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The Geoarchaeology of Agricultural Terraces in Europe: Construction, Resilience and Implications for Sediment Delivery

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ABSTRACT

Although the primary purpose of agricultural terracing can be assumed to be food production, it has been suggested that a secondary purpose was the control of soil erosion. In this paper, we explore this thesis with multi-proxy data from the TerrACE project, which studied 20 sites in a latitudinal transect across Europe. These sites show that terrace construction was often related to previous slope instability or erosion and that terracing maintained greater soil depths than the surrounding slopes. In some cases, it seems likely that the observation of landsliding that lowered slope angles and produced an accumulation of fractured regolith may have led to opportunistic terracing. The almost universal occurrence of multiple-phase sequences revealed maintenance and re-use that protected buried soil organic carbon. Three case studies show; headwater sediment and carbon retention by terracing, how terracing could be resilient to severe regional environmental events (eruption of Thera) and, lastly, the modelling of failure and sediment supply from vineyard terraces. Although there is no doubt that terracing reduced soil loss from slopes, whether the perception of an erosion risk was part of the conscious reasons for terrace construction is far harder to ascertain, but cross-cultural awareness of these factors does seem to be likely.

1 | Introduction

Agricultural or cultivation terraces were, until large-scale urbanization, the most common landform that humans had produced, created on slopes in almost all geographical regions and climates ranging from the Boreal to Tropical (Wei et al. 2016; Tarolli et al. 2019; Brown, Walsh, Fallu, et al. 2021). Their importance as anthromes (anthropogenic biomes) was and remains disproportionately significant when compared to their geographical extent due to the high level of ecosystem services that they can provide (Wei et al. 2016). Terraces have received faltering archaeological interest until relatively recently (Bevan et al. 2013; Brown, Walsh, Fallu, Cuchiarro et al. 2021; Turner et al. 2021; Pears et al. 2024), although earlier studies had devised both classification schema and theories of origins (Curwen 1932; Hall 1949; Spencer and Hale 1961). Both planform and terrace cross-sectional form have genetic and geomorphological implications (and consequences), with the binary classification of terraces into 'slow terraces', created through trapping downslope-moving soil and 'fast (or cut and fill) terraces', implying excavation and profile mixing if not inversion (Figure 1). Indeed, this is the primary division in terrace type between cut-and-fill terraces with walls, generally dry-stone walls, and lower generally less pronounced accretion type of terraces or lynchets (see Brown, Walsh, Fallu, et al. 2021 for further description). However, as illustrated in Figure 1, the two forms are not necessarily mutually exclusive as stone clearance could be part of both forms. Additionally, fast terraces with retaining dry-stone walls are more likely to pose a soil erosion threat after abandonment (Tarolli et al. 2014). Therefore, terrace form has a bearing on their impact on slope stability and sediment supply during the construction, use and abandonment phases. In addition, the construction mode is also likely to be partly substrate-controlled by both underlying lithology and surface conditions, as well as climate. This all has a direct bearing on four archaeological and environmental questions:

1. Were ancient terraces soil-erosion measures as well as examples of agricultural intensification, driven by population or cultural factors (e.g., ideology)?
2. Is there any evidence of cultivation and erosion on slopes before terracing?
3. Is there evidence that the creation of terraces was stimulated by environmental events?
4. Did the construction and use history of terraces impact on the historical record of soil erosion from catchments potentially providing an element of nonlinearity between population and erosion and causing variability in fluvial responses to anthropogenic disturbance (Verstraeten et al. 2017)?

These questions lay behind the TerrACE project and are specifically tackled in this paper. We go on to show how the

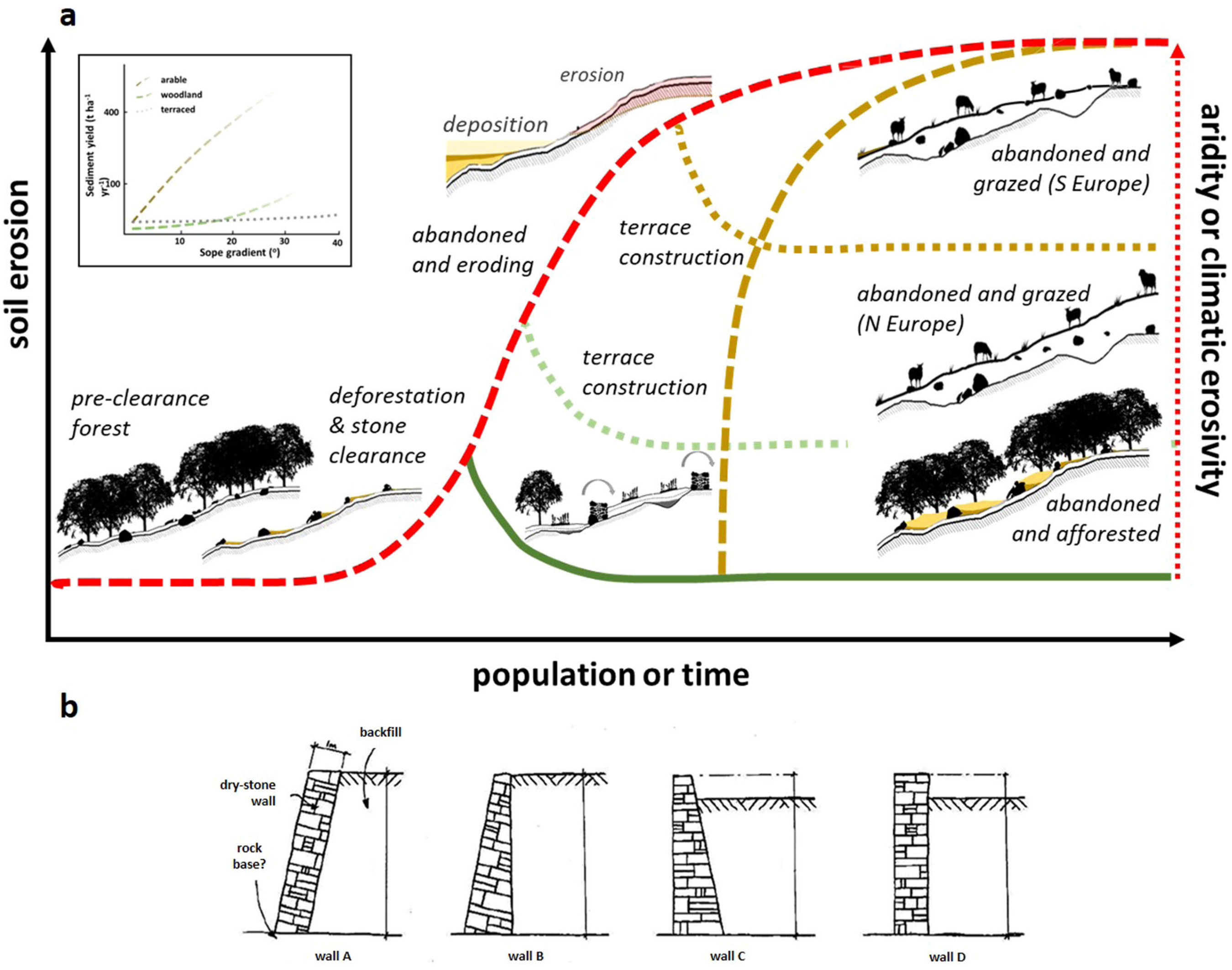

FIGURE 1 | (a) Terrace system history and soil erosion under different climatic conditions. The inset of hypothetical relationships between slope and sediment yield is based largely on Zhang et al. (2015) under different vegetation covers, with an assumption of terraced insensitivity to slope (b) dry-stone wall types (Burgoyne's wall geometries) adapted from Mundell et al. (2009).

geoarchaeological techniques used can potentially be used to predict terrace response to changing environmental conditions.

Terraces are closely connected to agricultural societies, although not necessarily domestication, as small terraces or lynchets are known from societies without domesticated plants or animals but where wild crops were cultivated, such as preagricultural Japan (Kagawa 1970). The chronology of terracing is now becoming clearer both in the Mediterranean and globally, and although there are examples in the earliest phases of agriculture, such as the well-known Neolithic Yemen terraces (Wilkinson 1999), their establishment across Eurasia largely dates from the European Bronze Age (c. 3000–1000 BCE), and most terrace systems are much younger (Turner et al. 2018; Srivastava et al. 2023). Notwithstanding, although some terraces appear to have been created in a single phase, in most cases, they evolved through multiple phases, including different construction methods at different times (Ferro-Vázquez et al. 2017; Brown et al. 2023). In most locations, the action of clearing woody-scrub or forest vegetation would have been the first phase in cultivation, and would have exposed ground conditions that could have required further action such as stone clearance. The action of creating field systems with walls, or even hurdles for stock control, has been observed to have created 'natural' lynchets (Verrill and Tipping 2010). This suggests an interplay of social and environmental factors and likely non-linearity of erosional response to population increase as well as unintended causality even in prehistory (Brown and Walsh 2016; Carleton and Collard 2020). In order to try and infer the cognitive aspects of terrace construction, we need to observe the physical factors constraining, or promoting, particular construction activities. These include the depth and workability of the pre-existing soils, stone coverage, soil fertility, terrace size and soil erodibility, all of which can then be compared to the terrace construction methods and chronology. This was an almost impossible task until the development of sediment-based dating, particularly luminescence methods, and even more recently, the application of new proxies for soil development, such as portable optically stimulated luminescence (pOSL) (Brown, Walsh, Fallu, et al. 2021; Srivastava et al. 2023). After considering the aggregate data for a transect of 20 sites across Europe, three more detailed case studies concerning terrace resilience are presented.

2 | Methods

A wide spectrum of geoarchaeological methods have been used in this study, and for the standard methods, reference is made to earlier papers for each area of research. The surveying techniques used included terrestrial laser scanning (TLS), unmanned autonomous vehicle (UAV) with structure from motion photogrammetry (UAV-SfM) and data fusion of topography methods (see Cucchiaro et al. 2020). The purpose of this multiple-technique approach was to capture both the vertical and horizontal detail of the terrace staircase, which allowed for modelling of volumes in some cases (see Section 5.3). For stratigraphic recording, pOSL and portable Xray-fluorescence (pXRF) were combined to yield high-precision proxy data on accumulation history and identify hiatuses or even 'reversals' caused by sediment overturning in the record as well as assess the degree of bioturbation. For dating, we used full OSL analyses supplemented by AMS radiocarbon dating. This was essential in areas with poor luminescence signals in the sediments, and where there was no material suitable for standard 14C AMS, we had to use hydrogen pyrolysis (HyPy AMS 14C) dating of the most resistant organic fraction of the soil or so-called black carbon. For the determination of land use history, we used pollen and spores, organic matter and phytolith analyses; see Brown, Walsh, Fallu, et al. (2021) and the Supplementary Information in Brown et al. (2023).

3 | Palaeo-Geomorphological and Hydrological Inferences From Geoarchaeological Data

The terrace project has analysed 20 sites (Figure 2), from which there are sufficient data to compare the geomorphology, chronology and terrace use over time, as summarized in Table 1.

3.1 | Norwegian Sites

The four sites in Norway have different geomorphic contexts. The most northerly, Bjørskinn, is on a steep south-facing slope on the island of Andøya in the Vesteralen Island Group (Figure 4a). The mean slope (0.30 m m^{-1}) is mantled by sandy glacial deposits with regularly spaced gullies and evidence of shallow landslides. The farm on which the terraces are located was of high importance, having been owned by Nideros Cathedral (Trondheim) since at least the 13th century CE and managed as a large mixed farm by the church thereafter. The lowest terrace has retained nearly 1.4 m of terrace soils derived from a small ploughed area. The stones for the wall almost certainly came from this area, as above it is an area of uncleared land with partially buried large stones and podzolic soils. The site is also prone to snow avalanches, one of which destroyed the church just below this location in 1740 CE. Given the estimated date of the creation of the lowest terrace (median 1745–1767 CE), it is likely to have been constructed soon after this event and when the church had been moved to another location, although the graveyard was left below the terraces (Figure 3a). An additional stimulus for terrace construction may have been the promotion of potato growing, by priests in this area (in Norwegian 'potetprest')—this is highly likely because the farm was under the jurisdiction of the Cathedral at Nidaros, from which the potato priests were sent out in the mid-1700s CE and they would have almost certainly visited a large church-owned farm such as Bjørnskinn (Brandt 1973; Sagrusten 2018). However, the site was never fully abandoned, although compromised by gullying, with some cultivation of cereals and potatoes occurring into the 20th century.

The other three sites in Norway are 'fjord farms' located along and at the end of the Storfjorden–Sunnylvsfjorden–Geirangerfjorden system in western Norway. Two of the sites, Småge and Skotet, are situated on the flat plateau edge perched above the Storfjorden wall at 270 asl and 240 m asl, respectively, underlain by glacial sands and silts on structural benches of igneous bedrock (gneiss, granites and mica-schist). The fine sand-coarse silt is transitional in grain size to loess, as recently recorded at Folldal in central Norway (Dahl and Nielsen 2024). The third site, Homolong, is just above sea level at the end of the Gerangerfjorden at Geiranger. At Smoge and Homolong, there is evidence in the form of large boulders over fine sediments, suggesting mass movements on the

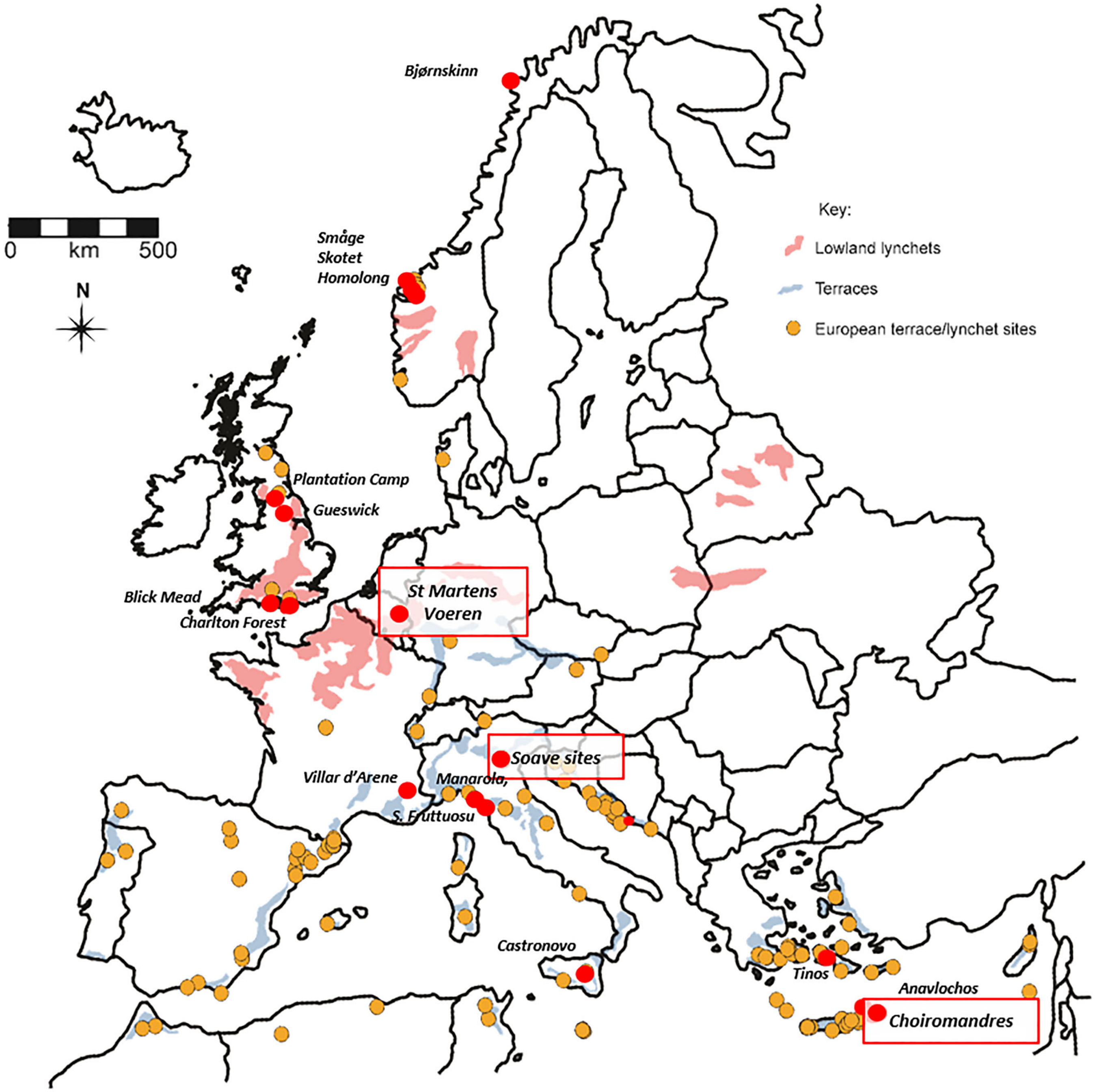

FIGURE 2 | Map of the TerrACE sites (red and named) and other terrace studies (yellow) held in the TerrACE database. Sites with red boxes around site names are the three case study sites in this paper, whereas the other sites mentioned in the paper are only named. The background colours are the areas known to be rich in terraces (blue) and lowland lynchets (pink).

slopes, and the terraces at Homolong clearly sit, and are developed on, the lower slope of a large landslide. The size of the boulders and the magnitude of the slide area suggest likely Late glacial or early Holocene age, although this cannot be confirmed. The terraces at Homolong use some of these boulders in their riser walling. From 14C dates on charcoal, it appears that this site dates from the mid-late 19th century CE (Supporting Information S1: Table S1, Figure 4b). This date and the thin and uncultivated soils behind the riser walls suggest that the site was not created for cultivation but probably for avalanche protection and grazing, although it is used today for goats. At Smoge, clearance dates to the Roman Iron Age (c. 1st century BCE) but intensive farming and the terraces date from the early Medieval age. At the large nearby farm at Skotet, terrace use dates from the 14th century CE to the present but with intensive use in the 16th century CE. Skotet is mentioned as a farm during the reign of Håkon the Good (10th century CE) in the Flateyarbok (Flatøb. III 312, cited in Skotte 2011, 82) and in the saga of St. Olav (13th century CE, Ol. D. hell, 1853, cited in Skotte 2011, 82), and Smoge has a Viking-age grave (10th century CE), probably of a blacksmith (RIngstad. 2014). Both the Smoge and Skotet terrace use overlaps with the later phases of the Gjørve excavated terrace site at Geirenger, which was Pre-Roman Iron Age, followed by high medieval, with evidence of agriculture in the migration period. Along with nearby

TABLE 1 | Geomorphic context and summary processes of sites within the TerrACE project.

Site, Lat Long.	Approximate dates functioning	Use	Phases	Substrate	Climate MAT Ann. Ppt.	Primary construction method	Geomorphic conditions	Erosion or collapse	Av. Slope Gradients and stability (m m^{-1})	Related references
Bjørnskinn	c. 1745–1767 CE-modern	Potatoes, cereals, grazing	2+	Late Pleistocene till	4.2°C 1140 mm	Stone clearance, ploughing	Avalanche track	Minor erosion	0.30	—
Skotet	Medieval (14–16th C CE)-modern	Barley, grazing	1+	Slope deposits over granitic gneiss	6.5°C 1356 mm	Turf inversion, ploughing	Deglacial fine sand and silts, colluviation	—	0.20	Dahle and Busengdal (2022)
Smogre	Roman Iron Age (1–2nd C BCE), Viking Age-modern	Barley, grazing	2+	Slope deposits over granitic gneiss	6.5°C 1356 mm	Ploughing	Deglacial fine sand and silts, colluviation	—	0.41	Dahle and Busengdal (2022)
Homolong	19th C CE	Grazing and avalanche protection	—	Diamicton over gneiss and granite	4°C 1268 mm	Stone clearance, dry-stone walling	Large landslide	—	0.34	Busengdal (2019)
Plantation Camp	Bronze Age to Medieval	Cereals	1	Glaciofluvial deposits over basaltic rocks	8°C 941 mm	Stone clearance, cut and fill	Periglacial slumping	—	0.25	Brown et al. (2023)
Gueswick	Late Iron Age to Romano-British	Cereals	?	Glaciofluvial deposits over sandstones	7°C 939 mm	Stone clearance, cut and fill	Periglacial deposits, colluviation?	—	0.18	Green (2020, 2022)
Charlton Forest	Bronze Age to Early Medieval	?	4	Loess over chalk	6.5°C 734 mm	Ploughing only	Tillage erosion	—	0.08	Pears et al. (2024)
Blick Mead	Early Bronze Age to Medieval		4	Loess over chalk	8°C 783 mm	Ploughing only	Tillage erosion	—	0.08	Pears et al. (2024)
St Martens Voeren	Iron Age to Post-Medieval	Cereals, hops, horticulture,	2+	Loess (reworked) over chalk	10°C 820 mm	Ploughing only	Periglacial reworking, colluviation	—	0.26	Cucchiaro et al. (2021); Pears et al. (2024, 2025)
Villar d'Arêne	Iron Age to present, peak in High medieval	Cereals, horticulture, grazing	3+	Mixed glacial sediment and weathered shales	5.3°C 861 mm	Stone clearance, cut and fill, some walling	Large arcuate landslides (T2, T3)	Gullying, wall collapse	0.27	Lavorel et al. (2017)
Beloca	Roman (200–400 CE)	Cereals, grazing	2?	Limestone, colluviation	15.8°C 907 mm	Cut and fill, ploughing, stone clearance	Colluviation	*Ploughed out in 2023*	0.17	—
Castle Soave	15th century–19th century CE	Vines, scrub woodland	1–2	Limestone	13.7°C 1170 mm	Stone clearance, ploughing, truncation	Sol truncation, erosion, gullying	Past erosion	0.11	—

(Continues)

TABLE 1 | (Continued)

Site, Lat Long.	Approximate dates functioning	Use	Phases	Substrate	Climate MAT Ann. Ppt.	Primary construction method	Geomorphic conditions	Erosion or collapse	Av. Slope Gradients and stability (m m^{-1})	Related references
Terrosa										
Fornace Michelon	15th century–19th century CE	Hemp, vines, scrub woodland	1	Thinly bedded sandy limestones	13.7°C 1170 mm	Cut and fill, wall construction	Scarp slope at the floodplain edge	Rilling, wall collapse (ongoing)	0.29	—
Manarola	17th century CE-present	Cereals, horticulture, vines	1+	Thinly bedded limestone, claystone and sandstones (turbidites)	13.6°C 1352 mm	Cut and fill, massive walling	Rapid valley incision, oversteepened slopes	Recent collapse, gullying, wall reconstruction	0.57+	—
San Fruttuoso, upper	11th century CE-present	Olives (recent horticulture)	1	Marls	13.8°C 1080 mm	Cut and fill	Arcuate slope form, probably from a large landslide (undated), springs	Severe erosion due to wild boar	0.59	—
San Fruttuoso, lower	800 BCE?	? olives	1	Conglomerates	13.8°C 1080 mm	Cut and fill, possible soil importation	Colluviation, truncation	Boar erosion, wall collapse	0.46	—
Castronovo	13th century CE-modern	Cereals, medicinal herbs, horticulture, vines	2+	Limestones, marls	16°C 400 mm	Cut and fill, pocket terraces, walls, burning	Redeposited marls infilling limestone valley	Wall collapse (c. 1600 CE)	0.27	—
Panormos, Tinos	Thought to be Roman, Byzantine and Venetian	Pistacchia, mulberry, goat?	2+	Schist	18.2°C 603 mm	Cut and fill, colluviation	Localized water erosion	Wall collapse ubiquitous	0.22	Vidali (2015); Lamont et al. (2019)
Anavlochos	Late Minoan IIC (c. 1200 BCE) to 7th century BCE (Early Iron Age)	Recent olives	2–3	Platy limestone	17.6°C 739 mm	Cut and fill,	Some colluviation	Wall collapse and burial	0.40	Gaignerot-Driessen et al. (2023)
Choiromandres	Pre-Minoan—post Minoan Period (c. 4000–1100 BCE)	Vines	2	Marls and sandstone	18.6°C 262 mm	Cut and fill	Valley incision, floods, tephra fall	Wall collapse, alluviation, erosion/ truncation	0.18	Vokotopoulos (2022)

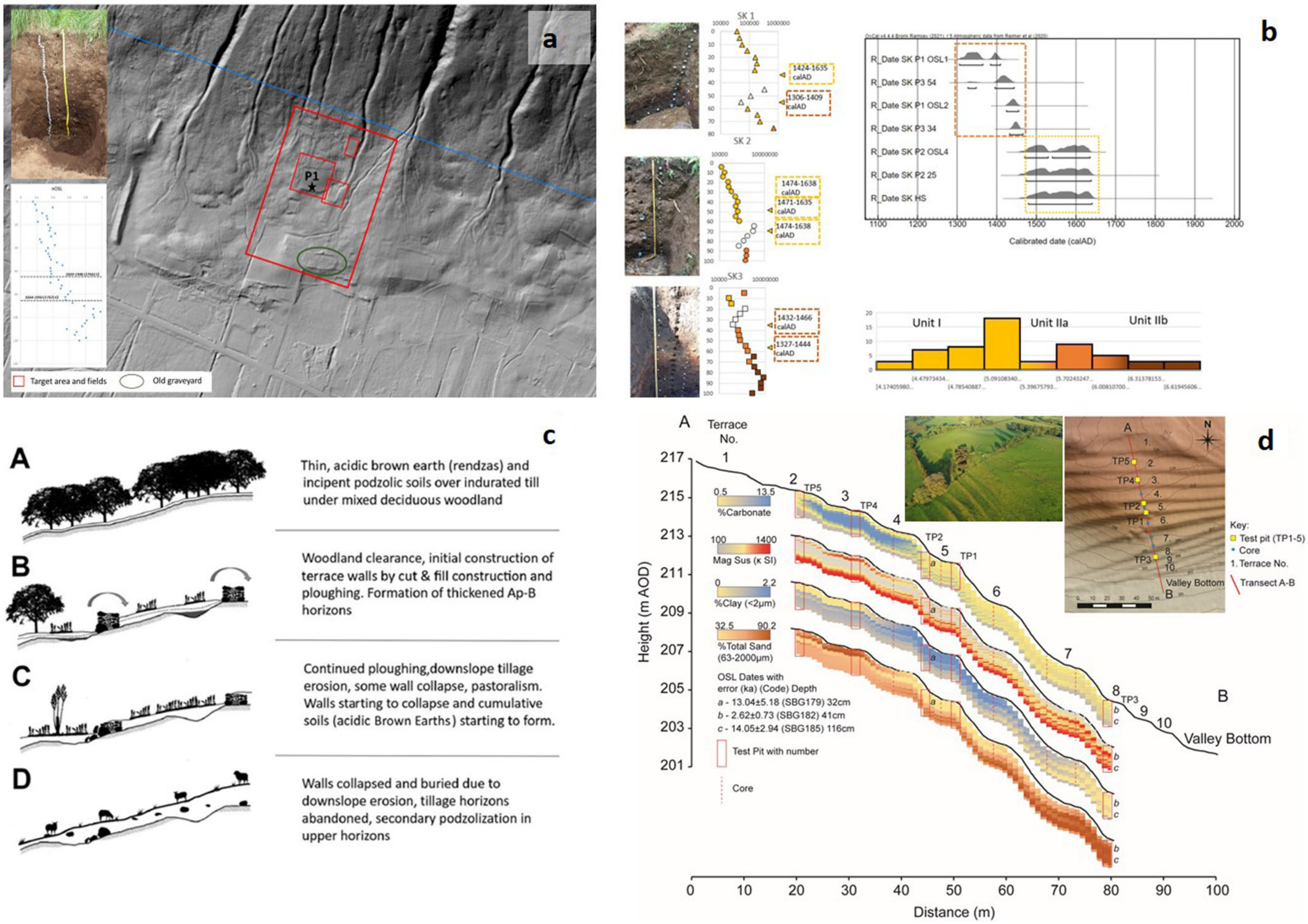

FIGURE 3 | Norwegian and UK sites (a) Bjørnskinn, Digital Terrain Model (DTM) obtained from aerial laser scanning (ALS) with pit 1 (P1) inset photo and pOSL, with depth in cm and pOSL in photon count per minute. (b) Skotet pits 1–3 with pOSL and dates. (c) Model of the Bronze Age terrace construction at Plantation Camp, Northumberland, from Brown et al. (2023). (d) Gueswick terrace geochemical transect modelled %$CaCO_3$, MS and %Clay content with insets of the terrace and sample locations on the DTM and an oblique aerial photo.

Viking graves (Busengdal 2019), these sites reinforce the importance of this fjord system for Viking-medieval habitation and agriculture in probably the most severe topography in the whole of Norway. There is also evidence of earlier Iron Age clearance and possibly earlier settlements in the outer parts of the fjords (Dahle and Busengdal 2022). Past land use data are only available from Smoge and Skotet and both were used for growing cereals (barley and oats) and grazing with cattle, sheep and goats. All the sites are geomorphologically stable and would be recolonized by birch-pine woodland if not maintained by cutting and grazing.

3.2 | The British Isles Sites

The four UK sites are more varied than the Norwegian sites both geologically and topographically. The most northerly site, Plantation Camp, is located on easterly facing slopes of the Beamish Valley (300–218 m asl) in Northumberland. The seven Mid-Late Bronze Age terraces are on a soliflucted diamicton derived from reworking the Kale Water Till Formation, which contained large erratic boulders. The stratigraphy suggests that these were moved or dug out and used to construct irregular walls (Brown et al. 2023). There is no evidence of slope instability before terrace construction on this relatively gentle concave slope (Table 1). However, the walls were eventually buried, and the terrace soil thickened irregularly down-slope, indicating that soil creep/tillage erosion occurred during their use or shortly after abandonment (Figure 3c). Today, the terraces are stable under grassland and no erosion from them has been observed over the downslope Medieval rigg and furrow. Approximately 90 km to the south at Gueswick in the Tees Valley, seven lynchet-type terraces were constructed probably in the late Iron or early Romano-British period (Green 2020, 2022) on a low-moderate concave slope (mean slope 0.20 m m^{-1}, Figure 4c). A number of pre-Holocene OSL dates are taken to indicate reworked late glacial substrate, suggesting that the treads were dug or ploughed into the slope creating the risers. No walls are present, but several large boulders were seen in the steep risers. Again, there is no direct evidence of slope failure; however, the sediments of the middle treads show depletion of carbonate and stratigraphy of the lowest tread fill (T3) showed pseudo-stratified sandy and silty horizon, suggesting erosional events down to 1.3 m below the ground surface (Figure 3), although we cannot be certain that this erosion probably dates from the Medieval period when the terraces were last cultivated for cereals. The two southerly sites, Charlton Forest, Sussex, and Blick Mead, Wiltshire, are both on

FIGURE 4 | Site views. (a) Bjørnskinn lower terrace wall and track, (b) Homolong lower terrace wall, (c) Gueswick under excavation (T4), (d) San Fruttuoso upper terrace erosion by wild boar, (e) Villar d'Arêne general view of the upper terraces and (f) Tinos general view (all photos by the authors).

lower slopes covered by late-glacial loess deposits and neither have evidence of either stone clearance or cut-and-fill activity. Both appear to be low lynchets created by ploughing over pre-existing lower-slope loess-rich soils (Pears et al. 2024). In both cases, earlier archaeological features were preserved under the lynchet sediments. At Blick Mead, the Bronze Age ploughing covered a nationally important Mesolithic butchery and likely camp site (Jacques et al. 2018; Hudson et al. 2022) and at Charlton Forest, where cultivation activity extended from the Bronze Age to the later Romano-British period, which truncated earlier ploughed soils (Roberts 2018; Pears et al. 2024). An association with loess is also evident at St Martens Voeren, in eastern Belgium, and is discussed further in Case Study 2.

3.3 | The French Sites

Villar d'Arêne, in the Western French Alps, was the last site to be studied in this project and analyses are still ongoing. The terraces cover a large NW-facing area from 1930 m asl down to the village of Villar d'Arêne (1644 m asl, Figure 4e), which sits on a terrace above the Romanche river. The Hameau De Valfroide massif has a large arcuate erosional form superimposed, on which are both small rotational landslides and linear gullies. The contour terrace system respect the larger gullies (e.g., Rif de l'Egoutail) but some smaller gullies cut the terraces. Each terrace has one or more associated stone piles and some risers are coursed dry-stone walls, whereas others are either stone-faced or earthen. The system is remarkably complex with archaeological features (two villages, several abandoned farms, a church, wells-fountains, paths and tracks), several hundred terraces and a complex land-holding system. Today, only the terraces above the village are cultivated (horticulture), but the system was under wide cultivation as late as the 1960s CE (Lavorel et al. 2017). The upper of two of the three terraces revealed a basal angular and dense, fractured, diamicton that resembled landslide or dry-debris-flow sediments over a smooth basal bedrock surface, and OSL dating of this units has yielded a date of c. 2400 Ka BCE. The terrace fills date from the Iron Age (c. 1950 BCE) to the 17th century CE, with a peak of activity in the high-medieval period (c. 700–1100 CE). Although there appears to be a gap of just over two millennia between the major slope failure(s) and the construction of the terraces, we know that the road that runs below the terraces through the town is Roman (or older), and some activity was causing deposition on the upper terrace at this time.

3.4 | The Italian Sites

Four terrace systems (S1–4) on different geologies were initially studied in the Soave region of NE Italy, only two of which were subjected to detailed further study. Site S1 at Terrossa is located on a promontory spur above two NE-SW–trending valleys cutting into the limestone scarp. There is also evidence of recent slope failures, some even cutting vineyards. Located on a slope bordering the Lessini Mounts, part of the Veneto Volcanic Province, the bedrock at Terrossa consists of fine-grained volcanic rock such as basalt. The basalt at Terrossa is deeply weathered, as is characteristic of the region (de Vecchi and Sedea 1995). Part of the site S2, Fornace Michelon, is the lowest site located at 36–64 m asl on the northern slopes of the Po valley and is the subject of Case Study 3. The Soave Castle site (S3) contour terraces are on south-facing slopes above the town, and although on a gentle convex–linear slope, there is topographic evidence of failures below the site and also in the adjacent valley, all of which have been terraced. Today, the site is under scrub and light woodland; although the areas around are mostly still under vines, we know that the vines were removed in 1975 CE and the scrub-woodland was removed in 2012 CE (Rinaldi pers. comm.).

The most northerly of the sites S4 at Beloca had a series of low-walled terraces, of which two were targeted for investigation. This area had been extensively ploughed and more terraces likely existed in the past. The mean slope and terrace tread slopes were low and the terraced area lay downslope of mature woodland covering a limestone scarp with abundant surface stones. The system is associated with a large farm and also a stone clearance pile over 3 m in height. The area has evidence of past settlement, including embankments, a circular tomb and lynchets on the plateau. The excavations revealed sequences of stoney silt clays up to 1.6 m deep, with a lower unit that dated to the late-Bronze Age to early Iron Age, but the sedaDNA evidence suggests that they were being used to grow cereals (barley) in the postmedieval period. The terraces appear on the Napoleonic cadastre and were vineyards in the 19th century. The site is closest to the town, Soave Castle, and has provided the most complete results with a chronology starting c. 1500 CE with possible abandonment in the 18th century CE. The sedaDNA from this site and Forace Michelon both show a period of Cannabaceae, most likely hemp, before the introduction of vines (both in the sedaDNA and historically attested). We can tentatively relate this to the expansion of the Venetian hinterland and widespread hemp growing in the region under the state-controlled monopoly of Venice (the 'Venetian model') in the 15th–16th centuries CE (Pezzolo 2006). Three other sites have been studied in Italy: two on the Ligurian coast and one in Sicily. Probably the most famous area of terracing in Europe, Cinque Terre, is also one of very few sites with World Heritage status due to its terraced landscape. At Manarola, two terraces were partially sectioned mid-way up the south-facing terraced hillside at 127–130 m asl (Figure 5e). Thick sandy silts retained by dry-stone walls have three OSL dates, which imply that the terrace was constructed in the 17th century (Table 1). SedaDNA suggests that although abandoned today, the terraces had been almost exclusively used for viticulture.

Fifty kilometres up the coast at San Fruttuoso, two terraces systems have been studied, both of which are associated with the Abbey of Fruttuoso. The geology here is mixed, with the upper terraces (Agrifugio Molini, Figure 4d) on red shale and the lower terraces (Abbey site) on a hard conglomerate. The upper terraces are clearly cut-and-fill contour terraces created within and downslope from a large arcuate slope form with a steep backwall and springs. This is most likely a past arcuate-rotational landslide of the marl above the harder conglomerates. The lower terraces are small pocket terraces constructed on conglomerate outcrops and a local story is that soil was imported by the monks to create these terraces. However, the evidence from the pXRF mineralogy shows a

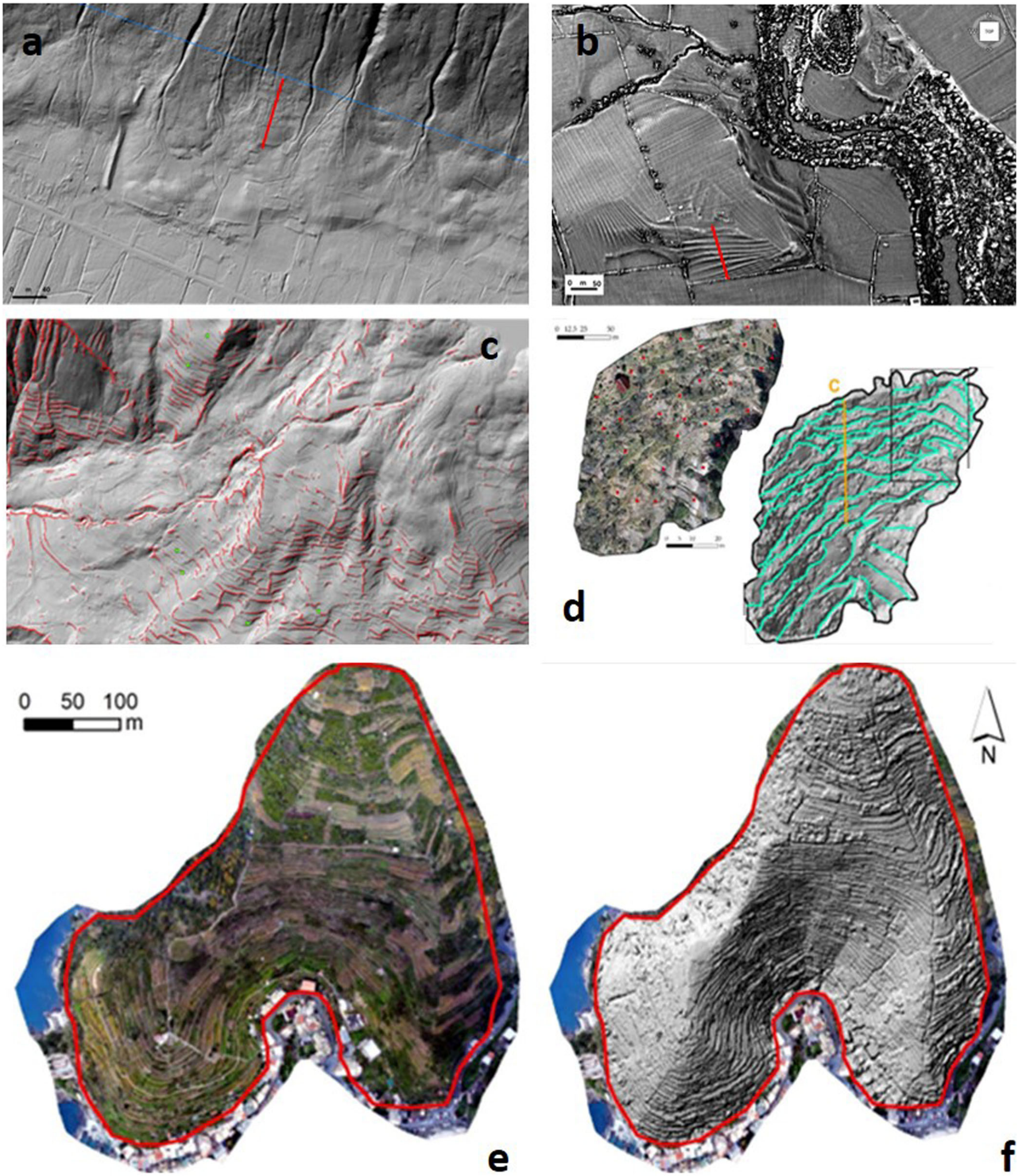

FIGURE 5 | DEMs of (a) Bjørnskinn (1 m Lidar), (b) Gueswick (1 m Lidar)k, (c) Villar d'Aêne (2 m Lidar with automatic terrace identification), (d) San Fruttuoso lower site (UAV-SfM with automatic terrace detection) and (e) Manarola UAV aerial mosaic and (f) Manarola UAV-SfM generated DEM.

clear difference between the sites that are most likely due to weathering of the iron-rich marls in the upper terraces (higher Mn/Fe) and conglomeritic sandstones in the lower terraces (higher Ca, Rb and Sr, Supporting Information S1: Figure S1).

One site was also investigated in central Sicily at Castronovo. One contour terrace with a walled riser was excavated in the Valle dei Mulini, adjacent to the medieval town of Castronovo di Sicilia, which is the subject of an ongoing archaeological project (Sicily in Transition Project) that has involved multiple studies of the archaeological history of the castle, town and its environs. The terrace has a complex stratigraphy on a slope under the Castronovo scarp that forms the boundary between the Sicanian Units of deep-water carbonates and the Numidian flysch that includes clay carbonates. The site has had material added, probably from the soils originally on the bedrock scarp above the terrace. The geomorphological origins of the site are unclear, but it is associated with springs, and the terrace has been created since approximately 1000 CE. The most notable geological aspect of the site is the high concentration of swelling clays (smectites) that make up the sediments that also contain, charcoal, pottery and bone fragments. This mineral is probably derived from the Numidia clay carbonates and is highly significant as a carrier of well-preserved sedaDNA. The terraces have been cultivated recently and there are no signs of erosion in the terrace system, and a riser-wall collapse that can be seen in the stratigraphy is dated to the 17th–18th century CE.

3.5 | The Greek Sites

Three sites were also studied in southern Greece: two from East Crete and one from the island of Tinos. The site at Choiromandres has provided a prehistoric chronology and forms Case Study 3. Approximately 70 km to the northwest of this site are terraces at Anavlochos associated with a Minoan and Greek Bronze Age settlement and necropolis site (Gaignerot-Driessen et al. 2023). The terraces cover several facets of the SW-facing slopes of the Anavlochos limestone massif (Figure 6).

The last site considered here, Panormos, is a terrace system on the Greek Island of Tinos in the Cyclades group. Tinos is one of the most terraced islands in the Mediterranean, approximately 80% covered by, now almost entirely abandoned, contour terracing (Vidali 2015). The dry-stone wall-faced contour terraces are of possible Hellenistic, Roman or Venetian age on schists and marbles. These profiles proved particularly difficult to date due to high mica content (preventing OSL dating) and a lack of charcoal; however, two dates from the base of the terrace fill in pit 3 yielded similar early medieval dates (6th–7th century CE, Supporting Information S1: Table S1). Although the oldest standing monastery on Tinos is 10th or 11th century (Kechrovouni), it is worth noting that the central Orthodox church of the town of Tinos was built of the site of an older church where a 7th-century CE icon was discovered (Figure 4f).

4 | Terrace Palaeohydrology

The biological techniques used in the project can also provide inferences for the short- to medium-term hydrological characteristics of the terrace soil profiles (Supporting Information S1: Table S1). In some cases, morphological evidence of gleying was seen in the field (by mottling and Fe:Mn nodules); in others, the Fe:Mn ratio suggests varying REDOX conditions (as seen in soil thin sections), and phytolith analysis provided evidence of both diatoms and freshwater sponges in several sites. Lastly, the sedaDNA occasionally revealed wetland taxa, and additional evidence is drawn from the examination of soils in thin section and the identification of diatoms and sponge spicules in Bjørskinn, Skotet and Gueswick during the micro-archaeological study. For example, in Skotet, the identification of *Pinnularia* and *Diloneis* suggests the presence of standing water in the area (Bathurst et al. 2010). In addition, the preliminary results of the ongoing study in Bjørskinn indicate an environment with sources of circumneutral freshwater, such as peat bogs and fens (Bathurst et al. 2010). Overall, the results for the Norwegian sites with the presence of diatoms of the genera *Pinnularia*, *Eutonia* and *Diploneis*, all related to pools and aerophilic environments, together with the absence of water control structures at these sites, suggest year-round moisture retention within the terrace soils. Finally, the identification in Gueswick of the genera *Nitzschia* suggests an alkaline environment (Bathurst et al. 2010) during this period. There are also palaeohydrological indications from the sedimentary ancient DNA (sedaDNA) where wetland plants are present and true aquatic plants that suggest ponds, channels of culverts (Supporting Information S1: Table S1). Terrace hydrology can be related to two factors: soil texture and the riser type. Unsurprisingly, the southern European sites were generally associated with channels and springs for irrigation. However, many northern European sites also showed evidence of water flow and retention, including two sites in northern England. As no water control structures were found at these sites, this suggests year-round moisture retention within the terrace soils.

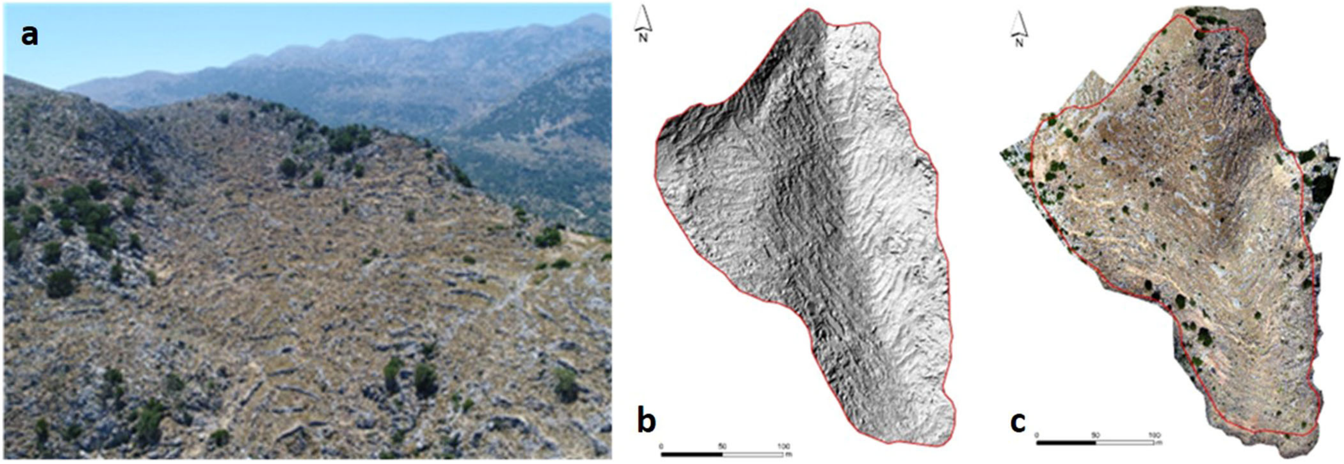

FIGURE 6 | (a) Anavlochos view from the UAV survey. (b, c) DTM and orthomosaic obtained from the UAV-SfM technique (0.5 m resolution).

Although not formally part of the TerrACE project, field measurements of the infiltration rate at the lowest profile at Villar-d'Arêne (T3, Le Légat) provide a steady-state estimate of up to 286 mL min^{-1} and using infiltrated DNA, this was clearly seen to be dominated by by-passing (preferential) flow particularly related to deep earthworm burrows (Beljadid et al. 2020). The combination of high infiltration rates on terraces and deep soils, often with an increase in clay at depth, allows drought resilience and maximizes growing-season productivity.

5 | Case Studies

5.1 | Loess and Small Catchment Sediment Accumulation Rates (SARs) at St Martens Voeren, Belgium

The study area in the Limburg province of eastern Belgium was selected due to the presence of lynchet-type terraces (Bats and Vanden Eed 1983; Van den Balck and Durinck 2012) in a small catchment (3.9 km^2, Figure 7a) and an earlier study of adjacent and similar lynchets by Nyssen et al. (2014). This study had estimated lynchet volumes and by applying hand-ploughing tillage erosion rates (from Ethiopia) had suggested that the lynchets would be approximately 1000 years old. Due to the presence and reworking of loess deposits over chalk, this site had high fertility and produced well-constrained OSL dates (Pears et al. 2024).

Despite cultivation and hilltop sediment transfer commencing in the Bronze Age (1900–700 BCE), lynchet formation at St Martens Voeren occurred from the Iron Age (700–50 BCE, Table 2, Figure 7). However, the most significant period of erosion and sediment transfer occurred in the early medieval (250–1000 CE) and medieval periods (1000–1550 CE), which resulted in major sedimentation and increased accumulation rates on the lower lynchet (Figure 7c) driven by arable cultivation. From the postmedieval period (1550–1750 CE), erosion decreased, with a shift to specialized hop cultivation and grazing on the lynchets.

The valley bottom sediment sequence from Sint Martens Voeren revealed over 2.5 m of alluvial sediments (T7), and the peak SAR is in the Medieval and Early Medieval periods (Table 2). Although comparable, the sediment flux rate (SFR) values for the lowest lynchet (78 m tread width) are lower than the peak catchment SFRs. Thus, even assuming that this lynchet is feeding into the valley floor, the peak rate is less than that of the catchment as a whole. This confirms that under the same population and climate pressure, there is an element of non-linearity that would be proportional to the area of the catchment covered by lynchets and the difference between the lowest lynchet SFR and the valley SFR.

The high lynchet and valley SARs at Sint Martens Voeren can be compared to the nearby Geul and Dilje catchments (Table 2). Pollen analysis from the Geul catchment suggests that complete forest cover was still present across much of the catchment in the Early and Middle Bronze Age (Bunnik 1999), but arable cultivation expanded in the Iron Age, Roman and particularly the medieval periods. This resulted in deforestation and significant soil erosion, with valley slope colluviation, the vast majority of which (80%) was stored within the catchment (De Moor et al. 2008; De Moor and Verstraeten 2008). This is also supported by research in the Nodebais catchment, to the west of Sint Martens Voeren, which has revealed that 4–6 m of colluviation occurred from the early Iron Age, Roman and medieval periods, a total clastic sediment mass in the valley bottoms of ~14×10^6 t (Rommens et al. 2007). Further calculations also demonstrated that the colluviation increased from c. 3.4 t ha^{-1} year, in the Early Iron Age to c. 5.4 t ha^{-1} year during the Roman Period, with a major increase in the medieval period (Rommens et al. 2007). Given the ubiquity of lynchets in this region and geological uniformity, lynchets likely played a major role in low sediment delivery ratios (Macaire et al. 2002; Lang 2003; Houben et al. 2006, 2012). These rates are also in line with erosion rates in the Belgian site ranging from 2.8 to 17.6 t ha year^{-1} for the last 1000 years and present-day rates of water erosion between 2.6 and 16.7 t ha year^{-1} (Verstraeten, Poesen, Goossens, et al. 2006; Verstraeten, Poesen, Gillijns, et al. 2006).

5.2 | Erosion and Resilience at Choiromandres, Crete

To investigate the deposition and use of these soils, geoarchaeological analysis (portable X-ray fluorescence spectroscopy, micromorphology, portable optically and Infrared stimulated luminescence profiling, optically stimulated luminescence dating and radiocarbon dating) and archaeobotanical analysis (phytolith and pollen analysis) were carried out. The ceramic chronology and bulk luminescence intensity of deposits within the valley channel show a rapid accumulation of material in the channel during the terminal Late Minoan IA period, to which the Theran eruption is also assigned. OSL dating for the channel deposit is centred on 1600 BCE. In the channel, deposition appears to cease until the Late Classical period (4th century BCE) based on the ceramic chronology. This hiatus is also reflected by a jump in luminescence intensity. Deposits from within the terraced area show accumulation during the following Late Minoan IB period. Importantly, deposits in the Choiromandres Valley preserve evidence of erosion in the 16th century BCE, predating the construction of the Late Minoan B terraces, as well as pollen and phytolith evidence for the cultivation of grapevines (*Vitis vinifera*) both before and after the Theran eruption.

The study site of Choiromandres in East Crete was selected for its secure ceramic chronology and its relationship with the upheaval caused by the Bronze Age eruption of Thera in the Aegean Sea in the 2nd millennium BCE. Although the eruption was one of the most significant natural disasters in the Mediterranean, its impact on the Minoan society on Crete, located approximately 150 km to the southwest, is heavily debated (Driessen and Macdonald 1997; Knappett et al. 2011; Driessen 2019; Lespez et al. 2021). The terrace and water management system at Choiromandres, near the Palace of Zakros on the east coast of Crete, presents compelling evidence that Minoan agriculture on East Crete survived the Thera eruption and that its effect instead stimulated an increased investment in agricultural infrastructure. At some point soon

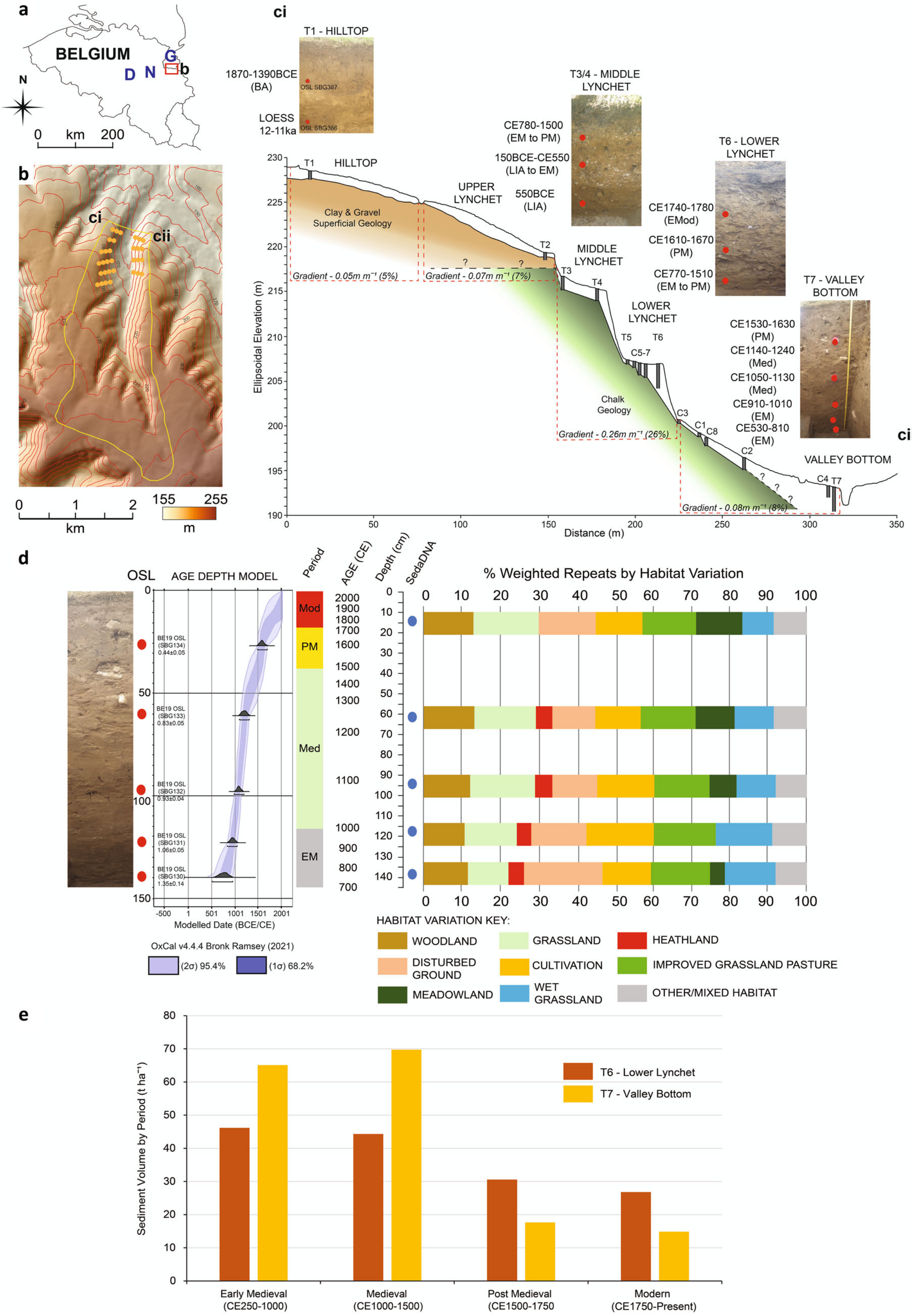

FIGURE 7 | (a) Location of Sint Martens Voeren in eastern Belgium, with comparable sedimentary systems discussed in the text (N—Nodebais, G—Geul, D—Dijle). (b) Valley catchment DTM for the transect and sampling location. The location of lynchets is marked with orange dots. (c) Sample cross section (ci–cii) at Sint Martens Voeren across the hilltop, lynchets and valley bottom land use areas, with sample sections and OSL dates. (d) Detailed section, age–depth model/sediment accumulation rate (SAR) for the dry-valley bottom with associated summary land use sequence derived from sedaDNA. (e) SFRs in tons per hectare for the Lower Lynchet (T6) and Valley Bottom (T7) between the Early Medieval and Modern periods.

TABLE 2 | Summary of Sint Martens Voeren (SMV) lynchet and valley bottom SARs, SFRs (by land-use area) and comparable data from studies in the region.

Landscape location/ catchment	Sample locations	Catchment area km^2	Av. surface gradient (m m^{-1})	Av. bedrock gradient (m m^{-1})	Chronological range	SAR (mm year^{-1})	SFR (t ha year^{-1})
SMV Hilltop	T1	—	0.06	0.05	Bronze Age to Modern	0.1	—
SMV Middle Lynchet	T3, T4	—	0.06	0.21	Iron Age to Modern	0.4-0.6	—
SMV Lower Lynchet	T6	0.008	0.03	0.26	Modern (1500 CE–present)	1.59	0.09
					Postmedieval (1500–1750 CE)	1.96	0.12
					Medieval (1000–1500 CE)	1.42	0.09
					E Medieval (250–1000 CE)	1.42	0.09
SMV Valley Bottom	T7	39	0.08	0.15	Modern (1750–present CE)	0.59	0.05
					Postmedieval (1500–1750 CE)	0.80	0.07
					Medieval (1000–1500 CE)	1.5	0.14
					Early Medieval (250–1000 CE)	0.93	0.08
Groensdal (Nyssen et al. 2014)	Groensdal	—	0.11	—	Est. 147 CE (336 BCE–630 CE)	—	(0.007)
	El Tawe	—	0.20	—	Est. 1623 CE (1560–1686 CE)	—	(0.014)
Geul (De Moor et al. 2008; De Moor and Verstraeten 2008)	Sections	380	—	—	Post-HMA (1500 CE–present)	—	0.60
Dijle (Notebaert et al. 2011)	Sections	758	—	—	c. 800–1000 CE	—	0.8–1.3
Nodebais (Rommens et al. 2007)	Sections	c. 0.3	—	—	Post-middle ages (1440 CE-present)	—	19.2 ± 1.9
					Middle ages (320–1440 CE)		18.0 ± 2.2

Note: The Nyssen et al. (2014) figures in parentheses are derived from observed hand tillage rates and the period is the resultant time estimate.

after the eruption, as indicated by the presence of tephra both in the foundation deposit and in retained terrace soils, the infrastructure within the valley was reconfigured to stop the flow of the channel and retain soils on the slopes. The valley was surrounded by a perimeter wall and a series of terraces walls were constructed in a herring-bone arrangement; furthermore, two dams were constructed at the top and bottom of the local channel. Deposits from within the agricultural system, which span the period of the eruption, show that an increase in erosion and redeposition was eventually controlled by the construction of the agricultural terraces (Vokotopoulos et al. 2014).

5.3 | Volume Estimation and Erosion Simulation at Soave, Italy

At Fornace Michelon high-resolution topographic (HRT) surveys using both TLS and UAV-SfM made it possible to produce high-resolution Digital Terrain Models (DTMs; 1 m resolution) from which geomorphometric parameters such as topographic curvature, walls and terrace edges could be extracted, even under scrubby vegetation (Figure 8a). The resultant DTM covered 3.5 ha area, with an elevation range between 80 and 115 m and an average slope of 35% (Figure 8a). Historically, the numerous frequently abandoned and collapsing dry-stone walled contour terraces with shrub vegetation (Figure 8a) across the steep slopes have been used to develop vineyards. However, after abandonment in 1975 CE, the soil had eroded entirely across several areas, exposing bedrock. Using the DTM of difference method (DoD) developed by Cucchiaro et al. (2021), the volumetric soil retention could be calculated (Figure 8b) and this can then be combined with geomorphological measures such as the index of connectivity (IC sensu, Cavalli et al. 2013). This was applied to the entire Fornace Michelon case study as well as one specific area of a drystone wall collapse (Figure 8c). The IC values have been classified into six classes (very low, low, medium, medium, high and very high) based on the Natural Breaks classification methods (Cucchiaro et al. 2021). The wall failure was used as a target for IC computations to identify the upstream connected area as the source area for sediment eroded and transported through the collapsed terrace. Knowing the connected area, it is also possible to quantify the volume of

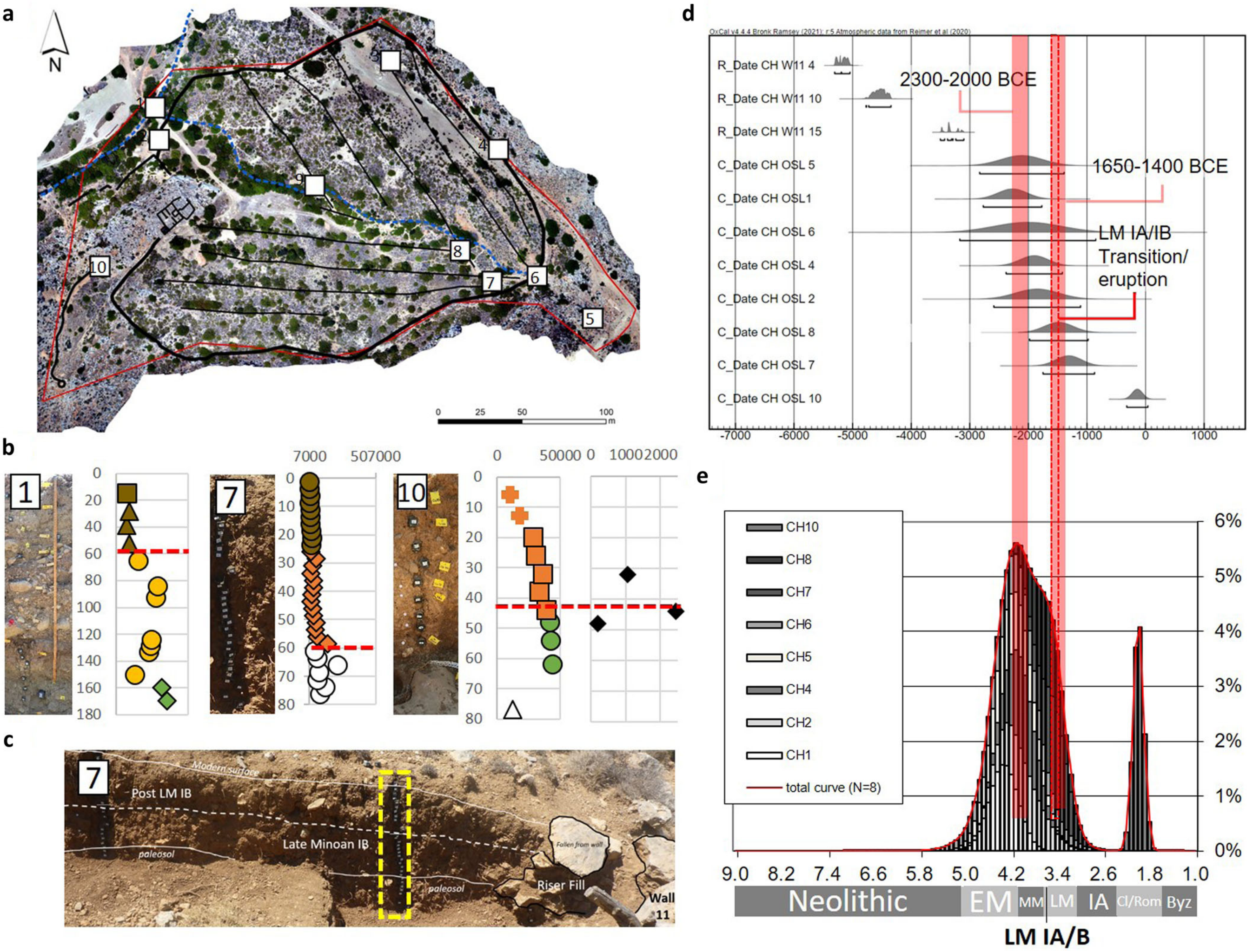

FIGURE 8 | (a) Plan (from UAV-SfM orthomosaic) of Choiromandres showing the sampling location, including the stream deposits (1), the wall 11 terrace (2) and enclosure wall 1 (3). (b) Luminescence profiles (1–3) and tephra concentrations (3) for sampled trenches. (c) Cross-section of a trench on the lower terrace and pOSL sampling profile, depths in cm and pOSL in photon count per minute. (d) Radiocarbon and OSL dates from Choiromandres, showing the time periods of the 4.2 ky climate even and the Thera eruption. (e) Summed probability distribution of the OSL dates.

sediments and associated soil organic carbon (SOC) that could be mobilized and exported downstream after a terrace failure. DoD computation (Figure 8b) for the area connected to the dry-stone wall collapse enables estimation of volumes of sediment that can be mobilized in the short term (i.e., zones with very high values of IC) and over more extended periods (i.e., zones with low IC values). Fortunately, in this case, most of the sediments that can be mobilized after the wall failure have a medium-low connectivity due mainly to a not very high slope in this zone. Here, the dry-stone wall collapse can result in the mobilization of a total of $332 \pm 24\,\mathrm{m}^3$ soil, corresponding to $5.91 \pm 0.43\,\mathrm{Mg\,C}$. This information can help us understand the consequences of neglect or abandonment of terraces.

6 | Discussion

The construction of terraces is an energetically expensive modification of the natural slope and geology. Therefore, it is unsurprising that most of the sites utilized facilitating geological structures or processes—either developing treads on linear outcrops of the bedrock (Skotet and St Martens Voeren), being constructed on previous landslides (Homolong, Villar d'Arêne, Upper San Fruttuoso) and/or utilizing thick upper slope loess or marls to provide a source of sediment to thicken terrace soils (Smågre, St Martens Voeren, Manerola, Upper San Fruttuoso, Choiromandres). This is in addition to evidence of the addition of charcoal or manure at Castronovo and Fornace Michelon, both practices at least as old as the Roman Period (Figure 9). However, we have not found evidence that soil was been transported into any site by hand (as alleged at San Fruttuoso-lower) despite it being historically recorded (Poirier 2016, Figure 10).

Of the 20 sites presented here, at least five show the collapse of dry-stone walling and three show the failure of unwalled risers. The mode of collapse of dry-stone walling depends upon the slope geometry and materials, or wall construction. Nonwalled risers (cf. lynchets) generally fail by shallow rotational soils slides, and gullying in highly cohesive soils is a function of slope angle, slope length, soil material (texture) and pore-water pressure. For dry-stone walls, failure can occur by bulging, bursting and toppling or a combination of these failure modes with or without soil piping (Powrie et al. 2002; Tarolli et al. 2014). The typically high infiltration rates are probably related to macropores and preferential flow pathways as revealed at Villar d'Arene and that can easily develop into piping as in Cinque Terre (Figure 1a), where it had caused wall collapse. The sensitivity of a wall to these modes of failure also depends upon the construction geometry of the wall—which can be classified using Burgoyne's retaining wall geometries (Figure 1b), where it can be ascertained. The form of wall construction and coursing is notoriously variable within even the same terrace systems and this was noted at many of the sites where it was related to topography and geology rather than age. The most common Burgoyne wall type is type D, with approximately the same width from the base to the top. Some bulging was seen, especially at Fornace Michelon and Cinque Terre (Manerola) and Homolong, but most collapse seems to be related to loss or displacement of top stones and the concentration of overland flow at this low point, as modelled in Case Study 5.3. More work is required on this, as wall geometry has varied over time, and culturally, thus providing differential resilience to collapse and retaining terrace sediments. Overall, the TerrACE study confirms the varieties of methods of agricultural terrace construction, which include cut and fill (Plantation Camp, Gueswick, Villar d'Arene), stone clearance (Bjørskinn, Plantation Camp, Villar d'Arêne) and ploughing (Bjørnskinn, Homolong, Charlton Forest, Blick Mead,) but also sites where multiple methods were used (Gueswick, St Martens Voeren). Several of the sites showed several phases of use (e.g., Villar d'Arêne), with likely abandonment or grazing use between cultivations. This has been found elsewhere, including in southern France (Le Vot et al. 2024), Israel (Davidovich et al. 2012) and throughout the Mediterranean (Turner et al. 2021), which is part of the long-term resilience of terrace systems.

Although not the central topic of this paper, studies of the carbon sequestration of selected terraces have (a) allowed estimates of the variable role of carbon storage of terraces, (b) revealed the extent of thermal sensitivity of this store and (c) highlighted the mechanisms, including accretion and weathering, that can facilitate SOC sequestration. Analysis at the Plantation Camp revealed 1.7 times more unprotected SOC in the terrace vs unterraced soils and a shift to more recalcitrant SOC with burial depth/age (Zhao et al. 2021). Paired (terrace vs. non-terrace) samples from five of the TerrACE sites revealed a difference in the controls on SOC stability that was increased in terrace soils by the accretion of new soil and lower respiration rates (Zhao et al. 2022). Finally, an analysis involving global data also revealed that terraces increased SOC stock by 19 ± 44% but that although always positive in the humid sites, it could be negative (a C loss) in arid terrace sites (Zhao et al. 2023). This study also has implications for the weathering rate, as a retention of higher SOC will increase weathering, particularly through hydrolysis, and this will increase reactive minerals, and work is underway in an attempt to quantify this effect.

Lastly, one of the impetuses for this study was the perceived mismatch between both climate and human activity as drivers of valley alluviation and the likely confounding factor of terrace construction (cf. Van Andel et al. 1990). This remains a difficult problem to resolve but the retention of soil on the lynchets and in the headwater tributary at St Martens Voeren and at the sites in Cinque Terre suggests a dampening role for terraces on sediment influx to main valleys that is culturally timed and may or may not be in phase with climatic drivers. If maintained, then terraces increase the societal resilience to detrimental climatic changes and so played an important innovatory part in facilitating demographic expansion—the so-called climate—population paradox (Brown and Walsh 2016; Weiberg et al. 2019). Terraces may only have been a part of this process along with the secondary products' revolution shifted up the demographic baseline (Sherratt 1981) and an adaptive cycle (Allen and Holling 2010).

7 | Concluding Remarks

This study has revealed a wide variety of terrace forms, ages and functions. Therefore, although lynchets and terraces may superficially look similar, this is rarely the case when examined in detail, and so stylistic dating is rarely possible, although it

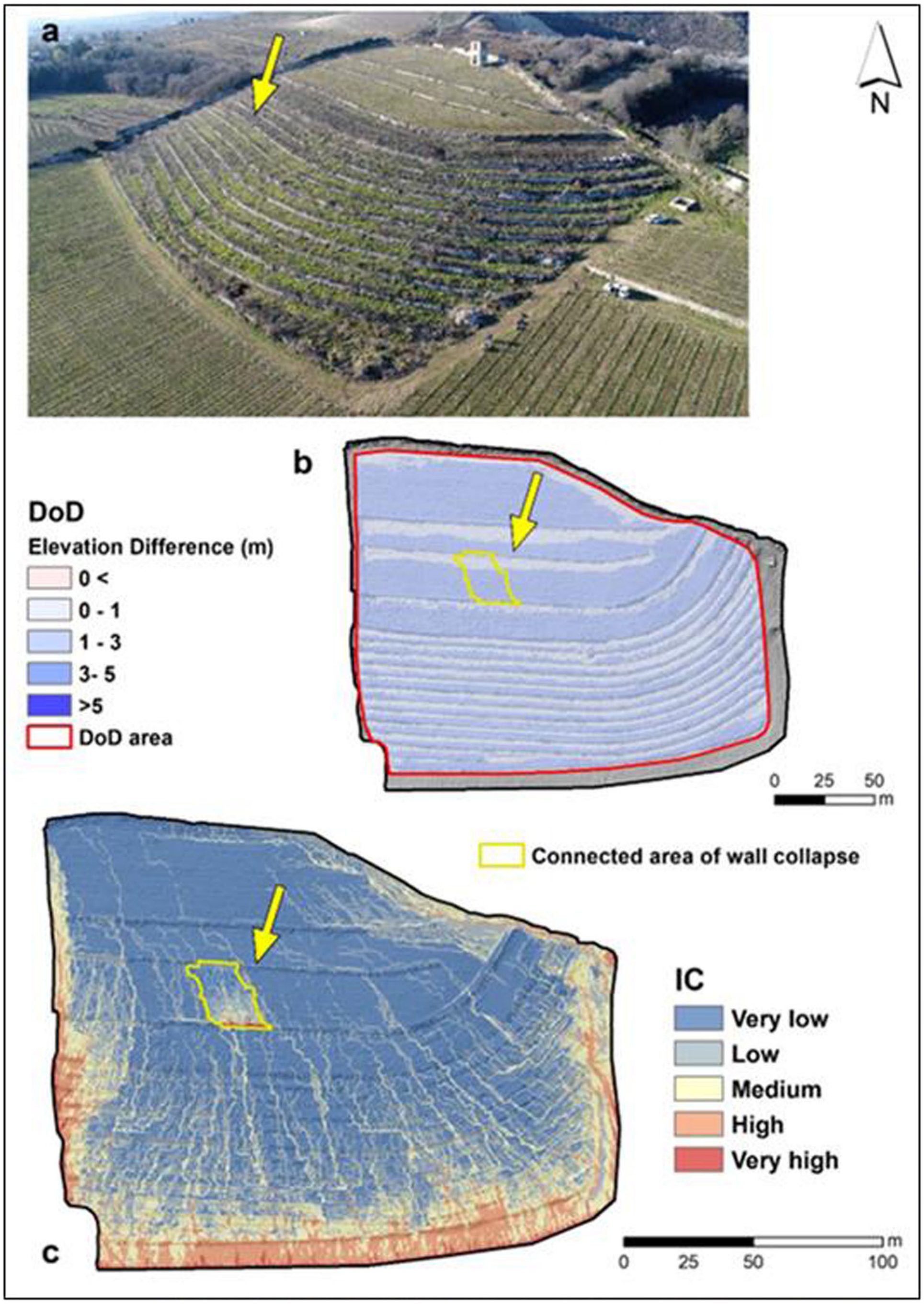

FIGURE 9 | Example of how it is possible to identify and quantify the soil connected to a dry-stone wall collapse using IC and DTM information in the Fornace Michelon DTM case study. (a) The Fornace Michelon study area with the identification of a drystone wall collapse. (b) DoD map used to calculate the volume of sediment that can potentially be mobilized. (c) IC map of the Fornace Michelon terrace system where the upstream area potentially connected in terms of sediment source with a dry-stone wall collapse was identified.

may reveal terrace remodelling (Pescini et al. 2025). Indeed, only two of the terrace systems presented here turned out to be the age that they had been assumed to be on archaeological criteria. Some have dated earlier, having been assumed to be of likely Medieval age (e.g., Gueswick and Beloca and Blick Mead). In the case of the late prehistoric terrace at Blick Mead, the site is in an area where chalkland lynchets are assumed to be Medieval despite very few dates sites (Pears et al. 2024). Other sites have dated more recent than they had been assumed to be (Bjørnskinn, Homolong and Castronovo). However, those with very strong spatial or archaeological associations with a particular period, such as Choiromandres and Villar d'Arêne, do fall into the same period as the archaeological structures associated with them.

Returning to the question posed at the outset of this paper, we can identify 'triggers' for construction in some cases. These include ecclesiastical—or elite, investment in the case of Choiromandres, San Fruttuoso, Soave Castle Site, possibly Panormos, Castronovo and even Bjørnskinn. Indeed, the economic role of the church is clear in some of these sites (San Fruttuoso, Bjørnskinn) but also highly likely in others such as St Martens Voeren. Other systems

FIGURE 10 | (a) Evidence of severe soil piping at Cinque terre in 2019. (b) Transport of manure and soil from the Pietro di Crescenzi, Condé Museum, Chantilly, France. Illustrations from Poirier (2016).

are best explained by increasing population pressure such as Plantation Camp, Gueswick, and probably Villar d'Arene—an area known to have been cleared and grazed from at least the Iron Age onwards. However, in several cases, no driving force is identifiable due to dating uncertainties and/or a lack of contextual archaeological information. Although we cannot *assume* that soil erosion was a contributory concern, it is likely that it played a role. This is especially true in Medieval sites, where practices such as the deliberate transporting and adding soil to hillside terraces are historically recorded, even if we cannot corroborate this posibility probably because it was uncommon. There is also an indirect link between several sites and slope instability—such as at Villar d'Arêne, San Fruttuoso and Homolong, which operated through the facilitation of terracing by debris flows and rotational landslide systems. The comparison of soil depths on the terraces with off-site control locations reveals the slope-storage effect of terraces and the study at St Martens Voeren also shows how the rates of within lynchet system sediment flux were an order of magnitude lower than the sediment flux produced by the rest of the largely unterraced catchment. Whether the retention of soil on hillslopes through the creation of slow-type terraces was intentional will probably never be provable in prehistory. However, this is largely a debate concerning how we frame ‘environmental management’ before the ‘Enlightenment’ and the degree to which we can assign a simple economic rationality to what were probably belief-driven actions ‘right or wrong’ (Patzel 2010). Certainly by the Classical period, it is clear that an understanding of soil conditions was becoming current at least among an educated elite, probably echoing local farm-based knowledge systems (Brevik and Hartemink 2010). Indeed, an appreciation of the valuable role of soil depth is well illustrated by the parable of ‘the sower’ in the New Testament of the Bible (Matthew 13: 1–23).

What is clear is that terracing, as probably the most obvious multi-biome anthrome, had high resilience in the later Holocene, both to landscape erosivity and socio-political events, the examples of which are volcanic eruptions and complex political changes in Medieval Italian governance and economy. This is largely due to their flexibility in terms of crops, allowing crop-switching and multi-crop production with variable labour demands. However, in general, terraces required a high rural population density and it is clear that abandonment, particularly in the 20th century CE, resulted from rural depopulation and the relatively high costs (both economically and in human terms) of crop production on terraces and not due to soil erosion. As encapsulated by the observation that life in working the terraces in the Alps was ‘6 months of hard work followed by 6 months of hell' (Villar d'Arêne resident).

The implications for future carbon storage and soil erosion will vary by climatic regime, with abandoned lynchets and terraces in northern Europe going under grass and at least for the foreseeable future having a low soil erosion risk. This is, however, not the case for southern Europe and the Mediterranean, where risks are posed by shallow landslide caused by the higher infiltration rate, collapsing dry-stone walling and gullying. If terraces are covered by forest, these risks may be lessened in the short term but fire poses a major risk that increases erosion rates in the medium-long term. It is clear that to prevent terraces in these areas turning from a beneficial legacy of human history to an ecosystem risk, planning and targeted societal intervention are required.

Acknowledgements

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.