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Perspective

Revitalising terraced landscapes: Co-production of ecosystem services for sustainable futures

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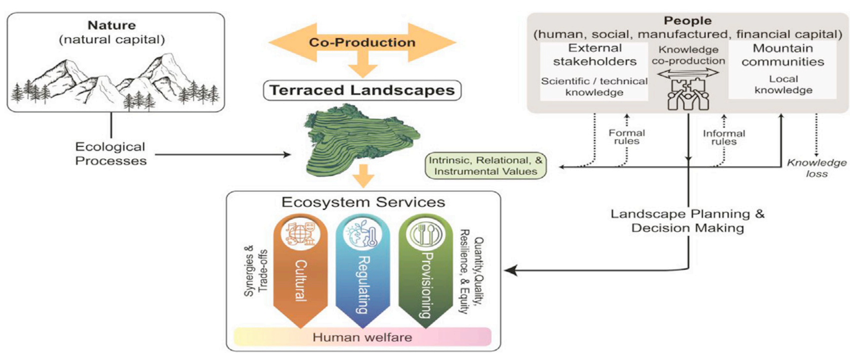
HIGHLIGHTS

- Terraces exemplify the co-production of ecosystem services in socio-ecological systems.
- Biophysical and technological advancements are vital for terrace assessment and restoration.
- Participatory research supports adaptive governance and socio-ecological resilience.
- Addressing knowledge loss in drystone walling ensures sustainable landscape management.
- Future research should focus on multifunctionality, biodiversity, and climate adaptation.

GRAPHICAL ABSTRACT



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ABSTRACT

The interplay between human and ecological systems has evolved from traditional conservation approaches to integrated socio-ecological frameworks that emphasise the co-production of ecosystem services. This paper aims to inspire new research pathways to advance the Nature's Contributions to People (NCP) perspective by focusing on terraced agroecosystems as emblematic landscapes that exemplify this co-production. Informed by recent studies in sustainability science, and drawing on our experience in Mediterranean environments, we explore the transformative potential of these frameworks for understanding and managing terraced landscapes. Addressing their multifunctionality, the challenges they face, and their socio-cultural and ecological significance, we highlight the importance of bridging scientific insights with local knowledge and participatory practices. We examine the use of advanced biophysical assessments, mapping tools, and stakeholder-driven approaches to enhance field assessment, monitoring capabilities and tackle management challenges under changing socio-economic conditions. We stress the urgent need for education and capacity-building initiatives to counteract indigenous knowledge loss and sustain traditional practices. Looking to the future, we propose potential avenues for research and practice that integrate ecological, cultural, and governance dimensions, contributing to the long-term sustainability of terraced landscapes and informing broader efforts for sustainable land management in an era of rapid environmental change.

1. Introduction

The relationship between humans and nature has evolved in how environmental and sustainability science conceptualise ecosystems and their value to society, shifting from conservation approaches, such as the "nature for itself" paradigm (Mace, 2014), to frameworks that acknowledge human-ecological interdependence. This dynamic is exemplified in human-shaped agroecosystems, such as terraced landscapes, where centuries of agricultural practices reflect the co-evolution of human interventions and natural processes. In the 1970s and 1980s, conservation frameworks emphasised the intrinsic value of natural ecosystems, prioritising their resilience in isolation from human influence, termed "nature

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despite people" (Mace, 2014). Recognition of socio-economic drivers, including rural abandonment, land degradation, and deforestation, has led to a more integrated view of human-environment relationships. The transition to a "nature for people" perspective (Mace, 2014) and the emergence of the ecosystem services concept, codified in the Millennium Ecosystem Assessment (Reid et al., 2005), reframed ecosystems as providers of measurable benefits to human welfare.

The ecosystem services concept has been increasingly adopted in policies (Maes et al., 2013) and reframed conservation towards sustainable development. Despite its significance in providing a foundation for linking human and ecological well-being (De Groot et al., 2010; Bennett et al., 2015), scholars argue that the ecosystem services approach tends to oversimplify complex socio-ecological systems, portraying nature as a passive provider and humans as mere recipients of its benefits (Schröter et al., 2014). The United Nations (2015) Sustainable Development Goals (SDGs) established 17 interconnected goals to be achieved by 2030, further recognising the need for developing frameworks that consider social-ecological interactions in ecosystem management (Reyers et al., 2013). Consequently, the need to adopt an inclusive perspective on human-nature co-production has been increasingly emphasised (Díaz et al., 2018).

The transformative "people and nature" approach, introduced by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), promotes this relational perspective, acknowledging the co-production of nature's contributions to people (NCP) (Díaz et al., 2015). This approach highlights the plurality of values associated with ecosystems and the multidimensional human-nature relationship, which transcends simplistic benefit flows, recognising that manmade interventions, knowledge, and cultural practices shape and co-create ecosystem structures, processes, and services (Kachler et al., 2023). This dynamic is evident in landscape stewardship and management, including terraced landscapes, where ecosystems and biodiversity are co-products of long-term human influence, collective action, cultural identity, and local management practices (Plieninger et al., 2015).

Co-production is increasingly appearing in the ecosystem services discourse, emphasising the integration of community values, local knowledge, and scientific understanding — or "knowledge weaving" (Tengö et al., 2017) — towards sustainable landscape management. Rather than viewing ecosystem services as products of natural processes, co-production frames them as co-generated outcomes of dynamic interactions between human and ecological systems that continuously shape and redefine one another (Lavorel et al., 2020). In this context, landscapes are understood as "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (Council of Europe, 2000: 2). Accordingly, effective ecosystem governance requires a shift from solely technical approaches to adaptive and collaborative frameworks that align with the complexities of interconnected social-ecological systems (Isaac et al., 2022). Thus, ecosystem services emerge from both natural and human contributions, shaped by local values, governance structures, and social norms (Plieninger et al., 2023). Research indicates that co-production plays a critical role across the service spectrum enabling communities to better navigate trade-offs, build resilience, and achieve equity (Palomo et al., 2016). Rather than "free gifts of nature," ecosystem services are as socio-ecological outcomes requiring governance that encompasses both formal institutions and informal networks to fully capture the roles of natural and human capital (Primmer et al., 2015). This is exemplified in mountain farmscapes (Branca, 2024), where management practices intersect with natural processes to transform local resources into human well-being. Such practices are inherently shaped and bounded by ecological constraints, including climate adaptation capacities, which influence both the scope and sustainability of these activities (Lavorel et al., 2020).

This paper aims to inspire new research pathways to advance the operationalisation of the NCP approach by focusing on terraced agroecosystems as emblematic landscapes that exemplify the co-production of ecosystem services. Informed by recent studies and frameworks in sustainability science, and drawing on our experience in these environments, we outline biophysical, ecological, and social dimensions that can be integrated into actionable research frameworks. Considering the socio-economic realities of mountain rural communities that both depend on and sustain terraced landscapes, we highlight opportunities to sustain the resilience, adaptive governance, multifunctionality, and flow of ecosystem services in these agroecosystems by bridging scientific understanding, local knowledge, and practical applications under changing environmental conditions.

2. Terraced agroecosystems: multifunctionality and challenges

Terraces emerged in Asia and spread throughout the Mediterranean region from the Bronze Age and classical Hellenic and Roman periods, to reach their greatest extent during the 18th and 19th centuries (Moreno-de-las-Heras et al., 2019). Nowadays they are a defining feature of mountain regions worldwide (Tarolli et al., 2014), representing a remarkable interplay between human ingenuity and the environment. Shaped over centuries, these agroecosystems epitomise the co-production of cultural landscapes, integrating ecological, socio-economic, and cultural dimensions. Terraces have been constructed primarily to facilitate agricultural activities on steep and otherwise unproductive mountain slopes and are often supported by drystone walls to stabilise the land and regulate water flow (Fig. 1a). This landscape transformation has not only enabled human settlement and agricultural development but also provided a wide array of ecosystem services, including soil conservation, water management, and biodiversity preservation (Tarolli et al., 2014; Varotto et al., 2018).

The multifunctionality of terraced landscapes underscores their significance (Table 1). Their primary function lies in provisioning services and agricultural productivity, enabling the cultivation of crops such as vines, olives, and vegetables in topographically challenging conditions (Blondel, 2006; Zoumides et al., 2022). By modifying slopes, mountain farmers use terraces to reduce gradients and control water runoff, thereby retaining the soil and mitigating erosion (Cots-Folch et al., 2006). These regulating ecosystem services not only enhance agricultural output but also contribute to slope stability and hydrological management (García-Ruiz and Lana-Renault, 2011), ensuring the long-term viability of mountain agroecosystems. In this context, terraces represent nature-based solutions, offering a viable option for climate adaptation, disaster-risk reduction, and biodiversity conservation (van Zanten et al., 2023).

Terraces are also deeply rooted in cultural heritage, embodying centuries of traditional knowledge and collective practices, tying communities to their landscapes. They serve as tangible reminders of human adaptation to environmental constraints and are imbued with relational values, cultivating a strong sense of place among local communities (Agnoletti, 2014). Their aesthetic appeal and historical significance have gained international recognition, driving renewed efforts to preserve and revitalise these systems. For instance, UNESCO's designation of "the art of dry-stone walling" as an Intangible Cultural Heritage of Humanity in 2018 underscores the global importance of these structures as cultural, ecological, and socio-economic assets, supporting the integration of traditional knowledge with modern conservation and land management practices (Jiménez de Madariaga, 2021; Pomatto et al., 2023).

Despite their critical role in mountain regions, terraced systems are increasingly at risk of degradation due to socio-economic and environmental pressures. The abandonment of terraced agriculture, particularly in marginal areas, has accelerated over the past century, driven by shifts in agricultural practices, rural depopulation, and the challenges of maintaining labour-intensive systems (García-Ruiz and Lana-Renault, 2011; Fayet et al., 2022). Recent comprehensive reviews covering over 290 case studies across the Mediterranean document the widespread abandonment, the cessation of terrace maintenance, and the collapse of drystone walls leading to increased soil erosion, aggressive gullying, and

Fig. 1. Two types of agricultural terraces: (a) well-maintained traditional drystone terraces in Lagoudera, Troodos Mountains, Cyprus, and (b) modern terraces constructed using mechanised methods and heavy machinery in Oikos, Cyprus. The contrast highlights differences in landscape aesthetics, construction techniques, and ecological impacts.

a heightened frequency of slope failures and landslides, particularly when vegetation recolonisation is limited (Moreno-de-las-Heras et al., 2019; Cicinelli et al., 2021). These dynamics reduce biodiversity and ecosystem functionality, and are further exacerbated by climate change (Moustakas et al., 2025), which intensifies the hydrological and geomorphological processes that terraces were originally designed to mitigate (Camera et al., 2018).

Mechanisation represents another challenge for terraced landscapes, driven by efforts to enhance agricultural productivity and adapt to modern farming techniques (Fig. 1b). In many cases, traditional terraces have been re-engineered to accommodate mechanised cropping, leading to significant disturbance of soils and bedrock, and reduced slope stability (Stanchi et al., 2012). This shift often involves the use of heavy machinery for intense terrace reshaping, resulting in land levelling and the creation of wider benches suitable for mechanised agriculture, with higher risers (Cots-Folch et al., 2006). Such changes frequently exacerbate geomorphic instabilities and create conditions prone to slope failure, compromising the natural drainage and infiltration processes that underpin terrace stability. Improper construction techniques can increase water infiltration and clog drainage pathways, magnifying the risk of instability and stonewall failures (Camera et al., 2014, 2018). While these interventions aim to improve food productivity and economic viability, they often do so at the expense of traditional structures and ecological balance, jeopardising the integrity, resilience, and multifunctional values inherent to terraced landscapes.

3. Understanding the biophysical basis of terraced landscapes

Understanding terraced landscapes requires the development of comprehensive frameworks that integrate physical structures, evolving land uses, and agroecological diversity. Such approaches are essential for assessing the status of terraced landscapes and designing conservation interventions that enhance their ecological and cultural resilience (Fayet et al., 2022).

Table 1
Ecosystem services of agricultural terraces; classified using CICES v5.1 and linked to relevant SDGs and target indicators.

Ecosystem service category	Ecosystem services of terraced agroecosystems[1]	CICES (v5.1)[2]	SDGs[3]	SDG indicators[3]
Provisioning (Biotic)	Increased crop yield, fodder production, and area: terraces boost crop and fodder yields, expand cultivation, and enhance food security and livelihoods	1.1.1.1	SDG 2: Zero Hunger	2.3.1 2.3.2 2.4.1
	Increased wood production: terraces support woody plants, providing renewable biomass for energy and livelihoods	1.1.1.2	SDG 7: Affordable & Clean Energy	7.2.1
Provisioning (Abiotic)	Increased water availability: terraces retain water, easing water stress and ensuring reliable availability	4.2.1.2: Surface 4.2.2.2 Groundwater	SDG 6: Clean Water	6.4.2
Regulation & Maintenance (Biotic)	Reduced soil loss and erosion: terraces prevent soil erosion, maintain soil fertility, and reduce land degradation	2.2.1.1	SDG 15: Life on Land SDG 2: Zero Hunger	15.3.1 2.4.1
	Improved water management: terraces slow runoff, enhance infiltration, reduce flooding, and retain soil moisture	2.2.1.3	SDG 6: Clean Water SDG 13: Climate Action SDG 11: Sustainable Cities	6.5.1 13.1.2 11.5.2
	Reduced irrigation demand: terraces retain soil moisture, lowering the need for external irrigation	2.2.1.3	SDG 6: Clean Water	6.4.1
	Reduced production failure risk: terraces buffer against climatic extremes, ensuring stable yields	2.2.1.3	SDG 1: No Poverty SDG 13: Climate Action	1.5.3 13.1.2
	Improved water quality: terraces filter runoff, improving water quality and reducing pollution	2.1.1.2	SDG 6: Clean Water SDG 3: Good Health	6.3.2 3.9.2
	Reduced fire risk: moisture and vegetation management lower wildfire risks	2.2.1.5	SDG 15: Life on Land SDG 13: Climate Action	15.3.1 13.1.2
	Increased soil fertility: terraces improve soil quality, fertility, and nutrient cycling	2.2.4.2	SDG 2: Zero Hunger SDG 15: Life on Land	2.4.1 15.3.1
	Biodiversity enhancement: terraces create diverse habitats, supporting local species and ecosystems	2.2.2.3	SDG 15: Life on Land	15.5.1
	Carbon sequestration: terraces increase carbon storage in soils and vegetation, aiding climate mitigation	2.2.6.1	SDG 13: Climate Action SDG 15: Life on Land	13.2.1 15.3.1
Cultural (Biotic)	Community and cultural benefits: terraces preserve heritage, strengthen social cohesion, local and scientific ecological knowledge, reduce conflicts and promote community work	3.1.2.1: Knowledge 3.1.2.3: Heritage 3.2.1.1: Symbolic meaning	SDG 11: Sustainable Cities SDG 10: Reduced Inequalities SDG 4: Quality education SDG 16: Peace & strong institutions	11.4.1 10.2.1 4.7.1 16.7.2
	Increased recreation: terraced landscapes provide aesthetic and tourism value, benefiting local well-being	3.1.1.1: Physical 3.1.1.2: Experiential	SDG 11: Sustainable Cities SDG 8: Decent Work and Growth	11.7.1 8.9.1

[1] The list of ecosystem services for agricultural terraces was adapted from Romero-Díaz et al. (2019).
[2] CICES classification and codes were derived from the Common International Classification of Ecosystem Services (CICES) V5.1 (Haines-Young and Potschin, 2018).
[3] SDG and target indicators were aligned using the final list of proposed Sustainable Development Goal indicators as contained in Annex IV of the Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators (E/CN.3/2016/2/Rev.1), March 2016.
***Note* on classification**: the table demonstrates how ecosystem services from agricultural terraces contribute, directly and indirectly, to sustainable development goals. The list is not exhaustive and there are some cross-cutting contributions between CICES classification and SDGs. For example: ecosystem services such as Erosion Control (2.2.1.1) address multiple SDG targets, including SDG 15.3 (Land Degradation Neutrality) and SDG 2 (Food Security); improvements in water availability and quality align with SDG 6, while climate resilience links to SDGs 13 and 1.5; educational benefits and cultural heritage preservation relate to SDGs 4 (Education) and 11.4 (Heritage Conservation).

Landscape structures refer to the spatial composition and heterogeneity of landscapes, reflecting both current land use practices and historical cultivation patterns, and are analysed alongside management intensity to characterise cultural landscapes (Tieskens et al., 2017). The structural diversity and management intensity of terraced landscapes are key indicators of their ecological and socio-economic functions. These features manifest as physical expressions of co-production, where natural and human elements converge. For instance, terraces vary significantly in their soil properties, hydrological functions, construction techniques, and management intensities — such as the use of drystone walls, traditional irrigation channels, or modernised infrastructure — each reflecting specific environmental and cultural contexts (Stanchi et al., 2012; Cicinelli et al., 2021). Advancing classification systems and typologies that encapsulate these co-production variations offers a pathway to operationalise the integration of structural elements and management practices, providing a deeper understanding of the spatial heterogeneity of terraced systems (Stanchi et al., 2012; Tieskens et al., 2017). Such typologies can be developed through collaborative science-society efforts, ensuring that landscape classifications are both scientifically robust and locally relevant, while facilitating the identification of terraces with high cultural and ecological values to guide targeted restoration or mechanisation efforts.

Mapping cultural landscapes is also essential for understanding and preserving the multifunctionality of terraced agroecosystems. Current European land-cover maps, such as the CORINE Land Cover, lack the granularity required to account for linear landscape features such as terraces (Levers et al., 2018). Site-specific and place-based assessments, complemented by GIS and remote sensing technologies, offer a way forward to address this limitation. For example, analytical methods and multivariate techniques can be employed to classify terrace plots based on structural diversity and management intensity, as well as to reveal relationships between biophysical and sociocultural indicators (Torralba et al., 2018). Furthermore, high-resolution spatial data derived from ground-based and UAV-based optical and laser sensors can provide detailed models that delineate terrace geometry and morphology, and assess physical integrity, including soil erosion pathways and the condition of retaining walls (Camera et al., 2018, 2024; Tarolli and Straffelini, 2020; Hain and Zagh, 2020). Incorporating uncertainty analyses and validation procedures in these ecosystem service assessments enhances the robustness, reliability, and decision-making relevance of mapping outcomes (Barton et al., 2024; Pereira et al., 2025; Walther et al., 2025).

Equally critical to the understanding of landscape geomorphology and structures is the investigation of land-use legacies

(Foster et al., 2003) — the enduring effects of historical human activities and disturbance regimes (including abandonment) that continue to shape ecosystem structures and functions long after the activities have ceased. Terraced landscapes are repositories of agrobiodiversity, shaped by layers of historical practices that have defined their ecological and cultural character. The biocultural heritage of Mediterranean terraced landscapes includes heterogeneous mosaics of land uses, such as agroforestry, viticulture, and smallholder farming, which have left lasting imprints on biodiversity, soil properties, and water management systems (Plieninger et al., 2023). Drystone walls create unique microclimates and habitats that shelter wildlife, support endemic flora and fauna, and prevent competitive exclusion and excessive homogenisation, thereby enabling the coexistence of diverse species (Manenti, 2014).

To assess these legacies and their biodiversity contributions, field surveys, species metrics and diversity indices can be employed alongside analyses of vegetation composition and beta diversity to identify patterns and drivers. Through such assessments, culturally important species can be identified, providing insights into their conservation status and socio-cultural value (Reyes-García et al., 2023). Furthermore, assessing land-use legacies and revitalising terraced landscapes requires methodologies that bridge their historical and ecological dimensions. Ethnobotanical surveys, for example, can document the traditional knowledge associated with mountain or terrace-adapted species used for food, medicine, or construction, offering insights into the interplay between cultural practices and ecological functions (Savvides et al., 2023). These insights can inform the reintroduction of forgotten traditions that align with contemporary conservation and sustainability goals. Similarly, diachronic studies tracing changes in land cover and vegetation composition over time can elucidate the impacts of abandonment or modernisation on landscape dynamics (Djuma et al., 2020; Jiménez de Madariaga, 2021). Such approaches not only reveal the ecological resilience embedded in traditional systems but also highlight the risks posed by their decline.

4. Stakeholders, rural communities, and the governance of terraced landscapes

The sustainable management and revitalisation of terraced landscapes require an understanding of and integration with the perspectives of diverse stakeholders, particularly rural communities. Investigating the values, rules, and knowledge systems that shape decision-making and influence co-production is essential (Gorddard et al., 2016). Moreover, the research community can benefit from stakeholder-driven approaches that incorporate local knowledge, perceptions, and formal and informal rules to support adaptive governance and long-term stewardship. Terraced landscapes are characterised by plural values — intrinsic, instrumental, and relational (Pascual et al., 2017) — that motivate decisions regarding their maintenance. Intrinsic values reflect the cultural and aesthetic appreciation of terraces as heritage elements, while instrumental values relate to their utility in agricultural productivity and the provision of ecosystem services (e.g., erosion control). Relational values, by contrast, capture the connections between people and terraces through local traditions and practices (Plieninger et al., 2023). These are deeply embedded in the everyday lives of rural communities, influencing stewardship roles through informal rules and social norms that govern land use and community cooperation, such as sharing water resources or co-maintaining terraces. Recognising these values and their contributions to decision-making processes enhances inclusive and effective landscape management strategies.

The rules governing terrace landscapes range from formal regulations to informal practices that have evolved over centuries. Formal rules (e.g., agricultural policies and land-use legislation) provide overarching regulatory frameworks for terrace management, yet informal rules (e.g., customary laws and community-based agreements), grounded in local traditions and community practices, often hold greater sway in rural communities and determine how these policies are implemented by local farmers. For instance, informal rules and local ecological knowledge may include longstanding traditions passed through generations, such as drystone walling, water harvesting techniques, and seed selection practices, complementing formal policies aimed at promoting agrobiodiversity (Cebrián-Piqueras et al., 2020). Exploring how these rule systems interact can strengthen institutional capacity and adaptability, enabling researchers to identify synergies and conflicts that influence the long-term management of terraces. Knowledge systems are equally diverse, encompassing local ecological knowledge and technical expertise that can complement scientific knowledge to create a holistic understanding of terraced systems and provide innovations to address challenges such as land abandonment (Plieninger et al., 2023). Qualitative and quantitative approaches, such as social surveys, participatory modelling, and workshops involving local farmers and land managers, regional authorities, and civil society organisations, can facilitate knowledge co-production and provide insights into socio-ecological drivers for transforming land-use systems (Okpara et al., 2020). Identifying unknown leverage points enables informed scientific interventions that align with local priorities, from community-led conservation efforts to policy-driven support for terrace maintenance (Zoumides et al., 2017).

Landscape stewardship, underpinned by adaptive governance, emphasises the importance of maintaining ecological integrity while addressing socio-economic needs. Scenario-based and collaborative stewardship approaches, such as the three horizons method (Sharpe et al., 2016) and the IPBES Nature Futures Framework (Pereira et al., 2020; Durán et al., 2023), can serve as blueprints for envisioning transformational and sustainable futures. Local visions and preferred pathways for terrace landscapes often move beyond agriculture to include tourism, nature-based solutions, and bio-economy initiatives (Pereira et al., 2020). Furthermore, traditionally marginalised groups, such as female and younger stakeholders, tend to advocate for innovative and self-sufficiency-oriented approaches, which reflect their optimism for sustainable futures (Fernández-Giménez et al., 2022). These methods enable stakeholders to identify actionable steps and the resources required for implementation while ensuring equitable representation in decision-making and governance systems that remain flexible and adaptive to evolving dynamics.

5. Knowledge loss and the need for capacity-building

The gradual loss of knowledge and skills related to drystone walling poses a significant threat to the preservation and functionality of terraced landscapes. This knowledge, rooted in centuries of human-environment interaction, is at risk of disappearing as younger generations migrate away from rural areas and modern materials replace traditional techniques. As Varras et al. (2006) note, drystone walling is a complex knowledge base enriched by regional characteristics that must be systematically passed down to prevent its disappearance. Given the historical importance of these structures in supporting rural livelihoods and biodiversity, their decline necessitates urgent attention. Addressing this decline requires multifaceted and organised efforts, such as community involvement, documentation of traditional practices, integration into territorial development frameworks (including tourism), as well as education and capacity-building initiatives.

Written guidelines and educational materials play an important role in preserving and disseminating knowledge. Manuals detailing construction and maintenance techniques ensure that traditional methods are codified and accessible to practitioners and trainers. In Cyprus, the 3PRO-TROODOS project (https://3pro-troodos.cyi.ac.cy/) has developed such resources and organised workshops to systematically document indigenous knowledge, aiming to inspire future generations to acquire the expertise needed to sustain and revitalise this ancient craft (Zoumides et al., 2017). In France, the development of the Code of Good Practice for Drystone Walling in 2008, supported by engineering research and endorsed at the national level, has formalised high standards of craftsmanship and contributed to the certification and official recognition of this skill (Council of Europe, 2019). Additionally, as a nature-based solution, drystone terraces align with the 2015 Energy Transition and Green Growth Act's goals, promoting the use of local resources and cooperative projects that integrate environmental and societal benefits.

Incorporating traditional techniques into formal and vocational training programmes is a necessity, as advocated by the Council of Europe (2019). For effective knowledge transfer, training programmes and professional curricula should include mentorship from experienced practitioners, promote experiential learning through hands-on workshops, and be adapted to site-specific contexts considering local materials and drystone techniques. Such initiatives can draw from successful experiences in regions like Mallorca, Spain, where restoration crews function as reference schools, training young people in traditional construction methods and enabling them to enter the job market as specialists (Varras et al., 2006). In Croatia, the Dragodid initiative has not only preserved drystone skills through workshops but also linked this craft to tourism by promoting it as a cultural experience (Svetlacic et al., 2021). Similar practices have been implemented in Cinque Terre and other regions of Italy (Varotto and Lodatti, 2014; Santoro et al., 2021; Pomatto et al., 2023), where community-driven restoration projects or terrace adoption by immigrant families have integrated historical knowledge into tourism and social cohesion strategies, demonstrating how traditional skills can support economic resilience. Ensuring the long-term viability of these efforts and the aesthetic coherence of restored structures, however, requires balancing tourism-driven demands with the need for broader landscape conservation efforts.

Similar initiatives could be scaled and adapted in other regions, with a focus on engaging young farm workers, immigrants, and unemployed individuals, offering an entry point into specialised professions while supporting sustainable rural livelihoods. To sustain these efforts, policies must prioritise capacity building as a core component of landscape management. It is essential for governments and regional authorities to financially support training programmes and incentivise community participation. The 'greening' obligations of the Common Agricultural Policy (CAP) already provide EU funding for the preservation of cultural landscapes (Vergamini et al., 2024). However, real progress often takes place at the local level, where actions are implemented to address knowledge loss and equip new people with the required skills. Incentives for private sector involvement, such as funding for businesses and NGOs specialising in drystone construction, can further reinforce these efforts by providing a tangible contribution to local economies and ensuring the resilience of terraced landscapes for generations to come.

6. Revitalising terraced landscapes: conclusions and future research priorities

Terraced agroecosystems exemplify the co-production of human ingenuity and natural processes to deliver diverse ecosystem services that contribute to multiple SDGs. As dynamic socio-ecological systems, these landscapes are at crossroad and require comprehensive approaches to preserve and sustain their multifunctionality under the pressures of mechanisation, climate change, abandonment and socio-economic transformations. Drawing from recent advances and the synthesis presented, future research can embrace the following recommendations towards their revitalisation:

- *Multi-scalar research leveraging technological innovation*: collaboration across disciplines can generate robust insights to address the ongoing challenges and inform conservation practices tailored to diverse biophysical and cultural contexts. Emerging progress in high-resolution UAV mapping, remote sensing, and GIS-based spatial analysis offers significant potential for improving the assessment and monitoring of terraced landscapes. At the local level, fieldwork and sampling campaigns, such as vegetation surveys and soil analyses, provide empirical data on the ecological and structural characteristics of terraced systems. Combining studies of physical landscape structures with diachronic analyses that track land-use changes can generate comprehensive data and refined classification systems, more effectively representing structural diversity and complexity and facilitating the identification of areas with high ecological, cultural, or vulnerable significance. At broader scales, these findings can enable the harmonisation of local and regional landscape planning and decision-making, and support the development of targeted, evidence-based management and restoration schemes that enhance the resilience and safeguard the flow and co-production of ecosystem services.
- *Participatory research towards adaptive governance*: bridging formal policies and informal local rules, while combining local ecological knowledge with scientific approaches, can inform conservation practices and advance the design of adaptive governance models. Stakeholder engagement through participatory approaches, knowledge co-production, and scenario-based planning can strengthen socio-ecological perspectives, helping to anticipate both current and future stewardship needs while embedding values, rules, and knowledge into adaptive landscape governance. These methods can reveal opportunities to integrate nature-based solutions and the conservation of soil, water, and biodiversity with emerging economic activities, such as agrotourism, thereby diversifying local income streams while preserving ecological integrity and cultural heritage.
- *Transmission of traditional knowledge and practices*: Sustaining and revitalising terraced landscapes requires more than financial support; it necessitates active community engagement and the transfer of traditional knowledge and skills to empower the next generation. Capacity-building programmes are essential to prevent knowledge loss of traditional drystone construction methods. Developing locally adapted training curricula, supported by governmental authorities, NGOs and technical education institutions, can enable the intergenerational transfer of skills. Incorporating these activities into territorial planning can further strengthen economic resilience and rural development through job creation and enhanced community engagement.

Declaration of competing interests

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.

CRediT authorship contribution statement

Christos Zoumides: Writing – original draft, Visualization, Investigation, Conceptualization. **Adriana Bruggeman:** Writing – review & editing. **Hakan Djuma:** Writing – review & editing.

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