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Mapping and quantifying medium-term soil loss rates in mountain olive groves using unmanned aerial vehicle technology ☆

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A R T I C L E I N F O

Method name:
SERHOLIVE4.0

Keywords:
Water erosion
Tillage erosion
Tree mounds
Structure-from-motion (SfM)
Soil loss rates

A B S T R A C T

Olive groves are one of the main agroecosystems in the Mediterranean region, but water erosion, aggravated by inappropriate soil management, is compromising the environmental sustainability of these crops. National and international public organisations, including the European Union via its Common Agricultural Policy, have acknowledged the problem and recognise the need to quantify the effects of this process. However, the variability of currently available short-term soil erosion measurements, together with limited understanding of the underlying processes, mean there is considerable uncertainty about the long-term effects of soil erosion. This paper presents an innovative procedure called SERHOLIVE4.0 designed to measure and model long-term soil erosion rates in olive groves, by means of structure-from-motion (SfM) techniques by which image information is obtained from unmanned aerial vehicles (UAVs). For the present study, the procedure was evaluated in mountain olive groves, where the erosion rate was calculated from historical surface reconstructions. Overall, this approach was found to be practical and effective. The method includes the following steps: [1] measure the current relief using UAV technology; [2] reconstruct the historical relief from field measurements; [3] calculate soil truncation (h) and obtain a soil erosion rate map; [4] determine the erosive dynamics of the slope and establish the relation between tree truncation, slope and mounds. The method we describe presents the following advantages:

- it quantifies soil losses by reference to existing tree mounds;
- it is straightforward to apply;
- its application enhances the calibration of erosion models.

☆ Related research article: **Reconstruction of historical soil surfaces and estimation of soil erosion rates with mound measurements and UAV photogrammetry in Mediterranean olive groves;** Francisco Lima, Rafael Blanco-Sepúlveda, Mikel Calle, Dionisio Andújar. Geoderma, 440 (2023). https://doi.org/10.1016/j.geoderma.2023.116708.
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Specifications Table

Subject area;	Environmental Science
More specific subject area;	Computer and electronic in agriculture
Name of your method;	SERHOLIVE4.0
Name and reference of original method;	Reconstruction of historical soil surfaces and estimation of soil erosion rates with mound measurements and UAV photogrammetry in Mediterranean olive groves. https://doi.org/10.1016/j.geoderma.2023.116708
Resource availability;	N.A

Method details

Background

A wide variety of methods, differing in accuracy, equipment and costs, can be used to calculate soil loss rates in agricultural areas. These methods include generic erosion models such as the Universal Soil Loss Equation (USLE), both the original version and its updates [1–4], and direct measurements in the field using experimental plots with water and sediment collection equipment [5,6]. Both approaches present certain deficiencies: the first is often limited by a lack of field observations, and even if these are available, they may produce unsatisfactory results [7]; in the second case, direct measurements only provide limited spatio-temporal information [8], especially when obtained from runoff plots. In addition, this method does not consider the translocation of tillage [9] or the limited time span of most experimental measurements, which restricts any consideration of the effects of high-intensity rainfall events that are responsible for most of the soil loss in areas subject to the Mediterranean climate [10]. In studies of erosion and deposition in agricultural soils, it is useful to analyse the permanent changes that may occur in soil topography [11]. These surface measurements can be carried out by various means, including; (a) reference stakes and profile meters [12]; (b) theodolite survey, with a total station [13,14]; (c) terrestrial photogrammetry [15]; (d) terrestrial laser scanning [16–18]; (e) LiDAR [19–21]. However, these methods may disturb the soil surface, be prohibitively expensive, or be difficult to apply on a large scale. Accordingly, the watershed scale is usually considered the most appropriate for the study of erosion and deposition processes [22].

Current estimates of soil losses are mainly derived from erosion simulation models, which all, to varying degrees, require ground data for calibration and validation. Collecting this data in the field is a labour-intensive process that is often conducted at the plot scale. This approach imposes limitations on achieving a comprehensive quantification of average soil erosion and sediment deposition. While the importance of soil erosion is widely recognised, and erosion models are frequently applied, the development of a reliable method for modelling and predicting erosion continues to pose significant challenges [23], despite the substantial progress that has been achieved in the development and parameterisation of input data for erosion models. Uncertainties persist, as does the problem of redimensioning results from local to larger scales [10,24]. These concerns are highlighted by recent studies that underscore the persistent knowledge gap regarding the validity, quality and reliability of results obtained from the application of erosion models [25]. Therefore, achieving an accurate, efficient quantification of historical soil erosion remains a work in progress. Nevertheless, this goal is of crucial importance, not only for enhancing the accuracy of traditional erosion models but also for evaluating environmental impacts and for formulating effective management guidelines and policies for erosion control [26]. This paper presents SERHOLIVE4.0, a straightforward approach for quantifying and analysing soil erosion, based on the use of Structure-from-Motion (SfM) and Unmanned Aerial Vehicle (UAV) flights. This method calculates tree truncation, which represents the difference between the current relief and the original relief, thereby generating a comprehensive map illustrating historical soil erosion rates and providing valuable insights into key factors influencing erosion, including relief characteristics (slope, profile and position relative to the mound) and agricultural soil management practices.

Compared to previous methods, SERHOLIVE4.0 offers several advantages:

a) It enables the quantification of actual erosion rates and provides insights into the spatial patterns of sediment transport and deposition at the catchment scale, both intra- and inter-plot levels, without being affected by edge effects.
b) It is more time-efficient and cost-effective than some traditional methods.
c) It is a non-destructive technique, enabling continuous spatial coverage and achieving high sampling density. This ensures a sufficient volume of data to obtain representative results for the study area.
d) It is straightforward to apply, making it suitable for implementation across various scales and agricultural scenarios.

The effectiveness of SERHOLIVE4.0 in quantifying historical soil erosion rates in mountain olive groves and generating erosion rate maps at the hillside scale is demonstrated in the present study, which focuses on a mountain olive grove that has been heavily impacted by tillage and water erosion, and where tree mounds are prominently visible.

Materials and instruments

General materials

a. Five Aerial Targets
b. Bulk density sampler

Key instruments

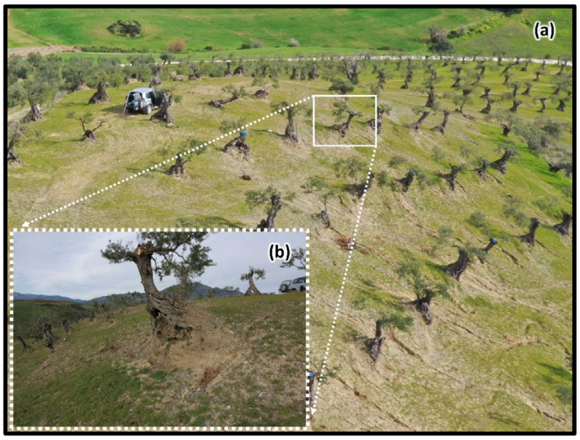

Fig. 1. The grove exhibits minimal ground vegetation cover (a), with the mounds free from weeds or suckers at the base of the trunk (b).

a. DJI Mavic 2 Pro quadcopter carrying a 1″ 20 Mp CMOS camera;
b. Trimble R2 global positioning system (RTK-GNSS);
c. Computer (>16 GB Ram, >1 TB SSD).

Software

a. Pix4Dmapper Pro (Pix4D SA, Prilly, Switzerland) or Agisoft Metashape Professional 1.8.4;
b. ArcGis 10.8.2 or Qgis 3.34.

Phases

The method consists of the following steps:

1. Measure the recent relief using UAV technology.

This process requires very high resolution images [27]. Flights should be conducted during the winter, after tillage in December, which removes vegetation cover from the ground. This requirement is easily met, as the conventional farming system usually employed in olive groves applies mechanised tillage two or three times a year. As a result, the soil is bare for most of the year. This results in a predominance of erosion forms among which splash erosion (35.83±15.65) and laminar erosion (46.39±11.60) in soils disturbed by implements are often apparent [26]. For the study area in question, this measurement was obtained on 15 January 2023. The exact date will depend on the periodicity of tillage in each region, which varies depending on rainfall. By eliminating the presence of vegetation cover in the images, we avoid possible alterations to the digital models from this factor (Fig. 1a), especially in the areas closest to the mounds (Fig. 1b). For the purposes of this study, a commercial UAV equipped with an RGB camera with a resolution of no less than 20 MP (3840 × 2160 pixels) providing digital terrain models with GSD < 4 cm is appropriate. The flight should consist of a double grid mission, with a flight altitude of no more than 30 metres, a lateral overlap of 70 % and a frontal overlap of 80 %.

Prior to each UAV flight, a set of ground control points must be geopositioned (Fig. 2), with at least five points, although additional points may be necessary depending on the size of the study area. These points must be accurately located using a Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS).

The control points are used to georeference two models: i) Recent Digital Terrain Model (RDTM) and ii) Recent Digital Surface Model (RDSM). Both are generated using specialised photogrammetry software such as Pix4Dmapper Pro (Pix4D SA, Prilly, Switzerland) or Agisoft Metashape (Agisoft LLC, St. Petersburg, Russia). This process involves sequential and automated steps, including image alignment and field geometry construction. Recent digital models have been generated using high-quality random triangulation and depth filtering, following the default Delaunay method in Pix4D. This method, which is appropriate for agricultural contexts, has proven to be effective in quantifying and mapping field-scale soil losses resulting from extreme precipitation events [28]. To ensure that the digital model represents only the ground surface, all aerial structures that might interfere with the results, including tree canopies, are removed from the model, by calculating the difference (-) between the RDTM and the RDSM using the "raster calculator" tool, which is available both in open-source GIS like QGIS 3.36 and also in licensed software such as ArcGIS 10.8.2. Finally, the slope of the current surface is calculated for the entire study area using the "slope" tool available in any of the aforementioned software packages. This tool enables slope maps to be created from the RDTM.

2. Reconstruct the historical relief from field measurements.

The historical surface is reconstructed in-field by considering the characteristic microtopography observed in mountain woody crops (Fig. 3a). This method, which draws from approaches employed earlier by [7,14] and later by [29], involves identifying the

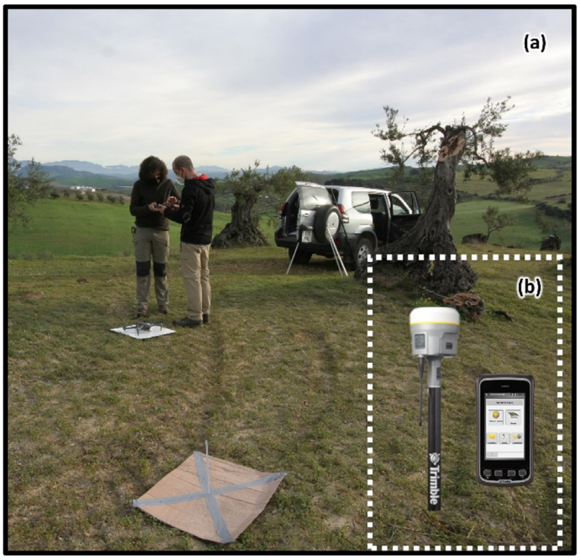

Fig. 2. Targets located as control points.

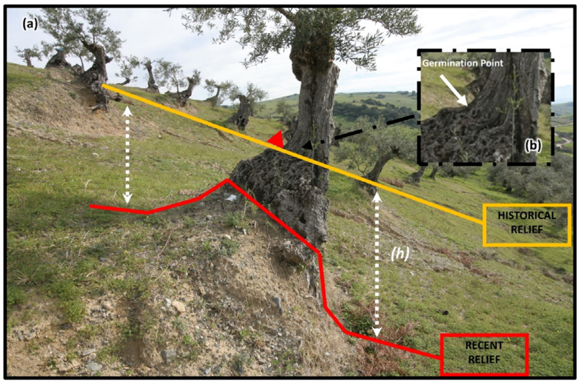

Fig. 3. Mound formed by erosion around a tree. The historical relief of the soil is highlighted by the yellow line, while the red line indicates the position of the recent relief. The difference between the two surfaces corresponds to truncation (h), with the eroded soil profile represented by a dashed white line (a). The GP is shown in detail (b). Taken from [27].

Germination Point (GP) on the circular mound formed by erosion around the tree, representing the historical relief when the grove was first planted (Fig. 3b). The historical surface is then reconstructed from this point onward.

In accordance with the observations of [29], the following criteria should be considered when measuring the GP:

i. Visible signs of root exposure due to erosion (Fig. 4a).
ii. The GP is typically located at the transition between the end of the trunk and the beginning of the root (Fig. 4a).
iii. Measurements should be taken 1 cm below the GP to account for the slight elevation caused by the thickening of the root cortex upon exposure to air (Fig. 4b).

After identifying the GP at 24 mounds, a Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) is used to obtain coordinates and heights. The GPs are treated as a ".shp" file in any GIS software, and the raster interpolation tool is used to generate a digital model from them, accurately reproducing the historical surface for the entire study area based on the z values (Fig. 5).

The raster obtained from this interpolation process is termed the Historical Digital Terrain Model (HDTM), generated through the application of the appropriate geostatistical wizard.

The interpolation methods applied facilitate the consolidation of robust digital models. In our study, the Delaunay triangulation method used in high precision photogrammetry enabled RDTM reprojection with an RMSE of 0.41. By contrast, the IDW method used for HDTM reprojection had an RMSE = 0.31 m, with a validation error of −0.29 ± 0.45 m. For the bulk density raster, the RMSE was 0.11 m with a validation error of 0.005 ± 0.07 m. For more information, see [27]. We then calculated the difference between the HDTM and the RDTM, on the basis of which we created a digital model with the same characteristics as the RDTM but representing the historical surface using mound heights. This procedure includes the assumption that the historical microtopography

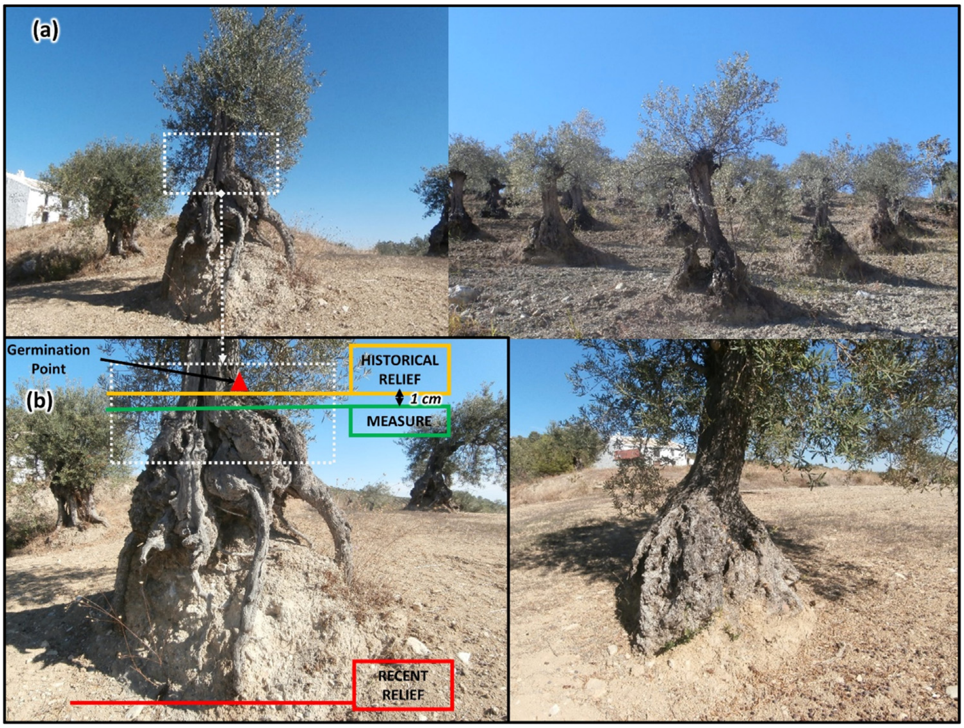

Fig. 4. Mound measurement method.

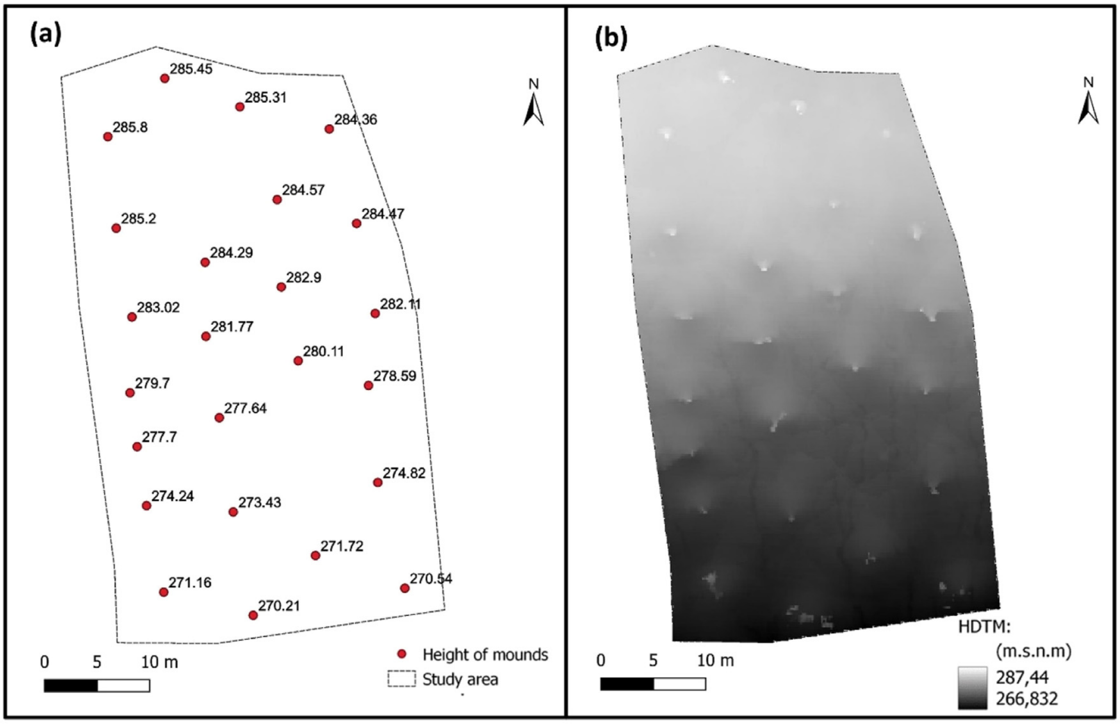

Fig. 5. Mound measurement (a) and HDTM (b) taken from [27].

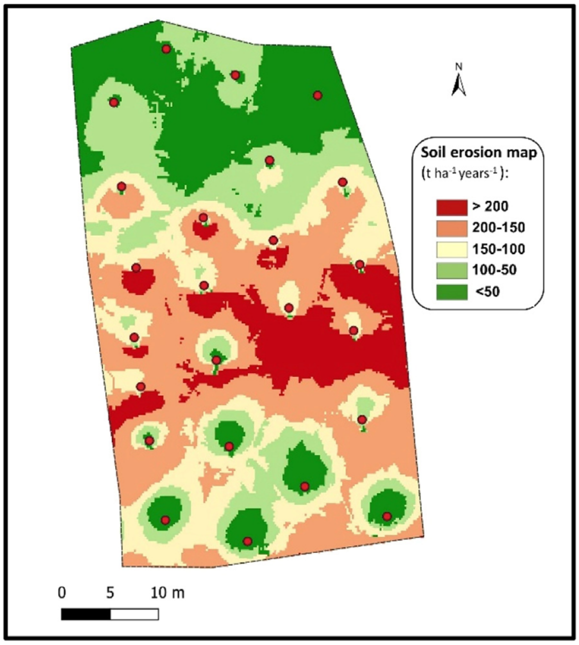

Fig. 6. Example of soil erosion rate map. Taken from [27].

of the terrain (HDTM) resembles the current aspect (RDTM) but without the truncation effect. This assumption is inescapable due to the impossibility of knowing the historical surface roughness. This process is considered more realistic than considering the historical surface continuously without roughness. Furthermore, current surface data are characterised by high resolution, whereas the historical surface data were obtained from interpolations based on a limited set of observations. Thus, the greater the number of mound measurements, the greater the accuracy of the historical reconstruction. A smaller number of mounds would limit the capability of the methodology used.

3. Calculate soil truncation (h) and obtain a soil erosion rate map

The historical truncation of soil since the establishment of the olive grove is determined by using tree mounds as indicators of area reduction. The "raster calculator" command is applied to convert the RDTM to the HDTM. This creates a new digital model showcasing the loss of the surface horizon, measured in cubic metres, referred to as the Truncation Digital Terrain Model (TDTM). The core method (Blake and Hartge, 1986) is then employed to determine bulk density. This involves collecting soil samples in cylinders of a known volume (e.g., 100 cm^3) around the mounds (one sample per mound), which are then dried (105–110 °C until constant weight) and weighed in the laboratory. After obtaining the bulk density data for each sample, the "raster interpolation" command is used by the IDW method to create a new raster with bulk density data for the entire study area.

The age of the plantation can be determined through dendrochronology, interviews with the landowner(s) [27] or through historical photointerpretation techniques (if available). It is essential to verify that the mounds result from erosive processes such as water erosion and tillage, rather than anthropogenic accumulation. For this purpose, it is essential to carry out field work. Taking into account the volume of eroded soil (TDTM), the age of the tree and the bulk density of the soil, the erosion rate can be calculated with the "raster calculator" following the method described in [14]. This process enables us to create a soil erosion rate map (Fig. 6).

$$SERM = \left(\left(L1^{*}L2^{*}TDTM^{*}DA\right) / HA\right) / Years$$

where:
SERM= Soil erosion rate map, L1= side of study plot, L2= side of study plot, TDTM= Soil volume eroded, HA= study plot area in Ha, Years= estimated number of years of planting.

4. Validate the results and analyse the influence of relief on erosion.

After obtaining the soil erosion rate map, the relationship between erosion rate and slope is determined by identifying control points, termed truncation/slope (Fig. 7a). These points are established using ArcMap's "create fishnet" command, which overlays a 5 m^2 mesh onto the study area. Truncation, slope and hillside profile data are then extracted from the centre of each grid cell. Additionally, to assess the impact of mounds on soil truncation along the hillside profile, buffers of 0.5, 1, 1.5, 1.5, 2, and 2.5 metres are created around the mounds. Along the line of maximum slope, perpendicular transects are drawn from these buffers to generate

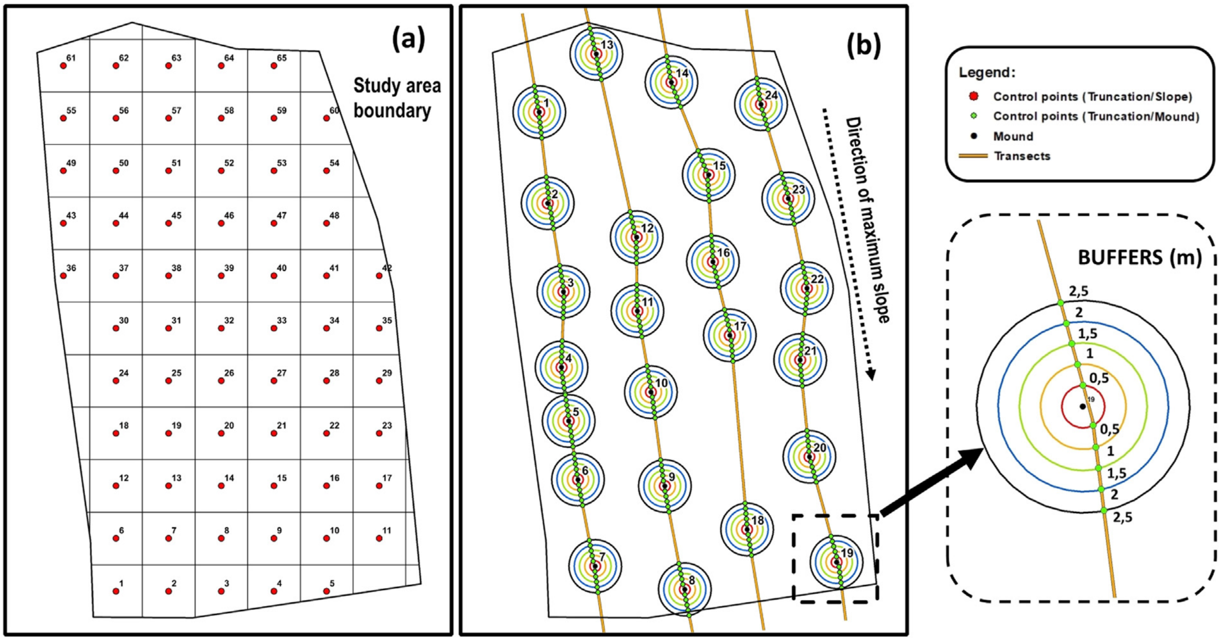

Fig. 7. Example of truncation data validation: with different slope positions (a) and position/proximity to the mound (b). Taken from [27].

new control points (truncation/mound) (Fig. 7b). Truncation and slope data are extracted for both the upper and lower parts of the mound at these points.

Finally, a database is generated with which to conduct a statistical analysis of the influence of terrain relief and soil management on the erosion rate. The relationship between the TDTM and the slope is examined through bivariate correlation analysis, employing Pearson's correlation coefficient (r). Furthermore, the variation in TDTM across different slope profile positions (high, medium and low) and their proximity to the mounds (high and low/0.5, 1, 1.5, 1.5, 1.5, 1.5, 2, 2.5) is assessed using analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) test on IBM SPSS Statistics 25.0. software.

In the present study, the method was applied in mountain olive groves with clearly visible tree mounds [27], where the climate is temperate Mediterranean, with an average annual temperature of 18.4 °C and precipitation of 636 mm, which is often torrential. The results were very satisfactory, showing erosion rates very much in line with those obtained by [7,14,29] in other Mediterranean regions using similar methodologies based on mound measurements.

However, the method presents certain limitations, among which are: a) the need to have a representative number of visible tree mounds (the more, the better); and b) the need for little or no ground cover when flights are carried out, in order to avoid the disturbance of the digital terrain models derived from the UAV.

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.

CRediT authorship contribution statement

Francisco Lima: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Rafael Blanco-Sepúlveda:** Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Supervision. **Dionisio Andújar:** Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mex.2024.102786.

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