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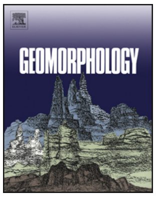

Invited review

Ending the Cinderella status of terraces and lynchets in Europe: The geomorphology of agricultural terraces and implications for ecosystem services and climate adaptation

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ABSTRACT

Terraces and lynchets are ubiquitous worldwide and can provide increasingly important Ecosystem Services (ESs), which may be able to mitigate aspects of climate change. They are also a major cause of non-linearity between climate and erosion rates in agricultural systems as noted from alluvial and colluvial studies. New research in the 'critical zone' has shown that we must now treat soil production as an ecologically sensitive variable with implications for soil carbon sequestration. In this review and synthesis paper we present a modified classification of agricultural terraces, review the theoretical background of both terraces and lynchets, and show how new techniques are transforming the study of these widespread and often ancient anthropogenic landforms. The problems of dating terraces and the time-consuming nature of costly surveys have held back the geomorphological and geoarchaeological study of terraces until now. The suite of techniques now available, and reviewed here, includes Digital Elevation Models (DEMs) - Structure from Motion (SfM) photogrammetry, Airborne and Terrestrial Laser Scanning (ALS-TLS); optically stimulated luminescence (OSL and pOSL), portable X-ray fluorescence (pXRF), Fourier-transform infra-red analysis (FTIR), phytoliths from plants, and potentially environmental DNA. Three process-related geomorphological questions arise from using this suite of methods; a) can they provide both a chronology of formation and use history, b) can we identify the sources of all the soil components? c) Can terrace soil formation and ecosystem services be modelled at the slope to catchment scale? The answers to these questions can also inform the management of the large areas of abandoned and under-used terraces that are resulting from both the economics of farming and rural population changes. Where possible, examples are drawn from a recently started ERC project (TerrACE; ERC-2018-2023; https://www.terrace.no/) that is working at over 15 sites in Europe ranging from Norway to Greece.

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1. Introduction

Agricultural terraces are volumetrically the largest and most common landforms that humans have ever produced (Brown et al., in press). They were created on all inhabited continents, and until the 19th Century CE, were the only major systematic, and worldwide, anthropogenic alteration to slopes. Agricultural terraces are therefore probably the most obvious geomorphological marker of the 'Anthropocene', but ironically their antiquity (some being over 6000 years old) presents a problem for any formal demarcation of the period (Brown et al., 2016). As landforms agricultural terraces have attracted almost as little interest from geomorphologists as they have from archaeologists, despite being:

1. A major modification to many hydrological catchments, occasionally forming the dominant slope form
2. A major store of sediment, soil and catchment nutrients (Ecosystem Services)
3. A potential cause of both stability and instability on slopes and in catchments.

The fundamental archaeological contexts of terraces are demographic and social (Broserup, 1965; Brown et al., in press), but the fundamental geomorphological context of agricultural terraces hillslope-based sediment and nutrient fluxes. This review and synthesis concentrates on the geomorphological context and role of terraces, as their formation, maintenance and abandonment are critical issues that govern the sustainability and the resilience of these landscapes to changing climate (Tarolli, 2014). The main reason for an upsurge in interest in the last few years has been their role in ecosystem services (Wei et al., 2016), which will also be reviewed here, as these environmental services are fundamentally geomorphological in nature. Under the umbrella term 'agricultural terraces' are a variety of landforms from ridges sub-parallel to the maximum slope created by ploughing and tillage erosion, often termed lynchets (c.f. classic lynchets sensu Curwen (1939)), to large horizontal benches cut into hillside bedrock. The processes involved in the creation and the stability of these forms are clearly different, so it is necessary to use some broad classification of the terrace form for differentiation. There have been several classification systems (Spencer and Hale, 1961; Wood, 1961; Grove and Rackham, 2001; Krahtopoulou and Frederick, 2008; Wei et al., 2016) and most are based on planform but include some slope-profile component or archaeological details. The classification proposed here is one that uses both planform and downslope profile, but minimal sub-surface information as this is typically not available. This is in line with first order geomorphological classification, and is also suited to the development of automated detection and mapping using remote sensing (Fig. 1) (Sofia et al., 2014a; Cucchiaro et al., 2020a).

A second reason for an increasing interest in terraces and lynchets is the emergence of new geomorphological techniques that are well suited to their study. This includes remote sensing, which fills a spatial gap in mapping technologies, direct sediment dating, geophysics, bio and geo palaeoenvironmental proxies and new analytical methods particularly field-based approaches.

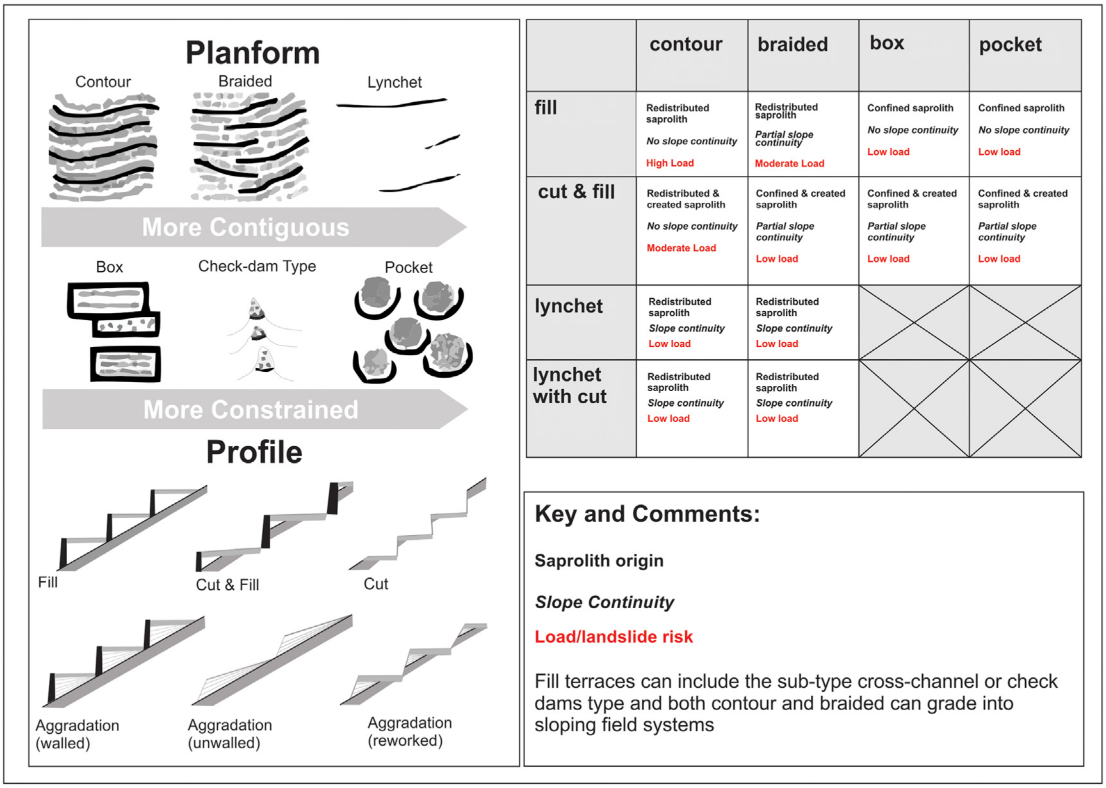
2. Terraces as modified slopes

Fundamentally a terrace is a modification of slope form which steepens one part of the slope, the riser, in order to reduce another part of the slope, the tread. We can therefore take a standard slope form, such as convexo-concave profile which can also act as the 'control slope', and sub-divide it into two slope populations (Fig. 2). The ratio between the riser distances and the tread distances will depend largely upon the initial slope if the tread is near to horizontal. Although *any* alteration of this type will alter sediment and nutrient fluxes (including water) the effect will vary depending upon the alterations of the sub-surface profile. This may be minimal with low ridges created on the regolith profile, or profound, with the relocation of regolith and re-deposition with no downslope profile continuity.

The starting point is the natural slope profile as a fundamental unit in geomorphology (Kirkby, 1971; Carson and Kirkby, 1972; Fig. 2b). Applying a simple continuity approach, the soil formation and hence the soil profile is the result of the soil production rate (Ps),which is itself a function of the rate of weathering, and any aerial input.

$$Sf = Ps - Ds \qquad (1)$$

where Sf is soil formation, Ps is the soil production rate = Ws + As, where Ws is the soil weathering rate and As is aerial input, and Ds is the total denudation rate combining erosion and chemical denudation. This can be reworked for soil mass by incorporating bulk density (Yoo and Mudd, 2008; Alewell et al., 2015). In this approach, if in dynamic equilibrium, the soil production rate is balanced by soil mass movement



	contour	braided	box	pocket
fill	Redistributed saprolith *No slope continuity* High Load	Redistributed saprolith *Partial slope continuity* Moderate Load	Confined saprolith *No slope continuity* Low load	Confined saprolith *No slope continuity* Low load
cut & fill	Redistributed & created saprolith *No slope continuity* Moderate Load	Confined & created saprolith *Partial slope continuity* Low load	Confined & created saprolith *Partial slope continuity* Low load	Confined & created saprolith *Partial slope continuity* Low load
lynchet	Redistributed saprolith *Slope continuity* Low load	Redistributed saprolith *Slope continuity* Low load		
lynchet with cut	Redistributed saprolith *Slope continuity* Low load	Redistributed saprolith *Slope continuity* Low load		

Key and Comments:

Saprolith origin

Slope Continuity

Load/landslide risk

Fill terraces can include the sub-type cross-channel or check dams type and both contour and braided can grade into sloping field systems

Fig. 1. Revised agricultural terrace classification system with geomorphological implications including risks.

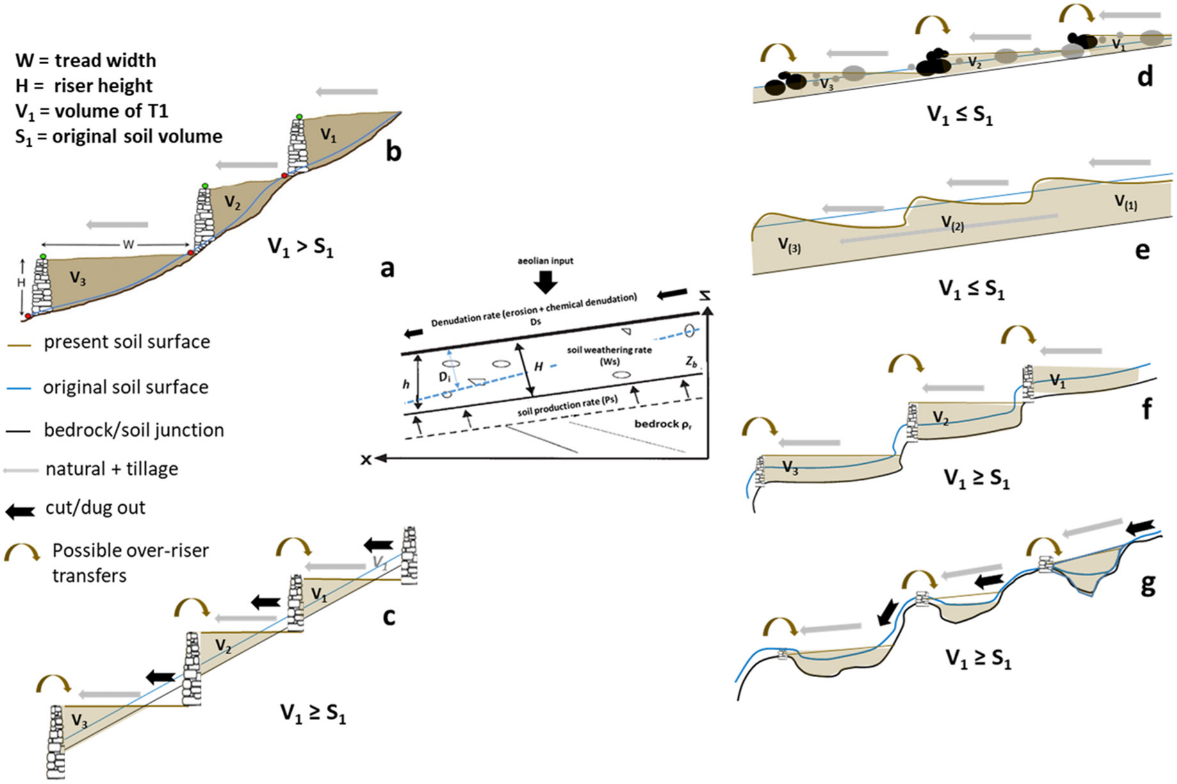


Fig. 2. Terrace profiles and nomenclature (a) soil and weathering system profile adapted from Heimsath et al. (2015), (b) simple idealized cut and fill terrace profile on a rectilinear-concave slope, (c) cut and fill terrace where bedrock is cut into on rectilinear slope, (d) terrace/lynchet created by stone clearance, (e) classical lynchets created by contour 8 ploughing and with headlands, (g) irregular bedrock-pocket terraces with bare bedrock in between terraces.

(creep), the surface erosion rate and the rate of downslope transfer of soil material as defined as the sediment transport rate (S in Eq. (2)). Many of these terms are known to be slope gradient dependent, most obviously the downslope movement of soil particulates by creep and rainsplash (exponent $n = 0–2$), and overland flow (exponent $n = 1.3–1.7$, Kirkby, 1971).

$$\mathrm{S} = \mathrm{f(x)}^{\mathrm{m}}\ (\mathrm{dh/dx})^{n} \tag{2}$$

where dh/dx is the slope gradient. This implies that S is proportional to distance from the watershed ($\mathrm{x^m}$) and this is disrupted by the creation of terraces, although not necessarily by lynchets. In trying to model this for continuous slopes there has been discussion over the role of soil depth and slope on soil production rates (Ahnert, 1977; Cox, 1980; Dietrich et al., 1995). The simplest model is an exponential function of soil thickness taken normal to the surface (Heimsath et al., 2000; Pelletier and Rasmussen, 2009). However, this leads to a problem as it implies that the highest rate of soil formation is at 0 soil thickness and there is abundant evidence that bare rock is not an optimum soil forming environment due to lack of moisture and organic activity. A more realistic model is a 'humped' relationship with the optimum being both rock type and climate dependent (Cox, 1980; Furbish and Fagherazzi, 2001; Brown and Walsh, 2016). In a natural system we can assume continuity downslope with a reduction in slope in convexo-concave slopes leading to time-dependent colluviation sequences at the soil base (Brown, 1992; Emadodin et al., 2010). Terracing perturbs this system into two sub-systems with limited but not normally zero continuity (Fig. 2c). The creation of 'slow terraces' by constructing walls along slope contours deliberately uses this disruption to trap soil from upslope, similar to a check-dam terrace type (Kabora et al., 2020). The result is that we can treat the system as composed of one sub-system (the riser) which has thinner or even no soil (in bedrock-cut terraces) and one sub-system with thicker soil at a lower slope. The slope continuity equation for the terrace sediment transport rate (St) can then be rewritten as varying from:

$$\mathrm{S_t} = \mathrm{f(x)}^{\mathrm{m}}\ (\mathrm{dh/dx})^{n}\ \text{to}\ \mathrm{S_t} = (\mathrm{dh/dx})^{n} \tag{3}$$

where $n = 0$ there is no net movement downslope and soil depth can only increase as the result of the soil production rate and any stable mineral content in anthropogenic additions, such as contained in manuring, or through subtractions such as cropping (for soluble nutrients). This model, and its variants, is derived from typical temperate soil-covered environments with moderate slopes, creep and overland flow dominating, with or without, basal sediment removal (Armstrong, 1982). However, many areas of terracing are in semi-arid, Mediterranean or tropical environments with steep slopes and thin soils (Agnoletti et al., 2019). Here, shallow mass failures are more common, and the role of terraces is variable (Fig. 2(d); Tarolli, 2014). If terraces are under the safety factor for slope stability then mass failure is reduced but if over then mass failure is induced. The problem is that the terrace mass changes over short timescales due to infiltration and saturation, but this load also increases over time as the soil thickens. This can be approximated by the safety factor of an infinite slope (Hammond et al., 1992) as formulated by Chae et al. (2015) for estimating the saturation depth ratio Hi(t) in Eq. (4). The result is that the most common form of terrace failure in these areas is shallow landsliding mostly of the riser face, but also occasionally to a slip-plane under the terrace system.

$$\mathrm{Hi(t)} = \mathrm{Di(t)/H} : 0 < \mathrm{Hi(t)} \leq 1 \tag{4}$$

where H is the depth of the unsaturated soil layer, and Di(t) is the saturation depth. From this it follows that the landsliding risk is controlled by soil volume (hence indirectly the weathering rate), rainfall, and factors which effect the infiltration rate such as soil porosity, organic matter and aggregate stability.

3. Terraces, weathering, soil formation and dating

3.1. Weathering and soil formation

As previously defined the soil thickness results from the balance of soil production and soil loss. In comparison to soil erosion, soil production has been rather neglected, largely because it is harder to measure and model, and it has a longer relaxation time. It is, however, critical as arguments about societal sustainability hinge on the "net rate at which it (a society) loses its soil" (Montgomery, 2007a,b). Most attempts to estimate the weathering rate have been made on natural or semi-natural soils (Table 1). Geomorphologists have developed a suite of methodologies for measuring the weathering rate of bedrock surfaces, ranging from tri-axial erosion meters to the use of ultra-sound, partly because of its relevance to building stone deterioration (Moses et al., 2014). More recently estimating the surface lowering rate has also been needed as an input to cosmogenic exposure age estimation (Balco et al., 2008). The measurement of in-situ rates of soil formation has always been a challenge. A classical approach is to use geomorphic chronosequences, such as resulting from Alpine glacial retreat (Egli et al., 2014; Matthews, 1992), sand dune stabilization (Jones et al., 2008) or dated lava flow or tephras (Vaughan and McDaniel, 2009). These have remarkably variable rates of soil development, measured as soil horizon thickness or nutrient retention capacity, both directly to plant succession, nitrogen fixation, and biologically mediated weathering. Rates can be as high as 70 mm $\mathrm{yr^{-1}\ kr^{-1}}$ but more commonly are under 2 mm $\mathrm{yr^{-1}\ kr^{-1}}$ (recalculated from Egli et al., 2014) but they are all either unconsolidated/weakly cemented substrates or very erodible rock. They all show a non-linear, generally sigmoidal relationship to time with rates decreasing towards the end of the time series, which in most of these cases is a few centuries. The most recent approach has been to use the in-situ produced cosmogenic method (Egli et al., 2014; Heimsath et al., 1997; Moses et al., 2014). This method measures the nuclide concentration in bedrock sampled under different soil depths (using Eq. (5), Fig. 3) enabling the plotting of soil production rates against depth (Heimsath et al., 1997).

$$\mathrm{Sf} \approx \text{э} = \Lambda/\mathrm{pr}(\mathrm{P}(\mathrm{h},\theta)/\mathrm{C}) \tag{5}$$

where э is the cosmogenic derived soil production, Λ is the mean attenuation length (165 g $\mathrm{cm^{-2}}$), pr is the rock bulk density, P is the nuclide product rate (in atoms $\mathrm{g^{-1}\ yr^{-1}}$) at depth h and slope θ, and C is the nuclide concentration (in atoms $\mathrm{g^{-1}}$).

Most of the cosmogenic studies are from cratonic areas and assume the soil is in equilibrium, even when it is suspected that this is not the case (Wilkinson et al., 2005). It has also been shown that very different rates can exist on a soil slope depending on the nature of the weathering processes (Riggins et al., 2011). It is, however, now possible to allow for the soil bulk density profile rather than assuming it as constant with depth, using a soil production rate procedure (Rodés and Evans, 2020). In a pioneering study on arable land on soft rocks in central England, Evans et al. (2019) found rates of soil formation that varied by depth (0.5 m to 2 m), by almost an order of magnitude and also varied with the petrographic nature of the bedrock (sandstone). Their estimate of soil lifespan (SI as calculated from Eq. (6)) was up to about 200 years, which is probably about the length of time the soils have been ploughed intensively but far shorter than the time since the land was cleared of forest and converted to agriculture which is probably c. 3000 years.

$$\mathrm{SI} = \mathrm{D/E} - \mathrm{F} \tag{6}$$

Table 1
Measurements of weathering and soil production. * estimate is minimum production rate, values in parentheses are averages.

Location	Climate	Geology	Method	Rate(s) mm kr^{-1}	Authors
N Sweden	Subarctic	Quartizite Amphibolite phyllite	“Qtz vein protrusion”	0.20.31.0	Andre, 1996
European Alps	Alpine	Silicates	Chronosequences	70–6670	Egli et al., 2014
Rocky Mts	Alpine	Granites	Chronosequences	0–650	Egli et al., 2014
California, USA	Mediterranean	Greywacke	^{10}Be, ^{26}Al	0.015–0.107	Heimsath et al., 1997
Oregon, USA	Temperate, Mediterranean type	Sandstone, siltstone	^{10}Be, ^{26}Al	0.033–0.359 (0.117)	Heimsath et al., 2001
Wyoming, USA	Temperate	Granite	^{10}Be, ^{26}Al	0.007–0.017*	Small et al., 1999
SEAustralia	Temperate	Granites	^{10}Be, ^{26}Al	Soil 0.001–0.068 tor 0.0007–0.023	Heimsath et al., 2000
Blue Mts, Australia	Warm Temperate	Sandstones	^{10}Be, ^{26}Al	0.0143–0.0281	Wilkinson et al., 2005
Central England, UK	Temperate	Sandstones	^{10}Be	26–96 ± 24–99	Evans et al., 2019
SW England, UK	Temperate	Granite	^{10}Be	10–20	Riggins et al., 2011
Alps, Europe	Temperate, Alpine	Paragneiss, granite	^{10}Be	Old soils 5.4–11.3 young soils 11.9–24.8 V young soils: 41.5–88.1	Alewell et al., 2015
Fujian, China	Subtropical	Alkali-feldspar granite	Quarry weathering pits	1.08 ± 0.05	Wang et al., 2020

where D is depth (equivalent to H), E is the erosion rate and F is the gross annual soil formation rate which equivalent to Sf. This again reflects the paradox of soils that appear to have been continuously or near-continuously cultivated far longer than is theoretically possible (Brown and Walsh, 2016). Taken together these methods all produce different results over several orders of magnitude (Egli et al., 2014), but this is not surprising since they are measuring different properties of varying bedrocks and solum in very different climates. Additionally, generalizing these rates to landscapes requires an assumption of equilibrium and the results from several of these studies (e.g. Heimsath et al., 2000; Wilkinson et al., 2005) imply that this is not the case. Taken at face value these rates of soil formation would indicate that over the Holocene soil weathering has made an insignificant contribution to terrace soils and that the process of artificially thickening soils would have reduced soil production rates.

However, there remains both theoretical and empirical ground to think that most of these rates may underestimate temperate weathering and soil production rates. Firstly, the thickest soil and also most productive/biologically active, are known to occur on soft, generally sedimentary bedrocks, and on soft volcanic soils. In these soils the bedrock-soil interface in the C soil horizon is variably permeable both hydrologically and mechanically (Wan et al., 2019). Critically, biological processes operate in this zone, now referred to as the ‘critical zone’ a term adapted from its use in chemistry, which emphasizes deep rock weathering-soil-biology interactions (Brantley et al., 2013; Chorover et al., 2011; Clair et al., 2015). These biological processes vary in scale from tree-throw bioturbation to oxidizing bacteria on mineral particles at the weathering front. Soil production is a complex biologically mediated set of processes which are affected by temperature, water availability and nutrient supply – part of which is bedrock derived. Attempts to quantify these processes have rarely been made although the use of weathering indices allows the comparison of bedrock weathering rates and plant available nutrient release particularly in extreme environments (Strømsøe and Paasche, 2011). The principle, is to use either, the excess of a non-reactive, biologically inert, bedrock-derived element (or mineral) in comparison to the bedrock concentration (also known as the chemical depletion factor (CDF, Alewell et al., 2015, Eq. (7))), or to use a ratio of a similar element (e.g. Zr or Ti) to a more labile element also derived from the bedrock (e.g. Ca or K). These weathering indices, which have almost exclusively been applied to geomorphic surfaces such as river terraces, and soil chronosequences have been shown to be sensitive to soil management (Derakhshan-Babaei et al., 2020). They are therefore potentially an indicator of the pedological effect of terrace formation if control soils are available.

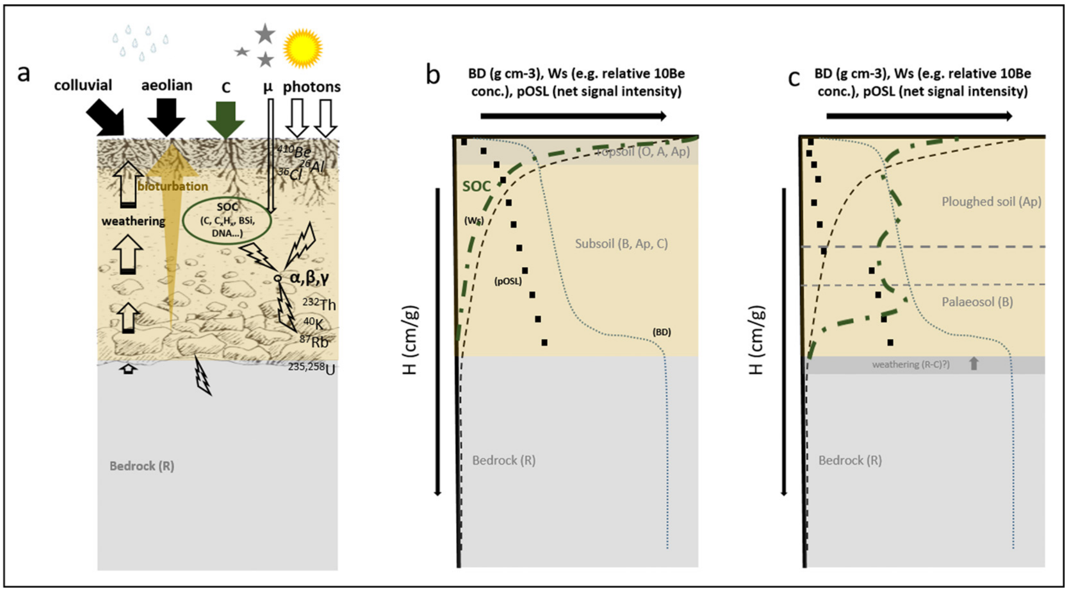


Fig. 3. The terrace soil profile with horizon notation and hypothetical depth profiles for measurement taken in TerrACE: (a) soil profile with mass (solid arrows) and energy inputs (unfilled arrows) to a particle in the soil profile, with typical unstable geological isotopes contributing ionizing radiation and target isotopes resulting from cosmic radiation (in italics) (b) hypothetical natural soil profile with depth trends in bulk density, weathering, pOSL and cosmogenic isotopes, (c) the same soil having been cultivated/ploughed. Due to homogenising effect of tillage the SOC of ploughed horizons should be approximately constant with depth.

$$\mathrm{CDF} = \left(1 - (\mathrm{Zr})_{\mathrm{rock}}/(\mathrm{Zr})_{\mathrm{soil}}\right) \tag{7}$$

where $(\mathrm{Zr})_{\mathrm{rock}}$ is the concentration of zirconium (or titanium) in the rock or parent material and $(\mathrm{Zr})_{\mathrm{soil}}$ is the concentration of Zr in the soil. Overall this research has shown that in most cases soil erosion on arable slopes exceeds soil production rates (Evans et al., 2019) and that in the absence of soil conservation measures cultivated soil has a lifetime in 10s–100s of years. Terraces, by reducing soil erosion, create conditions where Ds ≤ Ps and so soil remains a constant thickness or thickens over time. Even on terraces tillage, which almost always accompanies terrace creation and use, increases soil porosity, soil water retention capacity, soil organic matter stability and microbial activity, and the result of this should be increased weathering due principally to biohydroloysis, and this in turn should increase the soil production rate even if masked by increasing soil depth (Fig. 3). Soil erosion is also a loss of environmental function (unless it is captured downslope) and this is discussed further in Section 5. Models of soil formation and slope development are generally based on simple slope-systems either rectilinear or convexo-concave – as idealized natural slopes. However, the dependence of slopes processes on gradient and slope length implies that complex multi-compartment slope systems will be characterized by spatially variable rates of soil formation and erosion (Derakhshan-Babaei et al., 2020). Many of the terraces studied by the TerrACE Project display complex topographic profiles related to rock structure and lithological variation. There are also indications that the pre-existing spatial distribution of saprolite was highly variable, and that sediment now redistributed within the terrace treads came from specific sediment sources and particularly patches of superficial deposits, such as loess. Both these preliminary observations suggest that terrace construction may have exploited non-equilibrium slope conditions and they provide a challenge for the application of geomorphological theory and modelling with ecosystem services implications.

3.2. Dating terraces

Understanding anthropogenic landscape restructuring and terrace construction requires reliable age information so landscape features can be linked to cultural periods. One of the most common methods is correlating peaks in settlement to terrace construction (Gibson, 2001). Such approaches provide a broad indication of age but may be dominated by an intensive phase of occupation that may mask earlier phases of terracing (Wilkinson, 2003). Landscape survey and surface pottery scatters can also be used to compliment a terrace study as manuring processes, using household waste, can provide an indication of terrace use (Wilkinson, 1982; Bintliff and Snodgrass, 1988; Given, 2004). However, the presence of pottery may also be due to natural slope erosion processes and re-deposition of old material (Borejsza et al., 2008), and can thus provide only a maximum age of terrace formation. The application of chronometric techniques such as ^{14}C and optically stimulated luminescence (OSL) dating is thus essential for dating buried soil and fills of terraces. The success of OSL dating techniques depends on the availability of suitable minerals in the right grain size fractions (sand or silt) and the site formation processes (bleaching events). The following sections will discuss the use of these two techniques for dating terrace construction and maintenance or use. Establishing robust chronologies, especially in anthropogenic deposits, should make use of stratigraphic sequences and involve several independent techniques. Optical dating of sediments and soils using optically stimulated luminescence (OSL) techniques enables the direct dating of a burial event (Huntley et al., 1985). Commonly occurring minerals such as quartz and feldspar are exposed to light during erosion, transport and deposition (Aitken, 1985, 1998; Rittenour, 2008; Fuchs and Lang, 2009). After burial within a terrace, the absorption of a radiation dose induces a luminescence signal within the mineral that increases with time. The date of the burial event is calculated by measuring the amount of energy absorbed since burial (equivalent dose, De) divided by the environmental background radiation (dose rate) received (Wintle, 2008). Of the two minerals, quartz has an OSL signal that makes it most suitable for dating (Wintle and Adamiec, 2017) because the optical signal from feldspar is released more slowly and may fade over archaeological timescales (Wintle, 1977). For quartz, the single-aliquot dose regenerative (SAR) protocol is routinely used (Murray and Wintle, 2000, 2003). OSL dating techniques have been applied to a range of terrace, lynchet and colluvial deposits in Europe, the Mediterranean and the Near East where suitable luminescence characteristics have been found (Lang and Hönscheidt, 1999; Fuchs and Lang, 2009; Davidovich et al., 2012; Bevan et al., 2013, Beckers et al., 2013; Gadot et al., 2016; Kinnaird et al., 2017; Porat et al., 2018, 2019; Bell et al., 2020; Vervust et al., 2020).

3.2.1. Buried soils

Buried soils that are frequently found below the terrace wall provide an opportunity to understand the characteristics of the pre-existing environment prior to terrace construction and provide a minimum date (*terminus post quem*) for construction. The bleaching of grains in buried soils can be due to bioturbation (Bush and Feathers, 2003; Bateman et al., 2003, 2007), soil mixing due to mechanical processes, and even exposure of the surface to direct sunlight for a period of time prior to construction (Bailiff et al., 2018). In semi-arid environments, soils and sediments are sometimes imported to construct the terrace (Wilkinson, 2006), these deposits may derive from the same slope or from other locations, and so there may be limited opportunities for bleaching during the anthropogenic processes. The incorporation of wind-blown sediments into ground surfaces or trapped between terrace stone walls provide ideal opportunities for obtaining well-bleached grains for OSL dating (Davidovich et al., 2012), but these opportunities are usually limited to arid environments with strong aeolian dynamics.

3.2.2. Terrace fills

The study of terrace fills can provide opportunities to investigate maintenance events and rebuilding, as well as different phases of terrace use. In runoff systems, thin sheets of sediments are transported downslope by water, providing an opportunity for fine sediment to become bleached before being incorporated into the terrace fill (Avni et al., 2009). However, in fluvial and colluvial sediments, a residual signal may be left behind due to the incomplete exposure of the minerals to sunlight (referred to as partial bleaching) (Fuchs and Lang, 2009; Rittenour, 2008). If sand-sized quartz is available one way to identify the well-bleached grains within a sample is to apply small aliquots or single-grain dating techniques (Duller, 2008) and utilize statistical unmixing models. The comparison of multiple aliquots can reveal more than one grain age population related to the construction history of terraces as shown for Ramat Rahel, by Davidovich et al. (2012) (Fig. 4). Terrace fills are also subject to natural and anthropogenic alterations through time. Mixing by earthwork reworking of fills is common in certain environments (Bateman et al., 2003, 2007), which can provide opportunities for bleaching. Depending on the type of agricultural system, terrace fills are often routinely reworked for soil improvement. Ploughing for example, results in mixing of soil components and the distribution of fine clays within the sedimentary matrix (French and Whitelaw, 1999). It also moves sediment from deeper parts (the top 30-50 cm) to the surface of the terrace, thus repeatedly exposing grains to sunlight. This is modelled conceptually by a cascade model (Fig. 5) in which multiple events increase the probability of exposure to daylight and thus bleaching. However, incomplete bleaching remains a problem for which there are a number of solutions (Fuchs and Lang, 2009).

3.3. In situ luminescence

The portable OSL reader developed by SUERC (Glasgow, UK) is now widely used in geoarchaeological and geomorphological fieldwork as it

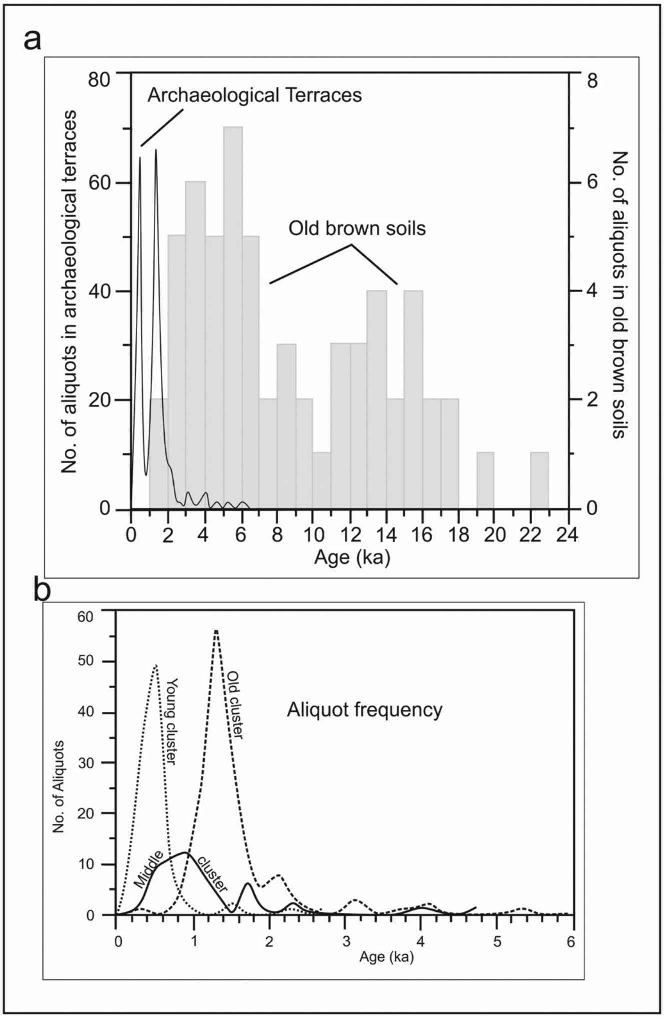


Fig. 4. Terrace and soil OSL dates from Ramat Rahel, Israel reproduced from Davidovich et al. (2012). (a) The distribution of individual OSL measurements for all samples including pre-existing brown soils, (b) frequency of individual OSL De measurements recalculated into ages compared with the three terrace types.

provides a rapid and cost-effective technique for characterising a stratigraphic profile (Sanderson and Murphy, 2010) and testing site formation hypotheses (Portenga and Bishop, 2016). The reader measures the bulk OSL and infrared stimulated luminescence (IRSL; specific to feldspar) of untreated samples. This provides valuable information about the variability in mineral composition and depositional processes within a profile (Bateman et al., 2015; King et al., 2014; Kinnaird et al., 2017; Munoz-Salinas et al., 2011; Pears et al., 2020; Porat et al., 2019; Sanderson et al., 2001, 2003, 2007; Stang et al., 2012; Stone et al., 2015). As OSL dating is a time consuming and costly procedure, this portable method is particularly useful for characterising sediments in regions where luminescence dating has not been applied. The technique also enables the targeted sampling of stratigraphic profiles by using the signal intensity as a proxy for age, dose rate and sensitivity of minerals present (Portenga et al., 2017).

3.4. Radiocarbon dating

The radiocarbon dating of soils is problematic as ideal, uncontaminated material, which provides a synchronous date for soil formation is rare, even in cumulative parts of soil-slope transects. Extensive radiocarbon dating of soil chronosequences, especially proglacial sequences, has shown that the residence time of organic matter increases as soils get older but radiocarbon dates typically under-estimate the true age of soils due to the continuous input of carbon into the soil profile (Wang et al., 1996). Soil radiocarbon age is highly variable with soil type, hydrological conditions, soil ecology and management all effecting both the total soil organic matter (SOM) content and also the amounts in pools of different stability and hence age (Paul et al., 1997). In practice the study of the SOM can provide information that could theoretically be used to model the ages of different SOM fractions (see section on SOM below). From terraces and field systems radiocarbon dating has most commonly been applied to charcoal fragments (Krahtopoulou and Frederick, 2008; Lang and Hönscheidt, 1999) and bulk organic carbon (Bevan et al., 2013) of sediments and soils. Organic material is common in such contexts due to the use of manure and fire in agricultural systems. It is incorporated in the soil by ploughing or transported down slope via colluvial and fluvial processes. Depending on the transport distance, angular fragments of charcoal indicate short transport histories, a more local source and a close association to the archaeological period of interest (Beckers et al., 2013). However, erosion and reworking are inherent in such depositional contexts and so careful attention is needed. In some situations where material has undergone limited reworking and has been well preserved, multiple ^{14}C dates can be modelled using Bayesian techniques to determine the chronological history of terraces (Acabado, 2009). In this context, the type of field system, environmental conditions and depositional histories all influence the preservation potential of organic remains. Ideally, this dating technique should be used in combination with other techniques (e.g. OSL) to check for stratigraphic consistency (Beckers et al., 2013; Borejsza et al., 2008; Davidovich et al., 2012; Kinnaird et al., 2017; Lang and Hönscheidt, 1999). For example, Lang and Hönscheidt (1999) found ^{14}C ages of charcoal fragments in reverse stratigraphic order, with oldest ages at the top of the profile, due to successive reworking of increasingly older sources. However, if discrete charcoal particles that have wood structure are present (Fig. 6), they can still be useful for providing a likely maximum age for cultivation, from cultivated horizons. Soil micro-charcoal or black carbon is problematic as it is not homogenous and can result from a range of processes (Ascough et al., 2010). However, controlled reductive removal of this pyrogenic carbon by hydropyrolysis (hyPy) can allow dating of the most stable component providing a more accurate age estimate where undifferentiated soil black carbon has to be used (Haig et al., 2020). The HyPy component of SOM is a slow cycling component of the global carbon cycle that contains some of the most recalcitrant organic carbon although this is as yet unquantified (Koele et al., 2017). An alternative has been to date the occluded carbon present within the plant silica phytolith (Piperno, 2016; Zuo and Lu, 2016).

3.5. Soil and sediment micromorphology

Alongside the macroscopic scale of terrace development, pedogenesis, history of cultivation and land use and erosion, terraces can also be investigated at the microscopic level utilizing soil and sediment micromorphology (Bullock et al., 1985; Courty et al., 1989; Fitzpatrick, 1993; Stoops, 2003). This use of micromorphology is cognate with other agricultural contexts including the Terra Pretas of Amazonian Brazil (Arroyo-Kalin, 2009, 2017; Ruivo et al., 2009), 'dark earths' across North West Europe (Macphail et al., 1990), Plaggen soils of the Netherlands (Mücher et al., 1990; van Smeerdijk et al., 1995; Spek et al., 2003) and deepened anthropogenic cultivation soils in Scotland (Bryant and Davidson, 1996; Davidson and Carter, 1998; Simpson and Barrett, 1996; Simpson, 1997, 1998). Micromorphology of agricultural deposits has also formed the basis of inter-disciplinary analysis with organic and inorganic geochemistry (Bull et al., 1999; Entwistle et al., 1998), stable carbon isotopic analysis (Simpson et al., 1999); multi-elemental research (Wilson et al., 2005, 2008) which has helped identify the organic, inorganic and minerogenic materials added to soils through cultivation and manuring. Both this and the determination of carbonized versus uncarbonized material (Pears, 2012; Simpson et al.,

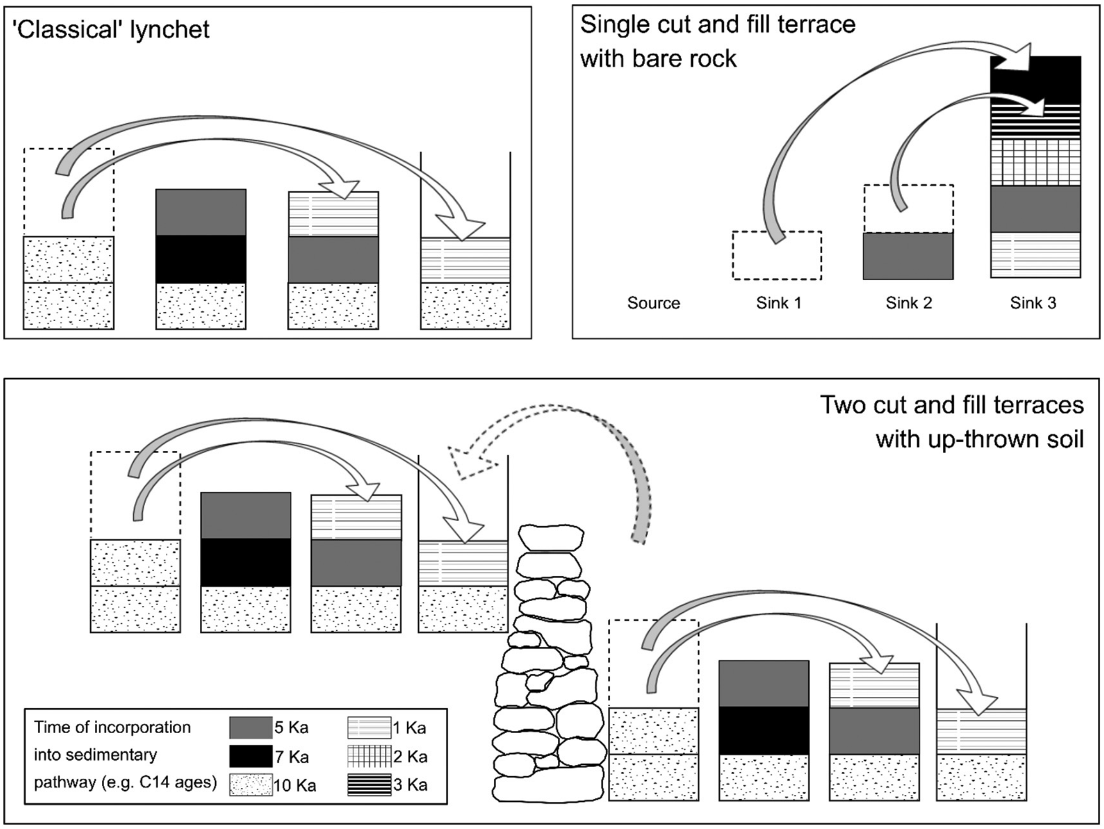


Fig. 5. Potential application of a cascade source-sink model to OSL dating terrace fills with a cascade system with temporary sinks. In this model the soil is not transported downslope in a single event, but may temporarily be stored on the slope/terrace tread and only later remobilized and transported to the foot of the tread or the lynchet where it is accumulated. Adapted from Fuchs and Lang (2009).

2003; Stoffyn-Egli et al., 1997) is relevant to understanding terrace soil formation (Fig. 6). In terrace contexts, micromorphology can also be used to determine and understand the processes of formation and function. As mentioned earlier the creation of agricultural terraces typically occurs in hilly or mountainous regions where suitable flat areas with a pre-existing deep soils are lacking or infrequent. Micromorphology has enabled insight into what landscape conditions existed prior to the construction and development of terrace tread fills, through the identification and analysis of former landsurfaces and palaeosoils (Fedoroff et al., 2010). Analysis of pre-terrace paleosols have demonstrated reworking from downslope movement resulting from possible vegetation clearance at Makriani, Amorgos in Greece (French and Whitelaw, 1999) and inter-slope variations in pre-terrace soils resulting from variable climatic conditions and land use in the Peruvian Andes (Goodman-Elgar; Nanavati et al., 2016; Kemp et al., 2006). Additionally DEMs of Inca terraces in Southern Peru have been used both to recreate the original pattern, and to measure the pattern and rate of post abandonment erosion, clearly illustrating how variable it is (Londoño, 2008). Micromorphological and meso-scale soil studies have also been used on buried soil horizons to demonstrate textural differences between pre-terrace and terrace deposits. In the Ebro Valley, Spain, such horizons were typically fine-grained and light coloured with evidence of surface erosion, truncation and colluviation (Quirós-Castillo and Nicosia, 2019). At Ricote, Murcia, Spain, the original thin soil under the terrace developed on an angle of slope (4.7%) and the first irrigated terraces were constructed to counter these shallow, dry, saline soils, which were poor in organics and nutrients (Puy and Balbo, 2013). Across other areas of Spain, the lack of pre-terrace soil horizons might relate to the complete stripping of horizons by an extensive period of erosion (Boixadera et al., 2016), but in other examples the absence of an original soil horizon may be a result of deliberate removal of the horizon through the terrace construction process and the redeposition of this material within the newly constructed agricultural landscape. Micromorphology has also proved valuable for understanding formation processes of agricultural terrace soils, their management, and agricultural practice. In almost all terrace the fundamental aim is to increase the surface area and the depth of soil for cultivation. How this is done, however, varies depending upon source material. Micromorphology has demonstrated terrace soils, which show clear textural uniformity with poorly developed irregular to sub-rounded, blocky ped microstructures (French and Whitelaw, 1999). In the Paca Valley terraces, Peru, upland terraced fields had deeper A-horizons with higher biotic activity than uncultivated controls, but less fine material and greater carbonate accumulation. Midslope fields were highly variable in depth and soil properties reflecting considerable substrate and anthropogenic variations in this growing zone (Goodman-Elgar, 2008). In Greece, examples have been shown to consist of multiple episodes of terrace construction marked by repeated buried soil horizons (Krahtopoulou and Frederick, 2008), whereas other examples show developed soil sequences consisting wholly of localized reworked soil (Puy and Balbo, 2013), alongside profiles with only limited macro evidence of imported material (Boixadera et al., 2016).

In terraced wadi fields of the Negev desert, Israel, evidence of fine charcoal, bone and pottery fragments from kitchen and domestic refuse alongside dung fragments and non-charred spherulites were identified in soil thin sections demonstrating input from kitchen, domestic and animal dung manuring (van Asperen et al., 2014; Bruins et al., 2020; Bruins and Jongmans, 2012) as well as turf (Fig. 6). The combination of micromorphology and geochemistry has also demonstrated variations in irrigation in African terrace soils in Engaruka, Tanzania (Lang and Stump, 2017) and Konso, southwest Ethiopia (Ferro-Vázquez et al., 2017). At both locations, textural structures including dusty and calcitic crystalline coatings in sediment void space, iron hypercoatings and redoximorphic nodules were present typical of sediment saturation

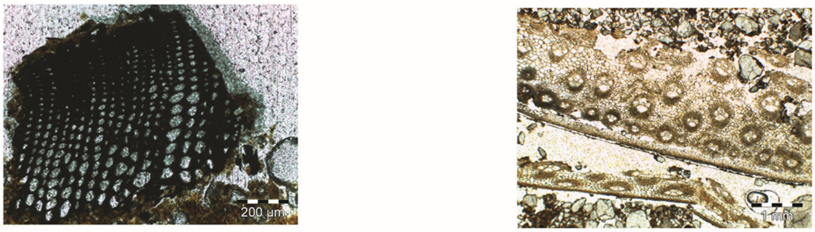
Organic & Inorganic & carbonised additions to agricultural soils (A-H)

A - Unburnt peat fragment 500µm (ppl)

B - Burnt peat fragment 1mm (ppl)

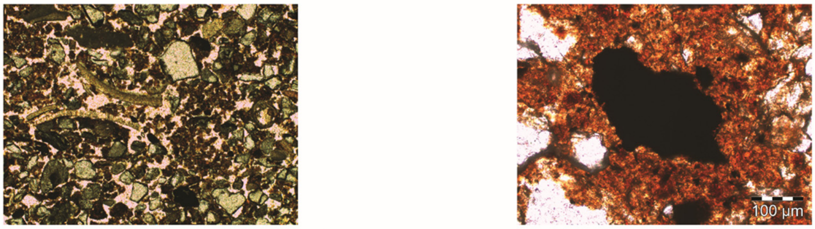
C - Unburnt turf fragment 200µm (ppl)

D - Burnt turf fragment 500µm (ppl)



E - Charcoal 200µm (ppl)

F - Degraded plant fragment 1mm (ppl)



G - Carbonate shell sand 500µm (ppl)

H - Amorphous black carbon 100µm (ppl)

Biological & hydrological reworking of agricultural soils (I-J)

I - Excremental pedofeatures
filling void space 200µm (ppl)

J - Fine grained mineral grain coating
from sediment water transfer 200µm (ppl)

Fig. 6. Examples of organic, inorganic and carbonized inclusions typically found within agricultural soils from anthropogenic addition (A-H), alongside examples of post-depositional biological and hydrological alteration (I-J).
From Pears (2012).

and waterlogging (Durand et al., 2010; Gregory, 2012; Lindbo et al., 2010). Similar textural features including silt cappings and coatings, and depositional crusts have also been associated with internal pedological water movement within terrace soils (Boixadera et al., 2016; French and Whitelaw, 1999). In China, water retention capacity has been demonstrated in terrace soils (Tan et al., 2012; Wang et al., 2007; Xu et al., 2011). In addition to this, the deliberate irrigation of terraces appears to have aided the aggradation of the terrace soils (Jiang et al., 2014).

Soil micromorphology has also been used to analyse the effects of terrace soil deterioration before, during and after abandonment in the Peruvian Andes. Despite the need to irrigate terraces, over saturation and intensive cultivation of the soil sequence resulted in the down profile transfer of fine-grained sediments leading to an abundance of clay coatings through leaching of nutrients and clays eluviation (Kemp et al., 2006; Nanavati et al., 2016). Additionally, evidence of surface weathering and colluviation between terraces has also be determined with micromorphology through the presence of poorly sorted, rounded water worn grain morphology and dusty clay infilling within pore space (Bertran and Texier, 1999; Deák et al., 2017). The effect of extensive cultivation may also result in a deterioration of the quality of terrace soils. Laminated silt pedofeatures have been identified in thin sections across

Andean terraces, which highlight the effect of tillage and the harvesting of tubers (Goodman-Elgar, 2008). The degradation of the agricultural terraces appears to have been increased by the gradual decrease in management and organic input, alongside increased downslope movement due to major landuse change (Goodman-Elgar, 2008). Soil depletion and organic matter loss from over-cultivation has also been shown for the Ebro Valley, Spain (Quirós-Castillo and Nicosia, 2019), and the localized colluviation of terrace soils also occurred at Les Garrigues, Catalonia, although most of the sediments were retained by the system (Boixadera et al., 2016).

Alongside the physical transport/additions/removal of soil, the effects of bioturbation have also been recorded by micromorphological analysis. Extensive research in the Negev desert has demonstrated the effect of ants and scorpions in the transfer of material within terrace sequences, although the effects of bioturbation are outweighed by the result of cultivation, both of which removed fine-grained laminations (Bruins et al., 2020). Strong faunal reworking by earthworms has also been shown from the presence of excremental pedofeatures (Quirós-Castillo and Nicosia, 2019) and is a major problem for direct sediment dating such as OSL. The degradation of agricultural soils through bioturbation can also be demonstrated in Northern Hemisphere contexts. Micromorphological analysis of cultivated sites in the Bowmont Valley, Scotland has highlighted extensive excremental pedofeatures and illustrates the extent of biological reworking over the last two centuries, and the loss of cultivation evidence (Davidson, 2002). In summary micromorphology has considerable potential to provide not only pedological but geomorphological information on the addition of soil to a terrace, its transformation, weathering through bioturbation and tillage as well as soil erosion. An important avenue of research in this context is the biological enhancement of weathering which can be observed using soil micromorphology.

4. Terraces and soil organic matter

4.1. Terrace driven SOC pools

As the volumetrically largest and most common human-made landforms, terrace construction has introduced an extensive perturbation of the global carbon cycle and the net C flux between the atmosphere and soil. Terrace construction involves cutting of the soil from the upper slope and filling the downslope part of the terrace, resulting in a redistribution of soil particles and associated SOC. Previous work has shown that terrace construction may have implications for the C cycle (De Blécourt et al., 2014; Shi et al., 2019; Stavi et al., 2019). The role of terracing in retaining C in soils has gained attention since 1970s (Cossens et al., 1971; Sandor and Eash, 1995; Ternan et al., 1996). By comparing the SOC contents of terrace landscapes with soils from an undisturbed landscape, these studies have shown that the construction of terraces conserves soil quality and SOC. Scientific attention has focused mainly on the effect of terracing structures, terrace age, terrace management and abandonment on SOC dynamics, and how terrace driven perturbations of the SOC pool are connected to the terrestrial C cycle (Chen et al., 2020b; De Blécourt et al., 2014; Gao et al., 2020; Jensen et al., 2006; Stavi et al., 2019, 2015). Although there is no doubt that terracing is an efficient conservation practice that provides multiple ecosystem services, e.g., erosion control, soil water recharge and nutrient enhancement etc. (Dunjó et al., 2003; Tarolli et al., 2015; Wei et al., 2016), whether terracing represents a net C sink or source is a matter of debate (Table 2). However, there seems to be consensus that in most cases, terracing has a positive effect on SOC sequestration (Antle et al., 2007; Kagabo et al., 2013; Shi et al., 2019; Walter et al., 2003; Welemariam et al., 2018; Xu et al., 2015). For example, Chen et al. (2020a, 2020b) reported that for landscapes in China, terracing on average increases SOC sequestration by 32.4%. This increase has been related to 1) the prevention of soil erosion, which reduces SOC losses (Nyssen et al., 2009); 2) increases in SOC input into soils by creating more fertile soils (soil water, available nutrients, pore structure) that supports plant growth and root density (Qi et al., 2020; Wei et al., 2016); 3) soil deposition and burial in the fill section of terraces results in the accumulation of SOC (De Blécourt et al., 2014). Negative effects of terracing on SOC sequestration have been also reported (Gao et al., 2020; Hamdan et al., 2000), especially in young terrace systems (De Blécourt et al., 2014; Stavi et al., 2015). When constructing terraces, slopes must be reshaped into small flat land units. Extensive soil redistribution during this process causes the breakdown of soil aggregates, leading to the enhanced decomposition of SOC previously encapsulated within the aggregates. Topsoil removal at the cut section of terraces directly causes a depletion of SOC contents (Gao et al., 2020); while the exposure of previously deep SOC by topsoil removal and associated changes in microenvironmental conditions are likely to enhance SOC decomposition (Doetterl et al., 2016). For example, newly formed organic matter from root and litter materials are brought into contact with the exposed subsoil SOC, providing readily available energy sources for decomposers, which speeds up the decomposition rate of older, previously stable SOC from subsoils (Fontaine et al., 2007) (also known as "priming effect", e.g. De Graaff et al. (2014)). This overview illustrates the many different and sometimes opposing mechanisms that control C cycling in terraced systems. Most of our process understanding of soil C cycling is derived from flat stable landscapes and this provides a challenge when quantifying C turnover in terraced systems, and the C sink or source term associated with terracing.

Process-based research has clarified two major mechanisms involved in stabilizing SOC in systems characterized by high rates of soil redistribution, such as terraces: (i) dynamic replacement of lost SOC at the cut section, and (ii) long-term burial of SOC at the fill section of terraces. Stallard (1998) first coined the concept of 'dynamic replacement' to describe the erosional SOC loss and replacement processes (mainly by production of new photosynthate). Since then, the dynamic replacement concept has been used to infer replacement of SOC lost by erosion (Hamdan et al., 2000; Van Oost et al., 2007) or by terracing (De Blécourt et al., 2014). Exposed subsoil typically has more reactive sites on mineral surface that are not saturated with sorbed C compounds (Doetterl et al., 2016). New C from photosynthate can form organo-mineral complexes with these reactive mineral surfaces thus stabilizing new C at the

Table 2
The studies related to the effects of terracing on SOC stocks across world.

Source	Location	Land cover	Terrace age/year	SOC change[a] in %
Sandor, 1995	Andes, Peru	Grass/shrub/cacti	1300–1700 B.P.	30
Walter et al., 2003	Brittany, France	Pasture/crop	–	13–38
Kagabo et al., 2013	Buberuka, Rwanda	Grass	20+	57
De Blécourt et al., 2014	Yunnan, China	Rubber plantations	5–44	2.8–12.5
Xu et al., 2015	Shaanxi, China	Crops	–	21.5
Welemariam et al., 2018	Mekelle, Ethiopia	Grazing	20	25
Shi et al., 2019	Shaanxi, China	Crops	27	6
Chen et al., 2020a, 2020b	China	Crop/grass/forest	1–30+	−6.4–169.4
Gao et al., 2020	Shaanxi, China	Crops	1–2	−4.8 ~ −9.4
Zhao et al., subm	Ingram, UK	Grass	Bronze age	8.7–141.2

[a] Changes in SOC stock (kg m^{-2}) of terracing soils relative to non-terracing soils.

cut section of terraces (De Blécourt et al., 2014; Hamdan et al., 2000). The available evidence indicates that it takes 5–29 years to replace the lost SOC due to topsoil removal when constructing terraces (Chen et al., 2020a; De Blécourt et al., 2014; Stavi et al., 2015). Hence, terracing driven SOC sequestration is significantly age-related: very young terraces (<5 years) tends to be a C source (Gao et al., 2020) while the old terraces drive a C sink for the atmospheric CO2 (De Blécourt et al., 2014) relative to non-terracing landscape. However, most studies of the 'dynamic replacement process' are restricted to relative young terraces (<30 years). Jensen et al. (2006) reported that the SOC stock increase significantly from a terrace dated to 7000 years BP to 10,000 years BP due to the historical climate change in West Greenland, pointing out the needs for considering much longer time scale when assessing SOC dynamics in terraced landscapes. Other studies have shown that the burial of soil materials due to terracing can stabilize substantial amounts of SOC (e.g. De Blécourt et al., 2014). Excavations in NE England by the TerrACE project have shown that the larger SOC stocks in terraced landscapes result mainly from the burial of paleosol horizons, where this old SOC store has been preserved due to the burial environment. Burial of the original soil profile at the fill section of terrace can slow down SOC decomposition by changing the environmental context for SOC decomposition, e.g. providing a low-mineralization context by reducing oxygen availability and soil pore space (Berhe et al., 2007; Vandenbygaart et al., 2012), or by increasing the soil moisture as gas (O2, CO2) diffusion barriers (Chen et al., 2020b; Wiaux et al., 2015).

In the context of land use and climate change, it is also important to consider the present and future stability of the large amounts of SOC that are being stored in terrace systems. Buried SOC pools in terraces are likely to be more sensitive to climate warming when terraces are older. Although there are limited data on SOC temperature sensitivity (Q10) in terrace soils (e.g. Gao et al., 2020), preliminary results from the TerrACE project (Zhao et al., subm) showed that the temporal trends in SOC pool composition lead to a shift in the relative importance of SOC quality versus SOC mineral protection for Q10. As a result, buried SOC becomes more sensitive to temperature change in older terrace systems (Fig. 7). Nevertheless, few quantitative data on the temporal evolution of soil geochemical and biological properties in relation to this shift in SOC quality and SOC mineral protection are available at this moment. Current studies almost exclusively focus on how terracing affects SOC stocks, while less is known about the underlying SOC stabilization/destabilization mechanisms and its sensitivity to disturbances This calls for the investigation of C cycling in terraced systems along relevant spatial gradients (i.e. climate, soil geochemistry) covering different time scales. Research is needed to clarify, in particular, the soil geochemical and biological evolution with terrace age, and how this evolution shapes SOC stability and SOC temperature sensitivity. This is of special importance to predict how SOC stores in terraced systems will respond to present and future perturbations such as terrace degradation as well as climate change.

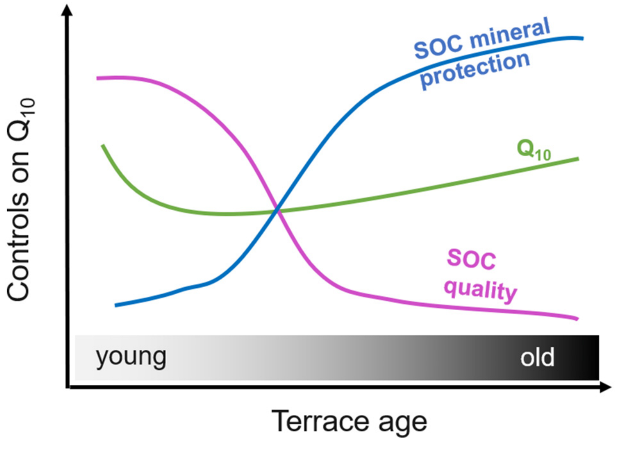


Fig. 7. Diagrammatic relationships between SOC stability, temperature sensitivity to decomposition (Q10), SOC quality and protection along with terrace age gradient. SOC mineral protection is indicated by the percentage of silt and clay associated OC; SOC quality is indicated by C:N ratio of bulk soil and SOC fractions (including coarse particulate OC, micro-aggregated OC and silt and clay associated OC) (Zhao et al., subm).

4.2. Organic-derived proxies of past terrace management

While this review is restricted to geomorphological aspects of agricultural terraces, significant advances have been made in the extraction of organic proxies, which can inform on terrace use and history. Terraces have been difficult for palaeoecological studies as pollen is rarely well-preserved, except in higher latitudes/altitudes, and plant and animal macrofossils are also rarely preserved except by carbonization. Where pollen is preserved it can be used as a local indicator of terrace vegetation and cultivation, although this use has been rare, but occasionally with other proxies such as phytoliths and diatoms (Trombold and Israde-Alcánatar, 2005). However, phytoliths, which are the silicious moulds of selected plant cells, have shown more promise (Piperno, 2006; Widgren et al., 2016) as they can potentially indicate soil mixing, manure additions and burning as well as identify cultivars. The most geomorphologically significant aspect is the assessment of soil mixing, or even soil importation, which has been invoked to explain what would appear to be anomalous quantities of soil in terraces. 'Marling' in the UK, which is normally taken to be the digging of lime-rich soil or sediment to put on acidic soils, clearly also included the addition of clay to very sandy or 'light' soils as revealed by the large number of 'marl pits' in clay sediments (Mathew, 1993; Tarlow, 2007). In a Mediterranean context at Pseira, off the north coast of Crete, the absence of silt accumulations behind up-slope check dams during periods of Late Bronze Age agricultural use has been explained by the removal and use of silty reservoir sediments as a mineral 'manure' to increase fertility and compensate for soil loss on the terraces below (Hope Simpson et al., 2005). It is therefore not inconceivable that the transport of soil from areas of thicker soil or sediment, particularly potentially fertile sediments such as sandy-marl or loess, to terraces took place – but it has yet to be conclusively shown in terrace research.

In addition to phytoliths, other biological micro-remains have also been noted in ongoing analyses of terraces in the framework of the TerrACE project. These include diatoms, siliceous sponge spicules, calcium oxalates crystals and fecal spherulites. The identification of diatoms will give information on irrigation practices, the quality of water and environmental conditions at the time of study. Calcium oxalate crystals are commonly produced mostly in dicotyledonous plants. Despite being less resistant than silica phytoliths, as some bacteria feed on them (Shahack-Gross, 2011), and when submitted to fire at 450-500 °C, they transform into a more stable phases (ash pseudomorphs) maintaining their original shape (Brochier and Thinon, 2003). When preserved they can provide information on other plant cultivars such as vines or olive trees where they are very characteristic. Finally, fecal spherulites are calcic carbonate aggregations formed in the digestive system of certain animals, mainly ruminants (Canti, 1997). When identified they indicate the presence of herbivore dung and thus can be related to manuring. An additional approach is to study environmental DNA, although active soils are probably the most complicated environment for the preservation of molecular proxies (Giguet-Covex et al., 2019). In contrast to lake sediments, where DNA leaching is not a problem (Parducci et al., 2017; Sjögren et al., 2017), DNA of more recent origin may leach down to older soil layers and thereby obscure the chronology of species at the site (Haile et al., 2007). Also roots penetrating to older layers or bioturbation due to for example earth worms may obscure the chronology. Nevertheless, as any taxa detected are likely to have a very local origin (within meters, Edwards et al., 2018), any taxa detected represents a species with DNA deposited at the site. The method has been used to detect e.g. bowhead whale at Inuit sites (Seersholm et al., 2016) and the microbial signatures of archaeological deposits (Margesin et al., 2017). Although in its infancy, the preservation of soil DNA within terrace sequences is possible under suitable climatic conditions (Yoccoz et al., 2012) and a systematic evaluation of DNA from terrace soils is currently being undertaken by the TerrACE project.

5. Management, heritage, and climate change adaptation

5.1. Digital terrain analysis: terraces mapping

Recent developments in remote sensing techniques have facilitated our capability to characterize and monitor the landscape at finer spatial and temporal scales than in the past (Passalacqua et al., 2015; Tarolli, 2014). Among high-resolution topographic (HRT) technologies Airborne Laser Scanning (ALS), which uses Light Detection and Ranging (LiDAR) technology, is a useful tool to map terrace systems over remote and vegetated areas across large areas (Sofia et al., 2014a; Godone et al., 2018; Paliaga et al., 2020). In addition, LiDAR instruments can be used on the ground by means of Terrestrial Laser Scanning (TLS) that permits a detail survey of terrace vertical surface (e.g., dry-stone walls) along hillslopes (Camera et al., 2018; Preti et al., 2013). More recently, the exploration of Unmanned Aerial Vehicles (UAVs) in parallel with Structure from Motion (SfM) photogrammetry techniques has had a transformative effect on geomorphic research (Carrivick et al., 2016; Cucchiaro et al., 2020b; Giordan et al., 2018; James et al., 2019; Manfreda et al., 2018;). SfM provides exceptionally fast, low-cost and very detailed surveys at hillslope scale for terrace complex monitoring (Diaz-Varela et al., 2014; Pijl et al., 2019; Wei et al., 2017;). In addition, data fusion of SfM and TLS data allows us to overcome the specific disadvantages of a single method in challenging contexts (e.g. rugged vegetated terrace systems Fig. 8) where complex topographic and landcover conditions can be a significant problem to create an accurate survey of the whole landscape (Cucchiaro et al., 2020a).

High resolution topographic surveys are fundamental for creating digital Terrain Models (DTMs or 'bare earth' models) that can supply quantitative land-surface metrics for the analysis of geomorphological features (Cao et al., 2020; Sofia, 2020). In turn these estimates are required to investigate land degradation process in 'Anthropogene' environments, and understand how human societies have been reshaped the geomorphology of landscapes over thousands of years (Tarolli et al., 2019). This represents a revolution in terrace landscape mapping possible from DTMs derived by LiDAR surveys, which have the capability to detect bare-earth topography even under vegetated surfaces, where no previous information was available. Some analytic methods have been developed to detect terrace features using automatic extraction algorithms (Paliaga et al., 2020) based on specific topographic characteristic of terrace landscapes (e.g., terraces show a much sharper shape than natural terrain features, and they can be considered as ridges on the side of the hillslope). As shown by Tarolli et al. (2014) and Sofia et al. (2014b), this geomorphometric information (e.g., surface derivatives such as maximum curvature) can be used to automatically extract particular features through a statistical threshold of the surface derivatives probability density functions. This method involves the use of the boxplot approach (Tukey, 1977), and the identification of outliers as points following Eq. (8).

$$C_{max} > Q_{3C_{max}} + 1.5 \cdot IQR_{C_{max}} \tag{8}$$

where Cmax is maximum curvature calculated by solving and differentiating a quadratic approximation of the surface as proposed by Evans (1979), Q3Cmax and IQRCmax are the third quartile and the interquartile range of Cmax, respectively. Fig. 9a and b shows examples of terraces and lynchets mapping using the above methodology in two sites in Europe: Soave traditional vineyards (a Globally Important Agricultural Heritage Systems (GIAHS) site) in the Veneto region of northeastern Italy, and Martelberg in the Saint-Martens-Voeren area of eastern Belgium. In both study cases, the availability of large-scale topographic LiDAR datasets allowed the construction of (~1 m) DTMs that were used for a first and rapid assessment of the location of terraces, particularly in abandoned systems. Once terraced positions have been labelled and identified, the SfM technique (through UAV) paired with TLS data (Fig. 9; Cucchiaro et al., 2020a) was used to carry out higher resolution surveys and DTMs (~0.10 m). These data are useful to analyse, at a very detailed scale, the topographic features (scaled plans, profiles and sections) and attributes of terraces and lynchet complexes.

5.2. Monitoring contemporary terraces erosion

In a complex context such as terraced areas, hydro-erosive processes are mainly driven by slope, which controls the surface water flow directions and runoff generated by intense rainfall, that is one of the main causes of soil erosion (Preti et al., 2018
). In addition, anthropogenic elements and process (e.g., lack of terrace maintenance) can further influence instability phenomena in such

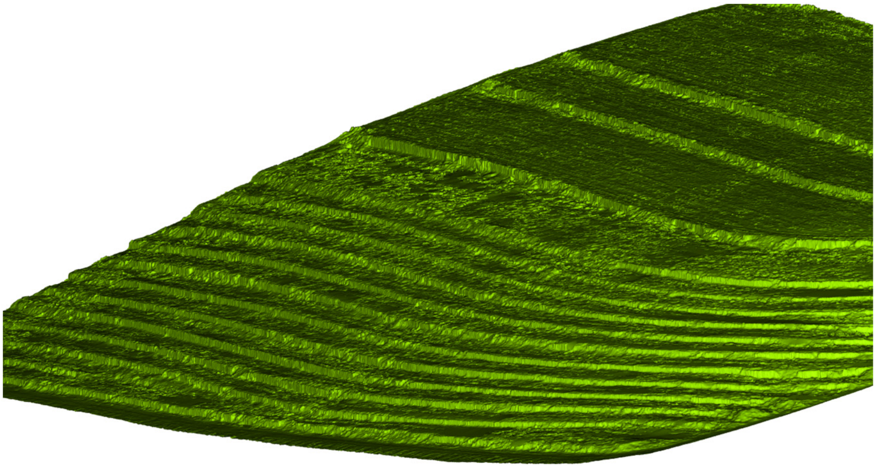


Fig. 8. Example of a data fusion SfM-TLS mesh covering a vegetated terrace complex in Soave (Italy). TLS data provided a more accurate representation of subvertical surfaces covered by vegetation (e.g., the vertical walls or risers of terrace) while UAV SfM survey quickly covered large areas on a relatively flat zone (Cucchiaro et al., 2020a).

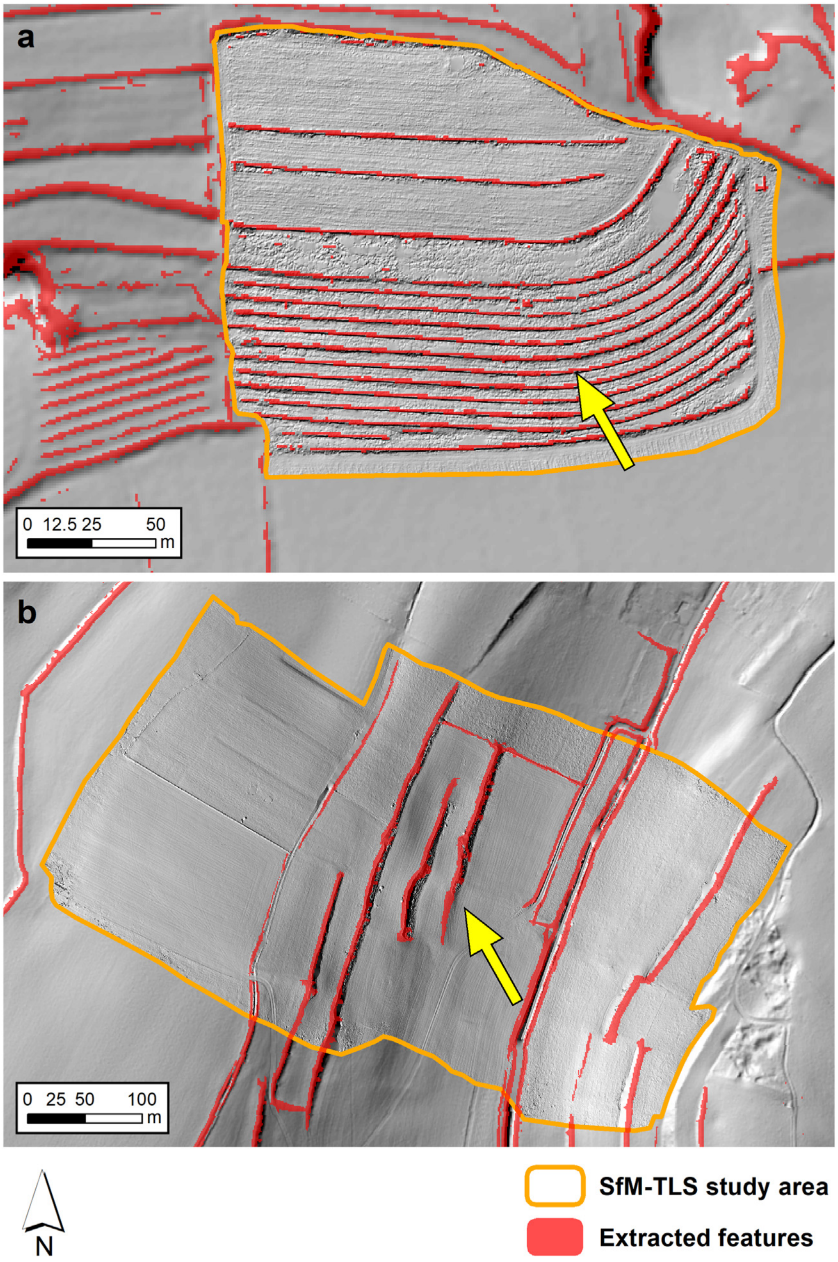


Fig. 9. Examples of terrace features extracted from a 1 m LiDAR-derived DTM according to the methodology based on landform curvature outliers identification (Sofia et al., 2014b; Tarolli et al., 2014). The shaded relief maps were created from LiDAR data at a large spatial scale while the detailed models were generated in the study areas through SfM-TLS data fusion of DTMs (at 0.10 m resolution). a) The terrace complex of the Italian site. LiDAR data provided by Environmental Italian Minister while SfM-TLS survey was carried out in December 2019. b) The lynchets system of the Belgian study area. LiDAR data provided by Flanders Information Agency, while SfM-TLS survey was carried out in October 2019.

steep-slope agricultural landscapes. High resolution topographic (HRT) data at catchment and sub-catchment scale helps us to analyse these processes in detail, exploiting useful geomorphometric information on terrace systems in Geographic Information System (GIS) software. For example, Tarolli et al. (2013) introduced the Relative Path Impact Index (RPII), that indicates preferential runoff pathways created by artificial landscape features (e.g., roads or terraces) through a comparison of contributing drainage areas including or excluding those morphologic features, following equation

$$RP = lfl((A_r\ Asm)/Asm) \quad (9)$$

where Ar is the contributing area evaluated in the presence of terraces on the hillslopes, while Asm is the contributing area evaluated in the absence of morphological alterations on the hillslopes. The link between the changes of the flow paths induced by terrace elements and the sediment dynamics can be assessed through the Index of Connectivity (IC) proposed in Borselli et al. (2008) and Cavalli et al. (2013). This geomorphometric index is intended to represent the potential sediment connectivity between hillslopes and features, which act as targets or sources for transported sediment, in different parts of the catchment. Fig. 10a, b and c show an example of the RPII and IC index application on the DTM obtained by UAV survey of a terrace system in Soave (the Fornace Michelon terraces). The RPII maps the areas presenting an increased drainage area due to the presence of anthropogenic features. A higher RPII value means a higher potential runoff that induced higher potential erosion. In Fig. 10a, the critical areas with the highest RPII values ($>2\sigma$) are those related to flow concentration by terraces, and subsequent release at topographic discontinuities (terrace wall failure; Fig. 10b), increasing the risk of soil erosion. In the terrace collapse zone,

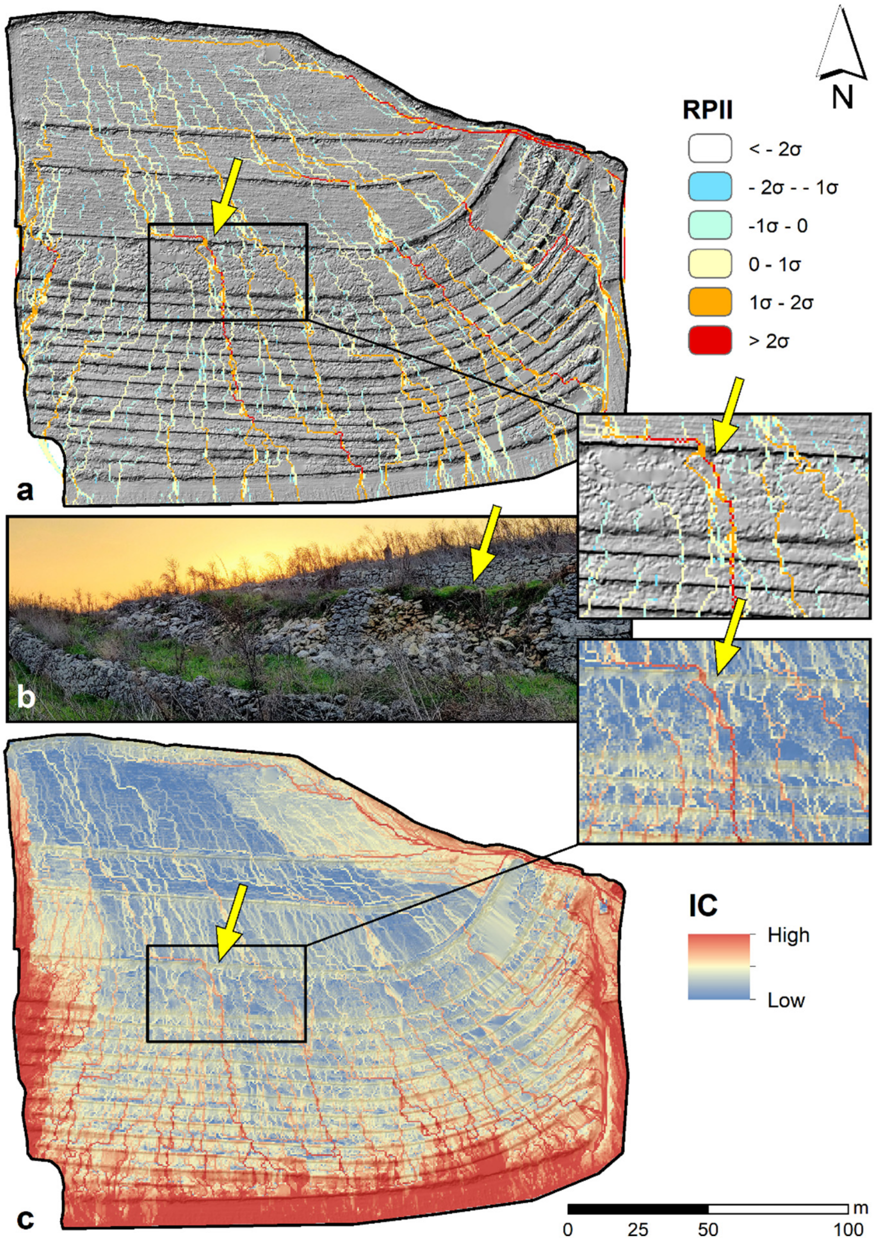


Fig. 10. RPII and IC index carried out for the DTM (Fig. 9a) obtained from UAV survey in Soave terrace. a) RPII index of Soave complex. The yellow arrows indicate an area of terrace failure (b; photo by K. Walsh) most prone to soil erosion according to RPII. c) Sediment Connectivity Index of the Soave system with a detail window on a terraced collapsed zone.

the IC (Fig. 9a) also shows high values that highlight how the sediment produced from terrace failures can quickly reach the outlet and be lost from the system. Terrace collapse can have a large effect both on sediment production and sediment delivery as illustrated in the Soave system. These outcomes are in line with the research of Calsamiglia et al. (2018), which highlighted how wall failures promote runoff concentration along preferential pathways where sediment can be mobilized depending on the frequency and magnitude of the driving forces. Therefore, the use of HRT for the analysis of anthropogenic geomorphologies can provide useful information for stakeholders for their implementation of highly targeted measures for agricultural terrace planning and maintenance at catchment scales (Tarolli and Straffelini, 2020). High resolution DTMs can also be used as inputs in numerical and physical modelling of erosion process in land degradation analysis of agricultural environments (Pijl et al., 2020; Prosdocimi et al., 2016). This aspect is particularly relevant in terrace systems that have an economic importance as vineyards, where the desire to reduce arable erosion rates has led to many monitoring studies of agricultural terraces (Preti et al., 2013; Tarolli, 2014; Prosdocimi et al., 2017; Wei et al., 2016). Under unsustainable management and increasing rainfall aggressiveness, terraced vineyards have become one of the most erosion-prone agricultural landscapes because they have been planted in steep areas that have never hosted vines, and which have 'dormant instabilities' (Tarolli et al., 2019).

5.3. Tillage erosion and lynchets

When soil is cultivated by tillage operations, it is not only loosened, it is also translocated. Tillage translocation is a gravity-driven process and is therefore controlled mainly by slope gradient. Soil translocation rates are high when tillage is performed in the downslope direction on steep slopes; rates gradually decrease on less steep slopes and are lowest when tillage is performed in the upslope direction. Soil translocation by tillage operations therefore varies in sloping landscapes and a net movement of soil occurs. When tillage operations are conducted up- and downslope, or only downslope, this results in a net downslope movement of soil. This leads to typical patterns of soil loss on convex and soil gain on concave landscape positions (Heckrath et al., 2005; Lindstrom et al., 1992; Van Oost et al., 2003). However, tillage erosion of terraces and its role in the formation of lynchets, is less well documented. The lynchet refers to the morphological response on a hillslope to the presence of field boundaries in cultivated landscapes (Bell, 1992). Both in-situ observation and numerical modelling show that tillage translocation can accelerate the formation of lynchets (Dercon et al., 2007; Vieira and Dabney, 2011). Field boundaries, or uncultivated strips, represent physical barriers and interrupt this downward soil flux by tillage. This results in net soil accumulation on the upslope side of a field boundary, while conversely, net soil loss occurs on the lower slope side. When fields are cultivated on both sides of a cross-slope boundary, lynchets or soil banks are formed along the boundary. Tillage operations thus contribute to leveling of the landscape (hilltops are eroded while valleys are filled) and the creation of lynchets. It is evident that the creation of lynchets via tillage is important in dissected landscapes where small fields are tilled (Dercon et al., 2003; Quine et al., 1999). The role of tillage erosion is particularly important for both terraces on low slopes with long treads and particularly lynchets, which it has been argued are a result of tillage erosion or soil redistribution.

The intensity of tillage operations controls the rate of lynchet formation. Downslope translocation is typically formulated as:

$$Q = k_{til}S \qquad (10)$$

where Q is the rate of soil translocation (kg m^{-1} yr^{-1}) and S is the slope tangent. ktil is a proportionality factor that is referred to as the tillage transport coefficient (kg m^{-1} yr^{-1}). Tillage transport coefficients are controlled mainly by tillage depth and tractor speed (Van Oost et al., 2006). Ktil values typically range between 50 and 400 per year/operation for mechanized agriculture, while they are much lower for non-mechanized agriculture (animal-or man-powered tillage tools) with a range of c. 30–100 kg m^{-1} yr^{-1}. Assuming a 10% slope and a ktil of 400 kg m^{-1} yr^{-1}, the formation rate of a lynchet can be as high as 7 cm yr^{-1} (assuming a bulk density of 1350 kg m^{-3} and a spread area of 4 m wide). Although tillage transport coefficients for animal or man powered operations are much lower, the cultivation of steep slopes can lead to even higher formation rates as soil translocation is also controlled by slope gradient (e.g. Dercon et al., 2007; Zhang et al., 2004). However, with ongoing tillage, slope gradients will decrease and the formation rate will slow down. The formation of lynchets and terraced landscapes induced by continued tillage operations is therefore an important factor for the creation and evolution of terraced landscapes (Fig. 11). The role of tillage in the formation of terraced landscapes has been described across the globe for low-relief landscapes under mechanized agriculture (Van Oost et al., 2000) and for non-mechanized agriculture in steeplands (Kimaro et al., 2005; Nyssen et al., 2000; Quine et al., 1999; Thapa et al., 1999; Turkelboom et al., 1999; Zhang et al., 2004).

6. Conclusions

As probably the largest systematic landform modification on the planet, agricultural terraces have received remarkably little research interest from geomorphologists, arguably because in most cases they work – in that they facilitate agriculture on slopes while minimizing accelerated erosion. However, despite this utility, which can be shown to have persisted for thousands of years in some cases, terraces and lynchets are under appreciated and under threat. In this review and synthesis we have shown that they can be approached as modifications of the slope-weathering-erosion system with positive implications for ecosystem services and particularly soil carbon storage. Indeed terracing maybe one of the main reasons that many civilzations avoided the self destruction through soil erosion sensu (Montgomery, 2007b).

One of the reasons that terraces were so neglected geomorphologically was that they were also expensive to map and survey. As shown here with both UAV/SfM and TLS technology this is no longer the case, and this allows complex terrace topography to be incorporated into 3D-distributed models of soil erosion. This is particularly relevant given the abandonment of terraces in many parts of the world principally due to rural depopulation. It has also become possible to date terraces, both using direct sediment techniques, principally luminescence-based, but also improved radiocarbon techniques. The understanding of terrace history can also be increased using these techniques as well as traditional palaeoecological techniques and, in the near future, molecular techniques. This has important heritage implications in that expenditure on preserving terrace systems can be targeted at systems of a known antiquity and history.

All these techniques will be required to preserve and maintain terrace systems in order to both control soil erosion and retain soil carbon. Agricultural terraces also continue to challenge our understanding of slope-soil systems being obvious examples of non-equilibrium but mostly stable conditions often on steep slopes. The balance between weathering/soil production, soil additions, redistribution, SOC dynamics, saprolite cover, erosion, creep and mass movements control terrace continuity and how terraces will respond to changing climate. An integrated/holistic approach is required, as for example while the ‘weathering contribution’ might seem to be

Fig. 11. Field boundaries represent a physical barrier for soil transport by tillage. Soil accumulates at the upslope side while severe truncation takes place at the downslope side, leading to the formation of lynchets (Castilla-La Mancha, Central Spain, Van Oost et al. (2006)).

one of the more theoretical elements in terrace geomorphology, the recent proposals to lock more CO2 up in agricultural soils by artificially adding crushed silicate rock, is highly topical (Beerling et al., 2018). Both theoretically and practically agricultural terraces are an important buffer against the effects of climate change on slope systems, as is being realized by both Global and regional institutions including the European Union and UNESCO-FAO.

Authors' contribution

The paper was jointly conceived and written by all the authors. AB was also responsible for the funding procurement and project management.

Declaration of competing interest

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

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