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Perspective

Sustainable water resource management in steep-slope agriculture

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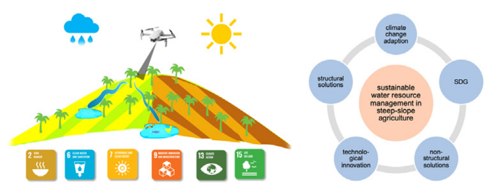
HIGHLIGHTS

- Steep-slope agricultural landscapes are under threat due to climate change.
- Sustainable water resource management is needed for mitigating climate change impacts.
- Structural measures and technologies are highlighted.
- Practical and resilient guidelines along SDG are recommended.

GRAPHICAL ABSTRACT



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ABSTRACT

Steep-slope agricultural landscapes are under threat due to climate change. On the one hand, the growing frequency of extreme high-intensity rainfall events concentrated in both temporal and spatial scales are causing flash floods or slope failure risk scenarios. On the other hand, future climate projections indicate a significant expansion of arid zones in the steep slope agricultural system. There is evidence that these landscapes face a high risk of growing water scarcity. Considering their unique role in crop production, ecosystem diversity, and crop production, ecosystem diversity, and cultural heritage, understanding sustainable water resource management for mitigating climate change-induced drought has never been more urgent than today. In these landscapes, unique indigenous knowledge of water conservation is adopted to manage water resources improving their resilience optimally. It is, therefore, necessary to promote water storage to mitigate floods or increase the resilience to prolonged drought (creating at the same time favourable conditions for biodiversity). Modern technological advances (e.g., high-resolution remote sensing and GIS-based modelling) are crucial in supporting these activities and understanding earth's surface processes.

1. Steep-slope agriculture: food-producing systems, historical heritage and ecosystem services under threat

Steep-slope agriculture landscapes refer to the cultivated agricultural area with slope values above 7° (FAO, 1999; Wang et al., 2022). Agricultural landscapes cultivated in hilly and mountainous regions represent intensive food-producing systems, historical heritage and cultural ecosystem services recognised by society. For example, agriculture on the steep slopes of tropical America can produce more than 30% of the crop, supporting more than 40% of the farmers' life (Posner and McPherson, 1982). In Italy, terraces are one of the most important factors affecting crop production and economic development (Pijl et al., 2020). Farmers in Nepal have cultivated maize and potato on steep slope agriculture as the primary source or supplement of staple food for generations (FAO, 2018)(.

FAO initiated the Globally Important Agricultural Heritage Systems (GIAHS) programme to protect, preserve and manage traditional agricultural knowledge and the landscapes they developed. An example is the GIAHS site of Soave's traditional vineyards (North of Italy), where agriculture has been practised through a sustainable management system that contributed to the uniqueness of the landscape (Fig. 1). Here, the so-called 'heroic agriculture' system survives on steep terraced slopes designed and constructed according to historical techniques. On the one hand, this traditional management practice is very fragile as terraces are intrinsically fragile and susceptible to hydrogeological risk. On the other hand, unsustainable management (land abandonment, heavy mechanization, etc.) and climate change have exacerbated land degradation in steep-slope agricultural landscapes (Tarolli and Straffelini, 2020).

Water scarcity is a common issue associated with the cultivation of steep hillslopes due to agricultural and domestic water withdrawals and climate change (Fig. 2, left-hand side; Alcamo et al., 2007; Tarolli and Straffelini, 2020). Projected future spatial-temporal rainfall variations are widely confronting farmers with the risk of drought, as increased seasonality and meteorological unpredictability challenge the sustainabil-

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Fig. 1. Soave's traditional vineyards cultivated on steep-slope landscapes (FAO-GIAHS site, North of Italy; photographs by P. Tarolli).

ity of water resources management (Arnell et al., 2011; Easterling et al., 2000; EEA, 2012a; EEA, 2012b; EEA, 2012c; Iglesias et al., 2011; IPCC, 2008; Rosenzweig et al., 2004). A widespread agricultural impact of climate change is the reduction of water availability in irrigation systems (EEA, 2012a). Climate change-induced drought causes a global average loss of at least 60 billion dollars annually (Ma et al., 2017). For example, in 2009, the Yunnan Province of China experienced the worst drought in 50 years, and 4.9 million hectares of agricultural land and drinking water for about 9.65 million people were severely affected (Ma et al., 2017; Wu et al., 2017). In addition, it is reported that central America, China, Mediterranean area, where the steep slope agriculture systems are widely distributed, were largely affected by flash droughts (phenomena characterized by a period of rapid drought intensification with impacts on agriculture) from 1980 to 2015 (Christian et al., 2021). Jiao et al. (2021) documented that global vegetation water deficit areas significantly increased from 1982 to 2015. Extreme climatic conditions also impact substantially soil moisture and groundwater that are closely related to food production and ecosystem services (Qiu et al., 2019). Aside from water scarcity, drought can also result in a loss of soil resources (Fig. 2, red labels) due to the reduced cohesion by vegetation (Gyssels et al., 2005) and crusting of the topsoil layer (Arnáez et al., 2015).

The challenge of growing aridity is paralleled by the increasing likelihood of extreme rainfall (Fig. 2, right-hand side) due to a widespread increase in frequency and intensity of precipitation in the 21st century (IPCC, 2019). Consequently, growing runoff rates are expected to challenge the sustainability of soil and water management in agriculture (Tarolli and Straffelini, 2020), e.g., by causing soil erosion, mass movement, and flood risk (Fig. 2, red labels). Furthermore, rainfall distribution in steep-slope areas varies dramatically within short distances due to the interaction between climate and topography. In some coastal areas, the precipitation on the windward slope exceeds 10,000 mm a year, while the rainfall on the leeward slope is sometimes only 50 mm (Willat, 1993). Due to the combination of a changing climate interaction and the local topographic setting, steep cultivation systems tend to be largely affected by drought or excessive rain more than other landuses.

2. Towards sustainable water management practices

2.1. Improved water storage and other structural solutions

Resilient water management systems play an important role to maintain agricultural productivity and mitigate the detrimental on-site and off-site environmental impacts, e.g., by harvesting and storage (Fig. 2, light-blue labels; Fig. 3). Sustainable structural solutions can improve water availability over extensive drought periods and effectively reduce the loss of on-site soil resources by soil erosion, landslides, debris flow, and other forms of land degradation (Tarolli et al., 2014, 2021). During extreme rainfall events, water resource management such as ponds, hillslope terracing, drainage systems (e.g., roadside drainage, terrace drainage, etc.) and dams are essential to flood and soil erosion control measures (Rockström and Falkenmark, 2015). A relevant example can be found in the steep agricultural landscapes of the Loess Plateau (P.R. China), where more than 58,446 check dams have been constructed for water and soil conservation and sustainable agriculture (Wang et al., 2018). Moreover, the buffering of water flow has off-site benefits, e.g., reducing flood risk or sediment deposition in mountainous river systems (Yuan et al., 2022; Mohammed et al., 2022). It is clear that suitable water storage and management effectively saves water resources and provide multiple goods and services (e.g., fish production, water supply, groundwater recharge and biodiversity) in sustainable agricultural development and ecosystem services (Aeschbach-Hertig and Gleeson, 2012; Garg et al., 2022; Hu et al., 2016). In drylands, engineered soil and water conservation structures (e.g., earth bunds) and water storage benefit to biodiversity, irrigation water reuse, and groundwater recharge (Garg et al., 2022).

Some engineering fortified settlements (e.g., stone wall terraces) are significant in water resources management for supporting a more resilient agrarian society. For instance, Konso Cultural Landscape represents an outstanding example of adaptation to a dry hostile environment of more than 400 years with ancient stone wall terraces (UNESCO, 2011). The 5-metre-wide dry-stone wall built of locally available rock plays a considerable role in maintaining water and soil, collecting rainwater, draining excess water, and creating agricultural areas. In the South-West of Jerusalem, the Battir cultural terrace system with dry-stone architecture constitutes a spectacular example of how engineering practices have enabled to change of the deep valley system into the land for agriculture (Kudumovic, 2021). The effective water distribution system is the main feature of the Battir agricultural sys-

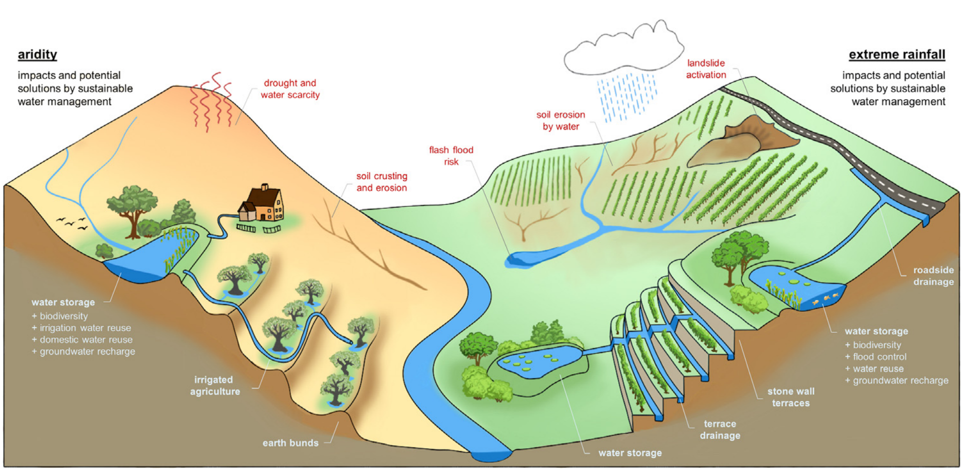

Fig. 2. Conceptual illustration of two relevant climatic challenges in steep-slope agricultural landscapes: growing aridity (left-hand slope) and extreme rainfall conditions (right-hand slope). Labels in red font show the key impacts related to these climate trends (e.g., drought or flood risk). Instead, labels in light blue colour indicate examples of sustainable water management solutions and best practices to mitigate climate change impacts (e.g., water harvesting, storage and reuse).

(a) (b)

Fig. 3. Water reservoir infrastructure in the vineyards of Soave FAO-GIAHS site, Italy (photographs by Wendi Wang).

tems and led to a good water supply (Wessels, 2015). Creating these dry walls terraces in the Battir cultural agrarian system is the basis for the perfect irrigation systems with good water supply (UNESCO, 2014). It is attested that this intact irrigation and drainage system (e.g., collection pool, channels, etc.), based on a simple mathematical analysis, would continue to benefit local people at least a millennium in the future (UNESCO, 2014). Another important example is the wide distribution of various indigenous water harvesting techniques (WHT), locally known as jessr and commonly distributed in Tunisia for water-saving. Jessr have been recognised as a helpful supplementary water resource during drought periods. Drought and low soil fertility are the main causes of low land productivity in steep agriculture areas in Africa (Wolka et al., 2021; Schiettecatte et al., 2005).

Sustainable water management should also consider nature and ecosystem functions while focusing on agricultural diversification and landscape preservation. Ecological systems in steep areas face threats and challenges from many aspects due to human activities, natural disasters and industrial development. Dong's Rice Fish Duck System (P.R. China) is a spectacular representation of an agro-ecosystem that shows how local people respect the environment during their interaction with nature (FAO-GIAHS, 2022a). It is famous for being rich in bio-diversity and well managed by Dong minority through traditional practice for thousands of years. It produces more than 40 types of rice for the local area to meet the needs of daily life while also serving as a habitat provider for more than 100 kinds of animals and 200 kinds of wild plants (FAO-GIAHS, 2022a). Elsewhere, Pu'er Tea agricultural landscape (P.R. China) is considered a complete, compact and self-sufficient agro-ecosystem of the largest tea tree communities. The landscape is the composition of economic crops, vegetables and free-range livestock with a multi-functional role for local agriculture, forestry, animal husbandry (FAO-GIAHS, 2022b). In addition, to protect this landscape and ensure the flavour of the tea, the local farmers avoid using artificial fertilizers and chemical interventions (FAO-GIAHS, 2022b).

Though several studies have shown the potential solution for agricultural systems, most of them are focused on how to improve the crop production by water harvesting technique (Piemontese et al., 2020). Little is known about the role of water resource management (e.g., water storages, water harvest, drainage systems, etc.) in the mitigation of the effects of climate change (e.g., extreme rainfall events and the long period of drought) for sustainable farming in steep slope agricultural landscapes. For steep-slope agricultural areas, we need to understand and answer such important questions as i) which kind of water resource management can optimize the sustainability, social-ecosystem services as well we crop production in steep slope cultivation systems, and ii) how to manage rainfed cultivated hillslopes at different scale resilient to the long period of droughts in climatic condition.

2.2. Technological innovation and nature-based solutions

Technological innovation (e.g., high-resolution remote sensing techniques such as LiDAR (Light Detection And Ranging) and a photogrammetric survey by drones, or cloud computation and sharing platforms such as Google Earth Engine) offers unprecedented access to detailed spatial and temporal geo-data to guide the design of resilient water management systems in steep slope environments. Fig. 4 illustrates a 3D example of simulated overland flow based on a real rainfall event (82.4 mm/h) with high-resolution LiDAR data and the physically-based hydrological model SIMWE (Mitas and Mitasova, 1998) in a small part of a vineyard (Soave, Italy). Simulations show a runoff concentration along the vineyard slope and accurately show the areas most susceptible to forming preferential pathways. The accurate and high-resolution simulations allow practical insight for designing diverse drainage systems and water storage. Such workflows have been previously demonstrated in comparing soil and water conservation impacts by different terracing systems (Pijl et al., 2020) or their drainage systems (Pijl et al., 2019). GIS-based hydrological simulations and designs can furthermore be used to determine the water harvesting potential (Sekar and Randhir, 2007), optimal sizing (Vema et al., 2018), and optimal location of new water storage facilities in watersheds (Singh et al., 2017). While the relevance of protecting these landscapes is evident because of their diverse values and the high hydrogeological risks, research is biased toward developed countries (Tarolli et al., 2020).

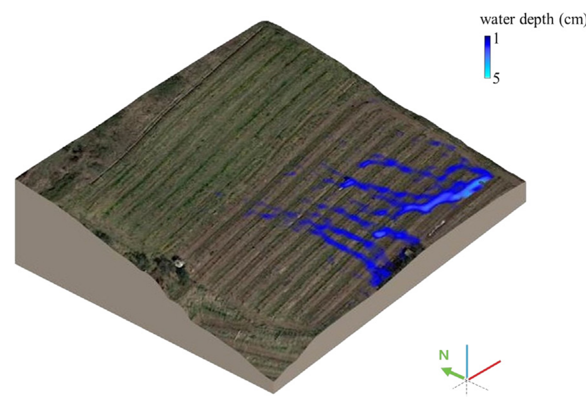

Fig. 4. A 3D example of simulated overland flowing a steep-slope agricultural system, based on high-resolution LiDAR topography data and the physical hydrological model SIMWE.

Accurate monitoring and forecasting of drought severity have received increasing attention in recent years (Ma et al., 2017). For instance, Wang et al. (2022) successfully quantified the impact of future climate change zones on steep slope agriculture. Using Google Earth Engine, they accurately predicted the percentage of areas at high risk of water scarcity in the future (2071–2100). This study has brought to light the urgency of sustainable water management practices in agricultural areas on steep slopes. Notably, the development of resilient water management in steep cultivation systems is not solely the result of scientific research, technological innovation, or efficient engineering design. Traditions, cultural practices, and indigenous knowledge in water resource

Fig. 5. The Sustainable Development Goals, as well as their specific targets, which are a solid guide for the design of future agricultural slope areas promoting the sustainable management of water resources.

management in these landscapes are often invaluable, as they naturally developed in response to their environment and site-specific conditions. In the Mediterranean area, where vineyards are widely spread, different types of nature-based solutions like organic farming mulches, geotextiles, cover crops, catch crops, chipped branches, no-tillage, managed rewilding, land restoration, etc. were applied for agricultural productivity improvement, climate change adaption, flood regulation, water provision (Cerdà et al., 2016; Keesstra et al., 2009, 2018). In Africa, grass strips, soil bunds and agroforestry were used for catching water and sediment from upstream for millennia (Keesstra et al., 2018; Vancampenhout et al., 2006). Studies have shown that these nature-based solutions can effectively reduce average runoff by 70%, reduce average soil erosion by 40%–70% and increase crop yields on steep slopes by at least 20% (Wolka et al., 2018). Explicit inclusion of local, often marginalised rural communities is relevant for achieving resilient steep-slope agricultural systems.

As the implementers of the water resource management practice, it is necessary to recognise farmers' important role in the application and adaptation of water resource measurement. Water conservation techniques may be successfully carried out in experimental stations, but remaining low adoption rates on steep slope farmland in some countries such as Uganda (Piemontese et al., 2021). The information on potential agronomic and environmental benefits of planning water resource measurement can be delivered in a straightforward approach for local farmers before making an adaptation decision. There is a great demand for policymakers to strengthen the dissemination of new water conservation technologies, interaction between professionals and farmers as well as the increasement of farmer participation (Poudel et al., 2000; Piemontese et al., 2021).

2.3. Sustainable Development Goals (SDGs) and future resilient steep-slope agricultural landscapes

Agricultural expansion worldwide has created a few problems, such as declining carbon sequestration or water depletion in arid areas (Zeng et al., 2018) . On the other hand, millions of people live on steep slopes, and their subsistence depends on agriculture in such areas. Sustainable agriculture is one meeting point for ensuring food security while respecting natural resources. Indications for mitigating water issues are already on the table. In 2015, the United Nations Member States adopted the 2030 Agenda for Sustainable Development. The document's core is a set of 17 Sustainable Development Goals (SDGs), a global and shared calling for improving life on Earth within 2030 by solving social and environmental problems. One of the Agenda's cardinal points is sustainability, the rational use of available resources to meet current and future needs. In the light of climate change and water scarcity threatening agriculture, this concept should guide any intervention in rural steep-slope environments.

This paper proposes an innovative conceptualisation of steep-slope agricultural landscapes in a future scenario where water management will have embraced SDG principles (Fig. 5). The first goal able to shape tomorrow's landscapes is the SDG2 (End Hunger), one of the most ambitious of the entire Agenda (Zhang et al., 2022). The role of steep slope agriculture is necessary as it ensures food production for millions of people worldwide (Wang et al., 2022). Optimising water use in such areas means ensuring food security. Farming practices should become more resilient by minimising waste and improving drainage networks (with particular efforts on abandoned land restoration) to mitigate the impact of drought seasons and protect crops from extreme weather events. These aspects are also aligned with SDG6 (Clean Water and Sanitation), which is committed to securing such resources across all sectors (Zhang et al., 2022). For instance, radical terraces have been recognised as effective in purifying water in some regions of Rwanda (Uwacu et al., 2021). A good practice could be exploiting the slope morphology to store excess water in reservoirs. If they are well designed, they ensure a usable supply in emergencies, such as long periods of drought. At the same time, they can collect excess surface runoff generated after heavy rainfall, limiting its critical accumulation. In addition, on slopes with water courses and high gradients, it could be interesting to develop micro-hydroelectric systems. They can convert water motion into clean and renewable energy, in line with the SDG7 (Affordable and clean energy), ensuring minimal environmental and landscape impacts (Fuso Nerini et al., 2018). The optimisation of water resources cannot ignore scientific and technological research, a key point of SDG9 (Industry, Innovation and Infrastructure). Modernization should support traditional knowledge, offering new ideas for improving agricultural activities.

A fitting example is 3D digital terrain models of cultivated slopes and high-definition GIS mapping of surface processes, which could guide stakeholders in improving farming sustainability by respecting ancestors' knowledge. Together, these approaches are fundamental to achieving SDG13 (Climate Action), which is based on increasing resilience and adaptive capacity (De Neve and Sachs, 2020). On cultivated slopes, it is crucial to implement natural-based solutions (e.g., to limit soil erosion by water) and to upgrade water conservation systems. The SDG15, "Life on Earth", is a further key goal that will be reflected in the landscapes of the future (De Neve and Sachs, 2020). Rural areas should be integrated with distributed forested spots, where water can favour habitats and ecosystems. Finally, widespread dissemination of micro wetlands, in line with the principle of water storage, can also be a suitable solution.

3. Final remarks

Steep-slope agricultural systems play an important role in global food production. Climate-proof water resource management is more than urgent for steep-slope agricultural areas. This paper highlighted firstly the importance of traditional water resource management that balances food production and ecosystem services. Secondly, we illustrated how key innovative methods and technologies like high-resolution remote sensing (e.g., LiDAR and drones) and GIS-based modelling provide valuable tools for time-efficient and cost-effective designing water management solutions. Such solutions are of utmost importance in light of the SDGs to promote the future resilience of steep-slope agricultural landscapes in the face of climate change. In general, this study provides a practical guideline for stakeholders and policymakers work in the agriculture sector to implement reasonable water resource intervention systems and design diverse water storage facilities.

Author contributions

P.T. conceived and designed the research; **W.W.** and **E.S.** equally wrote the first draft, and edited the manuscript and figures; **A.P.** produced Fig. 2, performed preliminary literature analysis, and reviewed the manuscript; **P.T.** reviewed and edited the final version of the manuscript, and supervised the entire research project.

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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