Semi-automated Human Terrace Recognition: A Case Study on Panarea Island, Italy

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Abstract. Terraces, found worldwide, demonstrate the interaction between humans and the environment, shaping landscapes, reducing slope, enabling agriculture, and mitigating erosion. Abandonment leads to negative consequences at the productive, economic, ecological, and landscape levels, with biodiversity loss and increased hydrogeological risk. In this view the semi-automated recognition of human terraces is crucial for land management, especially in areas with high historical and landscape value. Therefore, developing efficient and smart mapping methodologies is fundamental for protection, redevelopment, and valorization of such landscape. Geomorphological analysis tools were tested, with the r.geomorphon and r.param.scale modules proving most effective in delineating terraces. These methods, based on pattern recognition and local topography analysis, are well-suited to the identification of artificial structures like terraces. The r.geomorphon method generates geomorphometric maps from DEMs with a high number of cells, while r.param.scale helps to identify the characteristic of landforms, which can be useful in distinguishing terraces from other territorial features. The results of the research can be useful for terrace identification in other areas thus, supporting landscape conservation and valorization planning. Terraced landscapes preserve traditional agricultural practices, quality products, and biodiversity. The proposed methodology can came in handy in areas lacking terrace mapping that are abandoned or heavily vegetated.

Keywords: Terrace Identification · Semi-Automated Mapping · Geomorphometry · Cultural Landscape · Geomorphon · Dry Stone Walls · Land Degradation · Aeolian Islands

1 Introduction

Terraced landscapes are among the most evident demonstrations of human impact on the land [1, 2]. These structures, found in different parts of the world and in various environmental conditions, result from centuries of interaction between humans and the environment [3–8]. Terraces were created to establish cultivable areas on steep slopes,

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reduce soil erosion, improve water resource management, and increase agricultural productivity [9–12]. In many areas over the world, terraced landscapes are considered an invaluable historical and cultural heritage, as well as an ecosystem service that must be adequately preserved [13]. However, the abandonment of terraced landscapes is a growing problem in many areas, especially in mountainous and marginal zones [14, 15]. This phenomenon is often caused by socio-economic changes, migration to cities, difficulties in agricultural mechanization, aging of the rural population, and a lack of adequate support policies [16]. The consequences of abandonment can be devastating for both the environment and the landscape: i) increased soil erosion, the lack of maintenance of terraces leads to the collapse of dry stone walls, the formation of rills and landslides, and the loss of fertile soil; ii) loss of biodiversity, the abandonment of traditional agricultural practices promotes the spread of invasive plant species and the disappearance of native crops; iii) hydrogeological risk, abandoned terraces lose their function of water regulation and increase the risk of floods and landslides downstream; iv) landscape degradation: the loss of terraces alters the beauty and harmony of the landscape, with negative consequences for tourism and cultural identity.

In this context, the identification and mapping of abandoned terraced landscapes is a crucial task. Knowing the pattern and conservation state of terraces is essential to assess the risk of soil erosion and to plan targeted redevelopment interventions. Abandoned terraced areas often represent "hot spots" for erosion, as they are more vulnerable to extreme weather events and lack maintenance.

The redevelopment of abandoned terraced landscapes is a complex action that requires an integrated and multidisciplinary approach:

- restoration of dry stone walls;
- arrangement of drainage channels;
- consolidation of slopes;
- reintroduction of native crops;
- promotion of organic farming and rural tourism;
- creation of open-air museums, educational trails, cultural events;
- involvement of local communities with awareness, training, creation of job opportunities.

The retraining of terraced landscapes is not only an intervention for environmental protection but also an opportunity for economic and social development in rural areas [17–19]. Terraced landscapes represent a unique and valuable cultural heritage, bearing witness to the history, culture, and identity of a territory. Preserving and enhancing this heritage means investing in the future of our communities and ensuring sustainable development for future generations [20–24].

Terraced landscapes play a vital role in preventing landslides, floods, avalanches, soil erosion, and desertification, demonstrating a harmonious relationship between humans and nature. Human actions related to the maintenance of terraced structures can accelerate or divert natural events such as landslides and soil degradation. Maintaining terraces can improve tourism, recreational activities, the trade of agricultural products, and create job opportunities for new generations [1, 9, 25–28].

Summarizing, abandoned terraces should be identified for the environmental risks that they can generate, while an assessment of the conservation state is essential to address

appropriate recovery actions. In this perspective, we propose a GIS-based methodology for rapid and automatic terrace mapping.

2 Study Area

Panarea island, with a surface area of only 3.5 km^2, is the smallest and one of the lowest islands (421 m a.s.l.) in the Aeolian archipelago.

The Aeolian archipelago, located in the southern Tyrrhenian Sea north of Sicily, consists of seven main islands and several uninhabited islets. Geologically, the islands represent a volcanic arc. The formation of the archipelago is closely linked to the opening of the Tyrrhenian basin and the geodynamic evolution of the central-western Mediterranean area [29] (Fig. 1).

The Aeolian magmatic arc is the most active volcanic structure in the Mediterranean area, with active volcanoes such as Stromboli and Vulcano, and quiescent volcanoes such as Panarea and Lipari [29]. The active volcanoes are in the central and eastern sectors of the archipelago, while the western part does not record historical eruptions [29] (Fig. 1). The geological characteristics of the Aeolian Islands exhibit a remarkable variety. The volcanoes show composite structures resulting from alternating effusive and explosive activity [30]. The islands are the emerged portions of imposing submarine volcanic complexes, the bases of which lie at depths between 1,000 and 1,500 m below sea level. Along the coasts, one can observe marine terraces of the Late Quaternary, which are evidence of ancient coastlines and periods of eruptive quiescence. The geomorphology and distribution of eruptive centers are strongly influenced by local tectonic structures, oriented along WNW-ESE, NNW-SSE, and NE-SW directions. Many islands are surrounded by relatively flat abrasion platforms at shallow depths, interpreted as platforms formed in the Upper Pleistocene. Finally, the submarine landscape is furrowed by valleys and canyons, narrow and wide incisions that channel the transport of material from the slopes towards the open sea.

Differences in magma composition and eruptive styles have led to diverse volcanic morphologies, from cone-shaped edifices (Alicudi, Filicudi, and Stromboli) to pancake-shaped complexes (Vulcano, Lipari, Salina). Panarea has a vast submarine platform, indicating a complex volcanic history.

Panarea is the emerged portion of a much larger submarine volcanic complex, approximately 1700 m high from the seabed, with a diameter of about 18 km at a depth of 1000 m. The island rises to 421 m above sea level at Punta del Corvo. The rock types of Panarea vary from basaltic andesite and high-potassium basaltic andesite to dacite and high-potassium rhyolite, with some shoshonites [31] (Fig. 2).

The morphology of Panarea is characterized by:

- A relatively wide submarine plateau at about 100 m depth, extending well beyond the dimensions of the island;
- Minor islands and stacks east of the main island, such as Basiluzzo, Dattilo, Panarelli, Lisca Bianca, Bottaro, and Lisca Nera, which represent the summits of a largely eroded submarine volcanic complex. These islets delineate a semicircular structure and enclose a shallow depression with an active fumarolic field (Fig. 3);



Fig. 1. Map showing the Aeolian Islands, highlighting in red Panarea island. An inset provides regional context within Italy (image modified from [29])

- Relatively low coasts in the eastern and southern parts, with small beaches and flat areas (Fig. 3), where terracing once used for cultivation can be observed;
- A fault system oriented NE-SW and NW-SE that conditions both the subaerial and submarine portions of the island. These tectonic structures influence the arrangement of dikes, volcanic alignments, and major fractures;
- Marine terraces located up to 115 m above sea level, which testify to significant vertical crustal movements.

The volcanic activity of Panarea is currently in a quiescent state, with fumaroles and occasional gas emissions. However, in November 2002, a sudden submarine gas emission occurred near the islet of Bottaro, forming a crater and releasing significant amounts of SO_2, HF and HCl [29].

The coastal geomorphology is influenced by sea-level oscillations in the Quaternary. The marine terraces are evidence of different sea levels or paleocoastlines.

In summary, Panarea is a volcanic island with a complex morphology, shaped by volcanic activity, tectonics, and sea-level variations.

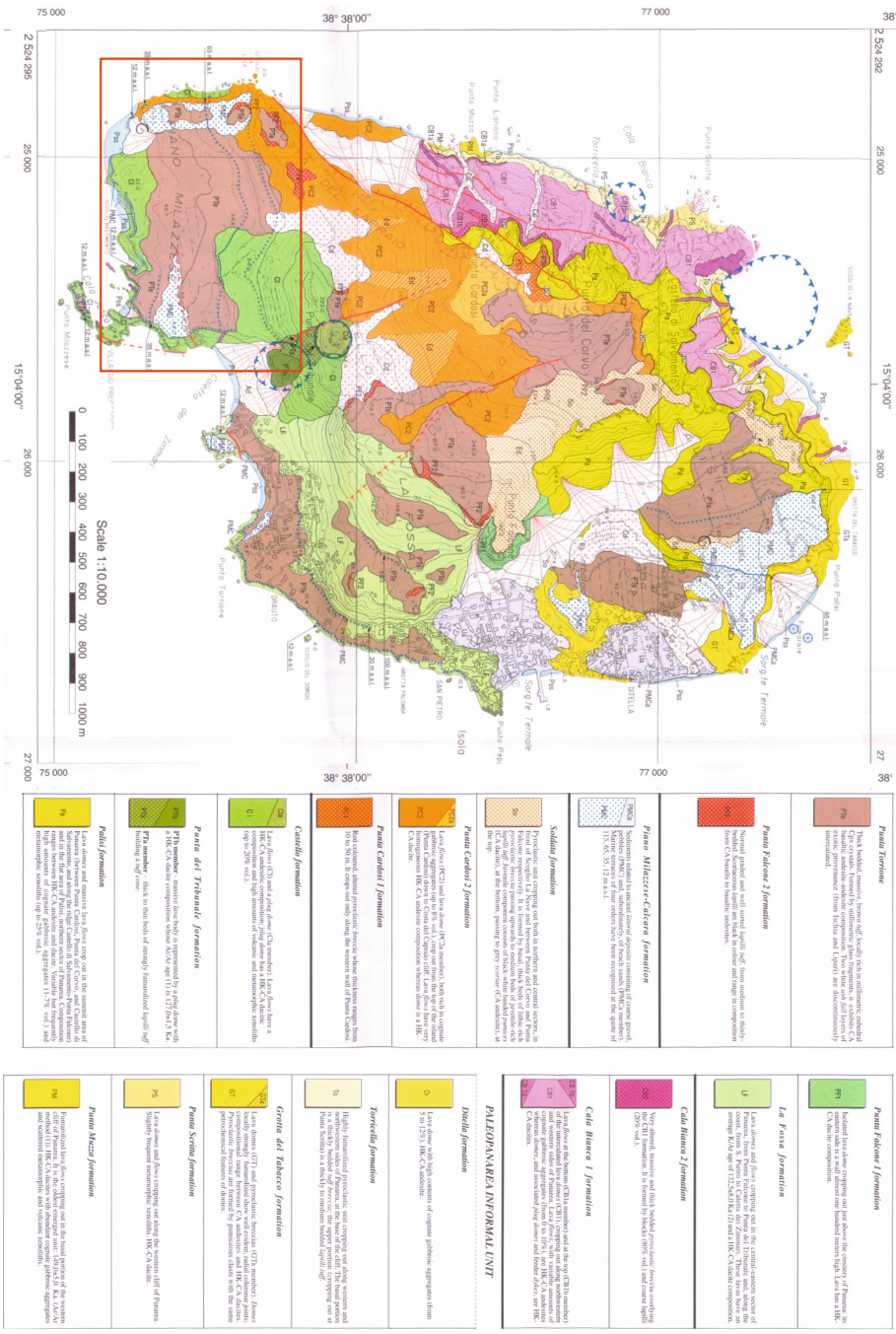

Fig. 2. Geological map of Panarea Island (from [31]), in red is highlighted the study area

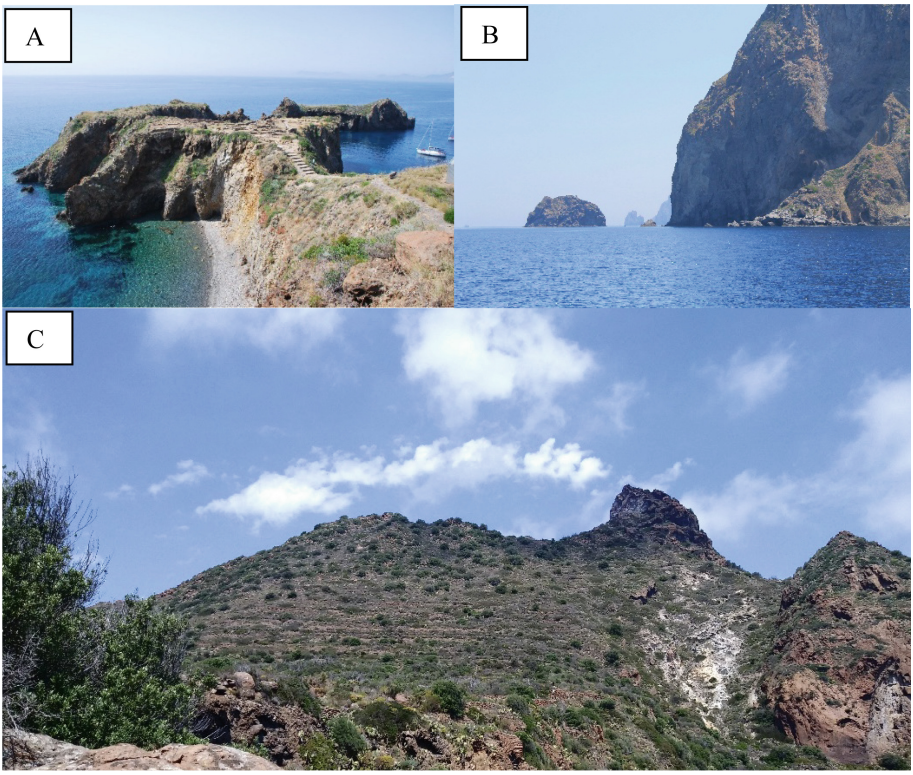

Fig. 3. Panarea island. A) a closer perspective of Punta Milazzese (South Panarea, photo by Alessandro Sardella). B) a panoramic view showcases the island's coastline, with the distinct silhouette of Basiluzzo islet standing to the left of Panarea (credits by Wikimedia Common, photo by Patrick Nouhailler). C) view from the south of the terraces studied and present in the study area delimited with the red rectangle in Fig. 2 (photo by Alessandro Sardella)

3 Methods

The methodology employed for the automatic identification of human terraces in the Panarea Island area is based on the adaptation of tools normally used for the identification of natural landscape elements. Specifically, two methods were tested.

3.1 r.geomorphon

The geomorphon method is based on the principle of pattern recognition rather than differential geometry. At the core of the method lies the concept of "geomorphon" (or "geomorphological phonotype"), a fundamental ternary pattern that serves as an archetype of a specific terrain morphology [32–34]. A finite number of 498 geomorphons constitutes a complete and exhaustive set of all possible types of morphological terrain, including standard landscape elements, as well as unknown forms rarely present in natural land surfaces [32]. The assignment of an appropriate geomorphon to each

cell of the raster takes place via a scan of the DEM, using a self-adapting procedure to identify the most suitable spatial scale at each location. As a result, the method classifies landscape elements at different spatial scales with unprecedented computational efficiency. The method does not use a fixed neighborhood size; instead, the size and shape of a neighborhood from which the landscape element is determined automatically adapts to the local terrain geometry. This makes it possible to determine the most appropriate landscape element (and its scale) in a single scan of a DEM.

3.2 r.param.scale

This approach involves an advanced technique of terrain classification based on its general topographic model [35–37].

The r.param.scale tool in GRASS GIS is designed for automated terrain classification based on landform geometry and elevation derivative values.

The following four steps illustrate the workflow:

- Multiscale Analysis: r.param.scale performs calculations at multiple scales, analyzing terrain with different moving window sizes;
- Moving Window: Setting different sizes for the moving window overcomes limitations from using default 3x3 windows, allowing derivation of variables based on larger environments than a single cell in a Digital Elevation Model (DEM).;
- Input Parameters: The tool requires three input parameters to control feature calculation 1) Slope Tolerance: Defines the flat surface; 2) Curvature Tolerance: Defines the planar surface; 3) Processing Window Size: Refers to the moving window size;
- Output: r.param.scale can derive basic morphometric variables like slope and curvatures, and classify six basic landforms, identified as morphometric features. Among these, the “planar” feature identifies relatively flat terrain.

4 Results

The study aims to identify a suitable method for recognizing the human terrace.

The following methods were tested:

- r.param.scale module implemented in GRASS GIS.
- r.geomorphon module implemented in GRASS GIS.

The r.geomorphon module proved to be the most suitable procedure for the delineation of relatively flat surfaces (in our case). In the r.geomorphon module, several settings of search radius L (2 px, 5 px, and 15 px) and flatness threshold t (5°, 7°, 10°) were tested. The r.param.scale module was tested using a range of search radius (L) values (5 px, 7 px, and 10 px) and flatness threshold (t) values (3°, 5°, 15°). With the increase of flatness threshold (t) the area of delineated plains increased, too, at the expense of other landforms. On the other hand, the area decreased with the increase of search radius (L). The final settings for parameters t and L were determined through expert visual comparison of the results across various input values, selecting those that best characterized the topography. The outputs generated by these two methods are illustrated in Fig. 4.

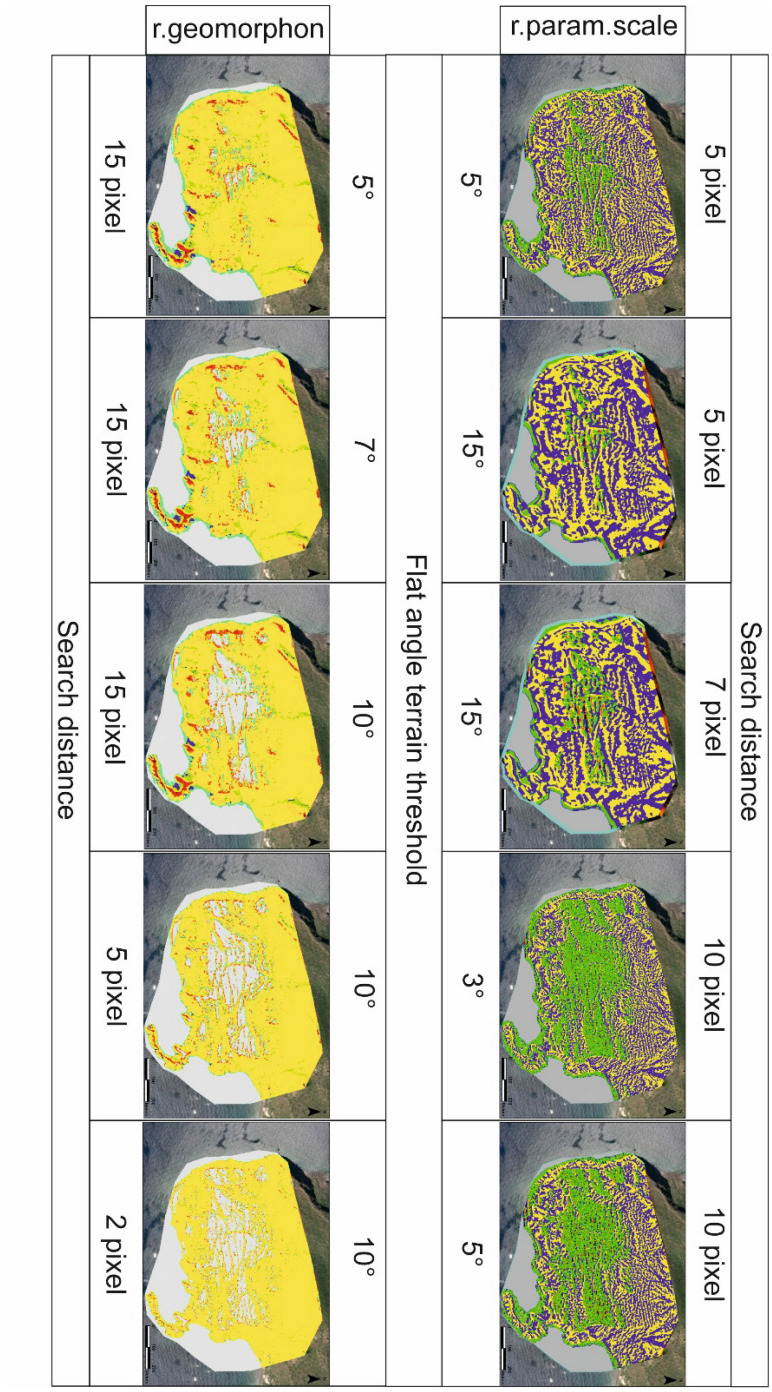

Fig. 4. Results obtained on the study area using the r.geomorphon and r.param.scale tools. Refer to Fig. 5 for the legend

Figure 5 presents the results obtained from the application of two methodologies. In this study, the r.param.scale algorithm did not identify human terraces, whereas the r.geomorphon algorithm identified some terrace features, primarily located in the central portion of the study area, as indicated in gray in Fig. 5.

The spatial resolution of the utilized Digital Terrain Model (DTM), derived from LiDAR data with a cell size of 2 m/px, impacted the performance of both methods. Given that the human terraces in the area of interest range from 5 m to 15 m in width, the following observations were made: r.param.scale did not effectively resolve terraces even at the 15 m scale, while r.geomorphon showed partial success in identifying terraces of larger dimensions in the central area. However, r.geomorphon did not detect terraces with widths of approximately 5 m, which were present in the northeastern area.

These results indicate that geomorphic tools can provide information relevant to the identification of anthropogenic terraces, although the resolution of the DTM is a limiting factor in accurately detecting features of smaller dimensions.

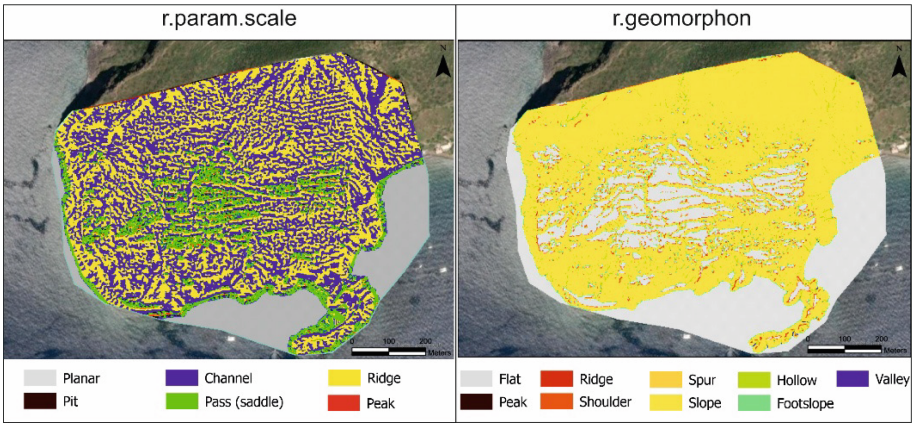

Fig. 5. Best results obtained by the two tools, on the left the result obtained with r.param.scale, on the right the result obtained with r.geomotphon

5 Discussion and Conclusion

Identifying terraces, especially those covered by vegetation, poses several challenges. Canopy can mask the physical boundaries of terraces, making them difficult to detect using traditional remote sensing techniques. Moreover, the degradation of terrace structures over time can further complicate their recognition.

Despite these challenges, identifying terraces covered by vegetation is crucial for several reasons:

- Archaeological and Historical Significance: terraces often represent valuable archaeological sites, providing insights into past agricultural practices and land management strategies. Identifying and mapping these terraces can aid in preserving and studying this cultural heritage;

- Ecological Restoration: abandoned terraces can contribute to soil erosion and land degradation. Identifying these areas allows for targeted ecological restoration efforts, such as re-vegetation and structural repairs, to stabilize the slopes and prevent further degradation;
- Sustainable Land Management: understanding the distribution and condition of terraces is essential for sustainable land management planning. By identifying areas where terraces have been abandoned or degraded, policymakers and land managers can develop strategies to promote their restoration and continued use;
- Disaster Risk Reduction: terraces play a vital role in preventing landslides, floods and avalanches, as well as combating soil erosion and desertification.

In this study conducted on Panarea Island, Italy, we applied the r.geomorphon and r.param.scale methods to semi-automatically identify human terracing using LiDAR data with a resolution of 2 m. These tools, typically used for landform identification, were adapted for identifying human landforms.

Functionality of r.geomorphon and r.param.scale:

- r.param.scale: this tool extracts terrain parameters from a Digital Elevation Model (DEM) using a multiscale approach, adapting quadratic parameters to windows of any size via least squares. The r.param.scale module uses values of curvature for flat surface delineation, which is not a suitable method for recognition of flat surfaces;
- r.geomorphon: this tool calculates geomorphons (forms of the terrain) and associated geometry using a computer vision approach. Geomorphons represent a different approach to semi-automated classification of terrain, identifying terrain elements using local ternary patterns in DEMs. The method compares a focus pixel value with surrounding pixels in eight principal directions, classifying forms based on two main parameters: L (maximum size of a search window) and t (tolerance of slope values in which terrain is considered relatively flat). The result is a geomorphic map that includes 498 possible geomorphons generalized into ten frequent landforms.

The r.geomorphon module is considered the most suitable method for human terrace recognition. The frequent elevation categories of flat surfaces can be considered as planation stages and can be correlated with elevations of cave levels. The module r.geomorphon has the highest ability to remove valleys, channels and other relatively flat areas from resulting flat landforms. Each area is specific, so efforts to minimize subjective decisions include field mapping, creation of DEM, and application of suitable method of semi-automated planation surface recognition.

Identifying terraces covered by vegetation is essential for preserving cultural heritage, promoting ecological restoration, supporting sustainable land management, and mitigating disaster risks. The application of methods such as r.geomorphon and r.param.scale, particularly r.geomorphon, offers promising avenues for semi-automated recognition of these features, aiding in their preservation and management. Further research and development in this area are crucial for enhancing our ability to understand and protect these valuable landscapes.

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