynamics and flowering cycles were used for comparison with fossil pollen assemblages. The dataset includes seven independent pollen sequences, two of which provide high-resolution stratigraphic records, enabling assessment of the reproducibility of the observed pollen cycles across sites.

Timing and spatial scale	The study focuses on Bronze Age occupation phases (Middle, Recent, Final) spanning five centuries, during which cyclic vegetation dynamics are observed. The temporal resolution of the pollen sequences allows identification of repeated changes occurring at decadal scales to centennial. Spatially, the study encompasses multiple sites within the Po Plain (northern Italy), enabling assessment of vegetation patterns at a regional scale rather than at a single-site level. The forest responses to anthropogenic disturbance identified in this study indicate persistent ecological effects that extend beyond the precise chronological and spatial framework analysed, highlighting the long-term impact of human activities on temperate forest ecosystems.
Data exclusions	Data from additional archaeological sites were not included where sampling and analytical procedures were not sufficiently controlled or comparable with those applied in this study. Only datasets meeting consistent methodological and contextual criteria were considered.
Reproducibility	Reproducibility is supported by the consistency of pollen patterns observed across multiple independent sequences. Seven sites were analysed, including two high-resolution records that clearly document repeated cyclic changes in forest composition. Comparable forest cover and vegetation patterns are observed across sites, supporting the robustness and reproducibility of the inferred vegetation dynamics. The approach used in this study, grounded in established palynological protocols, is readily transferable to other sites within interdisciplinary research frameworks, offering a reliable tool for reconstructing past vegetation dynamics at regional scales.
Randomization	Randomisation was not applicable to this study, as it is based on observational palaeoecological data derived from stratified sediment sequences.
Blinding	Blinding was not applicable to this study, as analyses were conducted on observational palaeoecological data with known stratigraphic context.
Did the study involve field work?	☒ Yes ☐ No

Field work, collection and transport

Field conditions	Fieldwork was conducted within controlled archaeological excavations of Bronze Age terramare settlements, under the supervision of academic or professional archaeologists. Palynologists were directly involved in the sampling process, allowing targeted collection of sediment samples within well-defined stratigraphic contexts. This ensured accurate contextualisation and preservation of the sediment sequences used for pollen analysis, and botanical survey on local environment.
Location	The study was conducted in the Po Plain, northern Italy.
Access & import/export	Samples were transported and analysed in accordance with applicable regulations.
Disturbance	Sampling was integrated within controlled archaeological excavations and did not result in additional disturbance beyond standard, authorised excavation activities.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☐	☒ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Palaeontology and Archaeology

Specimen provenance	Sediment samples analysed in this study were collected from stratified deposits within Bronze Age terramare settlements in the Po Plain (northern Italy). All samples derive from well-defined archaeological contexts documented during controlled excavations. Sampling was conducted with the permission and in collaboration with the directors of the archaeological investigations.
Specimen deposition	All samples are stored at the Laboratory of Palynology and Palaeobotany, Department of Life Sciences, University of Modena and Reggio Emilia (UNIMORE), Italy.
Dating methods	Chronologies were established using radiocarbon dating, stratigraphic correlation, and detailed archaeological frameworks based on well-documented occupation phases.
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Ethics oversight	Ethics approval was not required for this study.

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