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The application of terrestrial laser scanner and photogrammetry in measuring erosion and deposition processes in humid badlands in the Central Spanish Pyrenees

E. Nadal-Romero[1], J. Revuelto[2], P. Errea[2], and J. I. López-Moreno[2]

[1]Institute for Biodiversity and Ecosystem Dynamics. Earth Surface Science Research Group (IBED-ESS), University of Amsterdam, Amsterdam, the Netherlands
[2]Instituto Pirenaico de Ecología (CSIC), Procesos Geoambientales y Cambio Global, Zaragoza, Spain

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Correspondence to: E. Nadal-Romero (m.e.nadalromero@uva.nl)

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Abstract

Erosion and deposition processes in badland areas are usually estimated using traditional observations of topographic changes, measured by erosion pins or profile meters (invasive techniques). In recent times, geomatic techniques (non-invasive) have been routinely applied in geomorphology studies, especially in erosion studies. These techniques provide the opportunity to build high-resolution topographic models at sub-centimeter accuracy. By comparing different 3-D point clouds of the same area, obtained at different time intervals, the variations in the terrain and temporal dynamics can be analyzed. The aim of this study is to assess and compare the functioning of Terrestrial Laser Scanner (TLS, RIEGL LPM-321) and close range photogrammetry techniques (Camera FUJIFILM, Finepix x100 and Software PhotoScan by AgiSoft), to evaluate erosion and deposition processes in a humid badland area in the Central Spanish Pyrenees. Results show that TLS data sets and photogrammetry techniques provide new opportunities in geomorphological erosion studies. The data we recorded over one year demonstrated that north-facing slopes experienced more intense and faster changing geomorphological dynamics than south-facing slopes as well as the highest erosion rates. Different seasonal processes were observed, with the highest topographic differences observed during winter periods and the high intensity rainfalls in summer. While TLS provided the highest resolution models, photogrammetry was still a faster methodology in the field and precise at short distances. Both techniques do not require direct contact with the soil and thus prevent the usual surface disturbance of traditional and invasive methods.

1 Introduction

1.1 Humid badlands: strong geomorphological dynamics

Previous studies defined badlands as areas with scarce or no vegetation, where human activities, especially agriculture, are not possible (i.e. Alexander, 1982; Bryan and Yair, 1982; Fairbridge, 1968; Howard, 1994). Although badlands are considered characteristics of arid and semiarid environments, they are also found in humid and subhumid areas (Gallart et al., 2013). Badlands are a landscape with a very high frequency and magnitude of geomorphological processes, resulting in rapid landscape evolution, which makes them "ideal field laboratories". Sheet wash erosion, gullies and rills, landslides, and mudflows are often observed in badland areas; the constantly changing landscape makes it very difficult to analyze geomorphological dynamics and measure erosion.

In general badland areas show high erosion rates. The recorded values depend on the applied methodologies (Sirvent et al., 1997), on the spatial scale of measurement (Nadal-Romero et al., 2011, 2014) and also on the temporal scale, as erosion rates show high inter-annual variability (García-Ruiz et al., 2015). A recent comprehensive review by Nadal-Romero et al. (2011, 2014) of the scale-dependency of sediment yields from badland areas in Mediterranean environments showed extensive variability in erosion rates and sediment yields. In the Tabernas Badlands, Cantón et al. (2001) measured very low erosion rates (0.08–0.35 $\text{mm}\,\text{yr}^{-1}$) due to the low frequency of rainfall. Lam (1977) obtained 17.36 $\text{mm}\,\text{yr}^{-1}$ in the Hong Kong badlands. Higher values were registered in subhumid badland areas of southern Tuscany (15–20 $\text{mm}\,\text{yr}^{-1}$) (Ciccacci et al., 2008) and the Prealps catchments in France, with erosion rates of over 30 $\text{mm}\,\text{yr}^{-1}$ (Chodzko et al., 1991). Recently, Vericat et al. (2014), using a non-invasive technology, a Terrestrial Laser Scanner (TLS), measured an annual soil loss of around 60 $\text{mm}\,\text{yr}^{-1}$ in the Eastern Pyrenees (Spain).

1.2 Review: methodologies for analyzing geomorphological processes and erosion rates in badlands

The geomorphology of badlands has been extensively studied for the last 30 years, and there is a substantial body of literature on the subject. In this context, numerous methods have been used to understand geomorphological dynamics (erosion and deposition processes) and quantify erosion rates. The following presents an overview of the main methodologies for investigating erosion rates and sediment yields in badlands.

A total of 171 papers (starting from 1956) were identified using the Scopus and the ISI Web of Knowledge databases (search terms: "Badlands and erosion rates" and "Badlands and Sediment Yield"). The obtained information enables the classification of the studies according to the different methods (Fig. 1).

The analysis showed that there is no standard protocol for measuring erosion and sediment yield in badland areas, with a variety of methods (at different temporal and spatial scales) being used, both conventional and new remote sensing techniques. The most commonly reported method is a gauging station (i.e. Nadal-Romero et al., 2008), seen by different authors as the best approach for measuring sediment transport (Walling, 1999). Remote sensing technologies (i.e. Martínez-Casasnovas and Ramos, 2009), rainfall simulations (i.e. Martínez-Murillo et al., 2013) and erosion models (i.e. Mathys et al., 2003) were recorded in about 20 studies. Topographic surveys (i.e. Sirvent et al., 1997), runoff plots (i.e. Gallart et al., 2013) and erosion pins (i.e. Vergari et al., 2013) were used a bit less often (approximately 15 studies each). On the other hand, dendrogeomorphological techniques (i.e. Ballesteros-Canovas et al., 2013), TLS data acquisition (i.e. Sáez et al., 2011; Vericat et al., 2014), radioisotopic measurements (i.e. Sadiki et al., 2007) and bathymetric surveys (i.e. Grauso et al., 2008) have been sporadically applied in badland studies (Fig. 1).

The methods were classified as invasive tools (mostly traditional methods, e.g. gauging station, rainfall simulations, topographic surveys, runoff plots, erosion pins) and non-invasive tools (mostly new technologies, i.e. remote sensing, TLS, photogrammetry, aerial pictures). The annual evolution of the different methods is represented in Fig. 2 (data from 1980, $n = 164$). Figure 2 indicates that (i) during the last 30 years, studies on soil erosion in badlands have increased; (ii) the few studies during the 1980s all used traditional invasive tools; and (iii) from 1996, non-invasive methods are starting to be used in erosion studies in badland areas, with the sharpest increase in 2007.

1.3 New geomatic techniques: terrestrial laser scanner and photogrammetry

Field methods for geomorphological processes analysis and soil erosion quantification have evolved from traditional methods (most of them invasive) to those that do not disturb the soil (non-invasive). In the last decades, techniques to rapidly acquire high-density topographic data have proliferated; however, the tools to adequately analyze change within these complex data sets have only now become accessible (Barnhart et al., 2013).

Terrestrial Laser Scanners (TLS) are a non-intrusive, high precision tool, designed to retrieve information on the topographic characteristics of any surface. TLS use LiDAR technology (Light Detecting and Ranging), to accurately measure the distance from the device to the desired surface. By measuring the distance at thousands of points of a spatial mesh, 3-D point clouds of a very high spatial resolution are obtained. This information makes it possible to generate Digital Elevation Models (DEMs) that accurately reproduce the topographic surfaces. TLS serves as a monitoring tool to observe changes in surface morphology, and the data collected with TLS can be used for both calculations of volumetric changes as well as documentation of surface conditions (development of rills, roughness etc.). The acquisition time is relatively short, and the precision is sufficient for detailed erosion studies in very active areas. The high-resolution topographical surveys already conducted with TLS in badland areas (i.e. Lucía et al., 2011; López-Saez et al., 2011; Vericat et al., 2014) encourage its application in other study sites.

Photogrammetry is a remote sensing technology that obtains 3-D point clouds based on the triangulation process of images of the same area from different points of view.

The information from either aerial or terrestrial photographs is processed using one of a number of available software solutions, creating 3-D point clouds from several images of one area. Today, this tool offers new possibilities and innovative procedures, like creating DEMs in automatic mode to reconstruct surfaces (Bitelli et al., 2004). During the past 20 years, intensive research was published on the automation of the information extraction from digital images (i.e. the continuous development of processing algorithms) (Baltsavias, 1999). Several scientific fields, like geoarcheology and architecture, have already accepted photogrammetry as a useful tool (i.e. Verhoeven et al., 2012; Farenzena et al., 2008), and its advantages for geomorphological research have been long recognized (Castillo et al., 2012). However, to date few studies have taken advantage of the possibilities offered by geomorphology to generate terrain models, and no studies have been carried out in badland areas.

The main objective of this research is to assess and compare Terrestrial Laser Scanner (TLS) and close range photogrammetry for the evaluation of geomorphological processes (erosion and deposition) and topographic changes in two opposite active slopes (north- and south-facing) in a humid badland area in the Central Spanish Pyrenees.

2 Materials and methods

2.1 Study area: the Araguás catchment

The Araguás catchment (0.45 km^2) is a north–south orientated tributary of the Lubierre River, located in the Central Spanish Pyrenees. The altitude ranges from 780 to 1105 m, and it has a substantially large badland area, spreading over 25 % of the catchment (Fig. 3).

The climate of the area is sub-Mediterranean with Atlantic and Continental influences (Creus, 1983). The average annual rainfall is about 800 mm, varying from 500 to 1000 mm annually, and the average temperature is 10 °C.

SOILD
2, 337–369, 2015

Badlands occur on the Eocene marl of the Inner Pyrenean Depression. The Araguás catchment has been monitored since 2004 to study the hydrological and sedimentological dynamic in the badland area, using a gauging station at the outlet of the catchment. Previous studies showed that the dynamics of weathering and erosion processes are the principal factors controlling geomorphological development, showing extreme hydrological and sedimentological responses (Nadal-Romero and Regüés, 2010). The badlands are very active: intense sheet wash erosion, gullying and rilling, with heavy mudflows during the most intense rainstorms, produce substantial annual sediment yields (Nadal-Romero et al., 2008).

Two slopes with opposite aspect (facing north and south) were selected to apply the TLS and photogrammetric surveys (Fig. 3). These slopes were chosen based on two criteria: (1) according to the different geomorphological processes that can be observed on the dry slope (south-facing) and on the more humid one (north-facing), and (2) according to the differences in area extension between both slopes and the working distances from measurements were taken. The analyzed extension of the north and south slopes are respectively 3200 and 560 m^2. The average working distance for the TLS in the north-facing slope is 102 m, while for the south-facing slope is 25 m. The pictures for the photogrammetry software were taken from an average distance of 100–150 m for the north-facing slope, and 40–60 m for the south-facing slope.

2.2 Terrestrial laser scanner

The device used in the present study is a long-range TLS (RIEGL LPM-321) (see Revuelto et al., 2014, for the technical characteristics of the TLS and the procedure used for scanning and post-processing information can be checked).

Indirect registration (target-based registration) was used to merge the information from the different scan stations and for transforming the local coordinates of the obtained point clouds into a global coordinate system. The point cloud transformation makes it possible to compare scans made on different survey days. The indirect registration considers fixed reflective targets placed at reference points (metallic stakes), which are placed at the same positions at the study site. We installed 9 targets on the north-facing slope and 9 targets on the south-facing slope (the high number of targets increases the robustness of the experimental setup, see Revuelto et al., 2014), each was a cylindrical reflector 0.10 m in diameter placed at a height of 0.10 m.

Once the formal steps were completed (i.e. atmospheric correction, scan of targets, selection and delimitation of the area of interest), we started with the scan of the selected slopes.

In this study, the average resolution in point cloud acquisition was 625 points m^{-2} (0.04 m linear distance between points), and the angular scanning resolution was 0.027° on the north-facing slope, and 1890 points m^{-2} (0.023 m) and 0.054° for the angular resolution on the south-facing slope. For the areas closer to the TLS the point resolution is increased while at longer distances it is decreased. This is one of the main limitations of the technology: it does not enable a consistent distribution of the acquired information.

Finally, when the scan was completed, photographs were taken using a digital camera coupled to the scanner, to capture useful RGB (Red, Green, Blue) information for each point.

2.3 Photogrammetry

Close range photogrammetry allows the creation of 3-D models from multiple overlapping images taken at distinct triangulation angles. In this case, we used the FUJIFILM Finepix x100 camera, with a focal length of 23 mm (equivalent to a fixed lens of 35 mm), which provided better 3-D reconstruction (James and Robson, 2012). In each survey, in north-facing slopes 17 pictures were taken at an approximate distance of 100–150 m; in south-facing slopes 15 pictures were taken, at an approximate distance 40–60 m with a resolution of 12 MP (4288 × 2848 pixels). The pictures were taken by hand following a set-walking itinerary. The images were analyzed with Agisoft Photoscan Professional Edition® software, generating a 3-D point cloud of the study area. Differences in lighting can cause problems during data processing, and Agisoft software is a helpful tool

SOILD
2, 337–369, 2015

to overcome this risk, as it estimates the error potential and deletes questionable photos. The spatial resolution of the generated point clouds depends on the quality of the model processed with the images obtained with the camera. In this study, we used higher resolution modes, which provided a spatial resolution of 970 points m^{-2} for the north-facing slope and 2800 points m^{-2} for the south-facing slope. In photogrammetry, the resolution does not depend on the measuring distance; the point distribution within the area does not vary significantly and in general is quite similar for the whole study site.

2.4 Data processing

In order to georeference both data sets (photogrammetry and TLS point clouds) into the same coordinate system, we applied indirect registration (target-based) using the reference point coordinates of the targets (coordinates acquired with the TLS). Based on the target coordinates, a transformation matrix to a global coordinate system (UTM ETRS89 30N) using Riprofile 1.6.2 software is generated for the TLS point cloud. The standard deviation was lower than 0.015 m in all the TLS scans, which is in accordance to errors reported in other studies (Revuelto et al., 2014). Similarly, the point cloud obtained from photogrammetry is transformed onto the same coordinate system by a transformation matrix calculated in Agisoft Photoscan using the TLS-recorded target coordinates with standard deviation below 0.025 m.

In both cases, the post-processing (comparing point clouds to determine the topographic differences between dates) was accomplished using CloudCompare software (http://www.danielgm.net/cc/; Girardeau-Monaut et al., 2005), which generates maps of distances between clouds of points corresponding to different survey days.

Measurements were performed at similar intervals between July 2013 and July 2014; in total four topographic surveys of each study zone were conducted on the following dates: 24 July 2013, 12 November 2013, 26 March 2014 and 24 July 2014.

SOILD
2, 337–369, 2015

Rainfall data was recorded in the Araguás catchment (see Nadal-Romero and Regüés, 2010) and the volume and characteristics of rainfall during the study periods was also analyzed.

3 Results

Data analyses are conducted on different temporal scales – (i) survey/monitoring intervals, and (ii) at annual scale in both slopes (north- and south-facing slopes) – using both TLS and photogrammetry. Monitoring intervals and rainfall data are presented in Table 1 and Fig. 4. The length of the monitoring intervals ranged from 112 to 134 days. Maximum daily rainfall was from 24.6 to 77.2 mm, and the maximum 5 min rainfall intensity ranged from 14.4 to 148.8 mm h^{-1}.

The results are structured in 3 sections. First, the results obtained on the north-facing slopes are analyzed (Sect. 3.1), and then the results obtained on the south-facing slope are examined (Sect. 3.2). In both sections, spatial and temporal variability of topographic changes are described. Finally, a comparison between both data analysis and methodologies is carried out in the discussion section.

3.1 North-facing slopes

Observed topographic changes over different monitoring survey intervals on the north-facing slope are presented in Figs. 5 and 6 (TLS and photogrammetry data respectively). Erosion and deposition values are summarized in Table 2. Negative values reflect erosion processes. On the other hand, positive values may reflect deposition processes; however, swelling processes can also influence these values (Vericat et al., 2014).

On north-facing slopes, period 2 (longest period, winter period) showed the strongest and most variable topographic changes (Figs. 5b and 6b): −0.046 and −0.051 m with

TLS and photogrammetry respectively. Most sections of the slope showed signs of rills development.

However, the biggest absolute differences were observed during period 1 (summer). It was the rainiest period (334.8 mm) due to convective storms with high rainfall intensities (148.8 mm h^{-1}, see Table 1). During this period the maximum negative difference (−0.610 and −0.43 m with TLS and photogrammetry respectively) was registered due to small movements in the upper part of the slope. A small zone of regolith deposits was also evident just downhill of this movement (Figs. 5a and 6a). Period 3 (spring) showed the lowest values, which is consistent with the low rainfall (198 mm).

3.2 South-facing slopes

On south-facing slopes, period 2 showed the biggest and most variable topographic changes (Figs. 7b and 8b, and Table 3): −0.037 and −0.001 m (note the high standard deviation compared to the average difference in Table 1) with TLS and photogrammetry respectively. An important movement was recorded on the lower part of the slope, showing high positive and negative values (both erosion and deposition).

The changes in periods 1 and 3 were smaller, although important rill development was observed in both periods. Small movements and deposition processes at foot-slopes were recorded (see Figs. 7 and 8).

On the south-facing slope the biggest absolute differences were also observed during period 2, due to the important movement recorded at the lower part of the slope. The maximum negative difference was around −0.42 m, while the maximum positive difference was around 0.50 m.

3.3 Joint analysis

The magnitude of the annual erosion rates was higher on the north-facing slope than on the south-facing slope, −0.077 and −0.032 m respectively, recorded using TLS point clouds (see Tables 2 and 3). Photogrammetry yielded more moderate differences:

−0.017 and −0.002 m on the north-facing and south-facing slope respectively. Furthermore, on the south-facing slope the annual maximum negative and positive values are very similar (0.416 and −0.453 m with TLS, and 0.48 and −0.42 m with photogrammetry); however, important differences were observed between the negative and positive absolute maximum values on north-facing slopes (0.250 and −0.590 m with TLS, and 0.34 and −0.46 m with photogrammetry).

In both cases, the variability of topographic changes was very high, as indicated by the high standard deviations (which was even higher at the south-facing slope).

If differences between both methods are analyzed, we have to highlight that in south-facing slopes (short distance and small area) the values using both methodologies are really similar; however, on the north-facing slope (long distance and large area) the measurement differences between the two methodologies are remarkable.

4 Discussion

4.1 Geomorphological dynamics

Both techniques can produce high-resolution topographic models with subcentimeter accuracy. By comparing different point clouds of the same area, obtained at different time periods, we analyzed variations in the topographic characteristics of the terrain and the temporal geomorphological dynamics.

First, it must be highlighted that the variability of the recorded topographic changes was very high, as reflected by the high standard deviation (see Tables 2 and 3). The detailed analysis of the point clouds showed the geomorphological dynamics of these severely eroded areas. The results indicate that the geomorphological dynamics on north-facing slopes are more intense than on south-facing slopes, except punctual high variations on the south-face. Various studies have highlighted terrain aspect as an important factor in the geomorphological development of badlands (i.e. Calvo-Cases and Harvey, 1996; Descroix and Olivry, 2002; Pulice et al., 2013).

SOILD
2, 337–369, 2015

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

The values presented in Tables 2 and 3 also show that highest topographic changes were recorded during winter periods. Also other studies highlighted that the development and weathering dynamics of regolith in north-facing slopes are more active in winter, due to the freeze–thaw weathering processes, while south-facing slopes are dominated by the development of crusts associated with wetting–drying processes (Nadal-Romero et al., 2007; Nadal-Romero and Regüés, 2010). It has to be noted that shrink–swelling and freeze–thaw processes may cause dilation of surface material, which results in a net surface elevation; however, this study does not take these small variations into account.

North-facing slopes experienced small mud or debris flows, although also south-facing slopes had these flows due to the high slope gradient. These types of movements have also been recorded in humid badlands in southeast France using a small portable camera in the Draix catchment (Miniature Debris Flows – MDF) (Yamakoshi et al., 2009). Nadal-Romero et al. (2007), based on field evidence and laboratory work, suggested that in these badland morphologies shallow landslides and small mudflows commonly occur during prolonged rainfall events. These erosion processes produced the development of fans at the base of slopes and near the main channels, processes also observed in different badland morphologies (Balasch, 1998; Regüés and Gallart, 2004; Desir and Marín, 2007). It is also remarkable that during summer, convective storms of high intensity and short duration overcome infiltration capacity and generate intense concentrated runoff. Rills and gully development usually appear during these events and are significant in sediment production (Nadal-Romero and Regüés, 2010). Both TLS and photogrammetry captured these processes, which confirms that both are good techniques for studying geomorphological processes in badland areas.

TLS results on the north-facing slope indicated a negative difference of 77 mm yr^{-1}, while on the south-facing slope the negative values are lower, 32 mm yr^{-1}. More moderate differences are recorded using photogrammetry point clouds with annual values of 17 and 0.2 mm yr^{-1}, on the north-facing and south-facing slopes respectively. Nevertheless these values should be contextualized with the observed standard deviation of

3.8 mm for north-facing and 5.6 mm for south-facing slopes. Nadal-Romero et al. (2008) estimated erosion rates (represented as a lowering of the soil surface) determined from the suspended sediment loss measured at the outlet of the catchment (converted to centimeters) and taking into account the specific weight of the marl (2.75 g cm^3). During the study period (November 2005 to January 2007), March and September 2006 were particularly active in terms of sediment transport, with a recorded drop in soil surface of 13 and 8 mm, respectively. The estimate of annual erosion rates for the entire catchment was 27.5 mm yr^{-1}. High erosion rates, similar to the ones obtained in this study, were recorded in different badland areas. Using similar methodology, Vericat et al. (2014) measured an annual change of around minus 60 mm yr^{-1} in the Eastern Pyrenees (Spain). Lower values were registered in subhumid badland areas of southern Tuscany (15–20 mm yr^{-1}) (Cicacci et al., 2008) and the Prealps catchments in France (over 30 mm yr^{-1}) (Chodzko et al., 1991) using invasive traditional methodologies.

4.2 New non-invasive tools

This study demonstrates that both methodologies adequately facilitate subsequent analysis – both in a quantitative (metric) and qualitative (interpretive) way. Both offer a good opportunity to safely measure landform without soil disturbance, with high spatial resolution and in a relative short time period. Table 4 presents the advantages and disadvantages of both methods.

Both methods allow fast and automatic image processing. Nevertheless, photogrammetry reduces the data collection effort in the field, although post-processing is still labor-intensive. TLS is an expensive (and quite heavy) tool, while photogrammetry is relatively cheap and easy to use. Castillo et al. (2012) calculated the cost of TLS at 10 times the cost of 3-D photogrammetry.

Our study demonstrates that photogrammetry delivers good accuracy and has promising field application in geomorphological and soil erosion studies. In our case, the quality of the images should be improved in order to obtain better accuracy, paying

SOILD
2, 337–369, 2015

especial attention to illumination changes during the acquisition of the images, which have been observed as an important error-causing interference. Nevertheless, if the image acquisitions locations are well established and the image overlapping is done well, the number of needed images is not very high (5–10 pictures).

TLS shows better performance in differentiating small displacement of terrain (resolution of images) (i.e. rills development). However, the missing information due to terrain curvature observed in some areas with the TLS (north-slope), is avoided with photogrammetry because different points of view of the study area were easily acquired. Nevertheless, in the presented analyses and also in the images that show point cloud differences, these shadow areas have been removed in photogrammetry to consider exactly the same area with both methods.

Photogrammetry performs better for the spatial distribution of the point cloud, for areas closer to the TLS the point resolution is increased, while for longer distances it is decreased, which is one of the main limitations of this technology. However, TLS does provide higher resolution images.

TLS and photogrammetry data sets supported quantifiable data that previously had to be gathered through very labor- and time-intensive field measurement. Castillo et al. (2012) compared the accuracy, time and cost of the conventional and the new techniques. They observed that photogrammetry is the method that produces the best approximation to the TLS, with differences less than 3 cm. They also suggested that traditional methods (2-D methods) can produce significant volume errors. Marzolff and Poesen (2009) suggested that compared to remote sensing imagery field methods have the disadvantages of time consuming measurements, thus usually covering rather small areas with a limited sampled density. Perroy et al. (2010) concluded that old methods (traditional and invasive) are time consuming, tedious, labor intensive and sometimes more expensive.

SOILD
2, 337–369, 2015

4.3 Future research

Further research needs to focus on analyzing geomorphological processes (erosion and deposition) and their controlling topographic (slope, aspect, roughness) and meteorological factors (rainfall and temperature) over a number of event–scale monitoring periods. The next stages of the project will focus also on the analysis and comparison of TLS and photogrammetry data with data obtained with a new turbidimeter installed in the catchment at the beginning of 2015.

5 Conclusion

The study applied and compared the performance of the Terrestrial Laser Scanner and the photogrammetric technique in investigating the geomorphological dynamics and topographic changes on two active slopes in humid badland areas. TLS and photogrammetry (non-intrusive methods) show high precision and obtain high-resolution topographic information. We used the combination of TLS and photogrammetry to maximize their advantages while minimizing the disadvantages of each technique.

The results show that TLS and photogrammetry data sets provide new opportunities in the study of topographic change of very erosion-prone landscapes (i.e. badlands) where the use of conventional, invasive topographic technologies is limited. Photogrammetry is a powerful and low cost tool for evaluating the rate and spatial-temporal development of denudation processes at short-distance and small areas. Small problems could be solved using a camera with higher resolution. In that way, we could consider that photogrammetry would be a good opportunity in geomorphological in short distance studies.

The data recorded in the course of a year at different seasonal intervals demonstrated that north-facing slopes experienced more intense and faster geomorphological dynamics than south-facing slopes. Different seasonal processes were observed: the biggest topographic differences coincided with the winter periods and the high intensity rainfall incidents in summer.

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SOILD
2, 337–369, 2015

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E. Nadal-Romero et al.

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SOILD
2, 337–369, 2015

The application of terrestrial laser scanner and photogrammetry in geomorphology

E. Nadal-Romero et al.

Table 1. Summary of time intervals and rainfall data recorded during the monitoring period.

	Monitoring interval	Number of days	Total rainfall (mm)	Max. daily rainfall (mm)	Max. rainfall 5-min intensity ($mm\,h^{-1}$)
Period 1	23 Jul 2013–12 Nov 2013	112	334.8	77.2	148.8
Period 2	12 Nov 2013–26 Mar 2014	134	308.8	24.6	14.4
Period 3	26 Mar 2014–23 Jul 2014	119	198	30.2	33.6
Annual period	23 Jul 2013–23 Jul 2014	365	841.6	77.2	148.8

SOILD
2, 337–369, 2015

Table 2. Mean differences, standard deviation and maximum differences (Max +, deposition; Max –, erosion) of point clouds obtained for different survey periods with TLS and photogrammetry on north-facing slopes.

North-facing slope		Period 1	Period 2	Period 3	Jul 2013–Jul 2014
TLS	Mean ± SD (m)	−0.020 ± 0.032	−0.046 ± 0.050	−0.012 ± 0.027	**−0.077 ± 0.049**
	Max + (m)	0.31	0.25	0.14	**0.25**
	Max – (m)	−0.61	−0.39	−0.28	**−0.59**
Photogrammetry	Mean ± SD (m)	−0.035 ± 0.044	−0.051 ± 0.042	−0.003 ± 0.025	**−0.017 ± 0.038**
	Max + (m)	0.41	0.16	0.21	**0.34**
	Max – (m)	−0.43	−0.39	−0.25	**−0.46**

annual data in bold

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

SOILD
2, 337–369, 2015

SOILD
2, 337–369, 2015

Table 3. Mean differences, standard deviation and maximum differences (Max +, deposition; Max –, erosion) of point clouds obtained for different survey periods with TLS and photogrammetry on south-facing slopes.

South-facing slope		Period 1	Period 2	Period 3	Jul 2013–Jul 2014
TLS	Mean ± SD (m)	−0.006 ± 0.026	−0.037 ± 0.066	0.011 ± 0.027	**−0.032 ± 0.071**
	Max + (m)	0.179	0.52	0.24	**0.42**
	Max − (m)	−0.194	0.416	−0.176	**−0.45**
Photogrammetry	Mean ± SD (m)	−0.010 ± 0.025	0.001 ± 0.055	0.011 ± 0.0211	**−0.002 ± 0.056**
	Max + (m)	0.18	0.48	0.22	**0.48**
	Max − (m)	−0.22	−0.42	−0.17	**−0.42**

annual data in bold

Table 4. Advantages and disadvantages of Terrestrial Laser Scanner (TLS) and Photogrammetry methodologies for studying geomorphological processes in badland areas.

	Advantage	Disadvantage
TLS	– non-invasive – pinpoint accuracy – high accuracy potential and automation level – high data adquisition – post-processing is fast	– high economic cost – heavy material (difficulties for portability) – longer measure time – problems with little misalignments of reference points
Photogrammetry	– non-invasive – low costs – small format: low weight – reduce data collection time by $\sim 80\,\%$ – high number of photos to minimize missing areas	– centimetric accuracy – worse adaptation to survey large areas – post-processing is still labor-intensive – problems with illumination changes

SOILD
2, 337–369, 2015

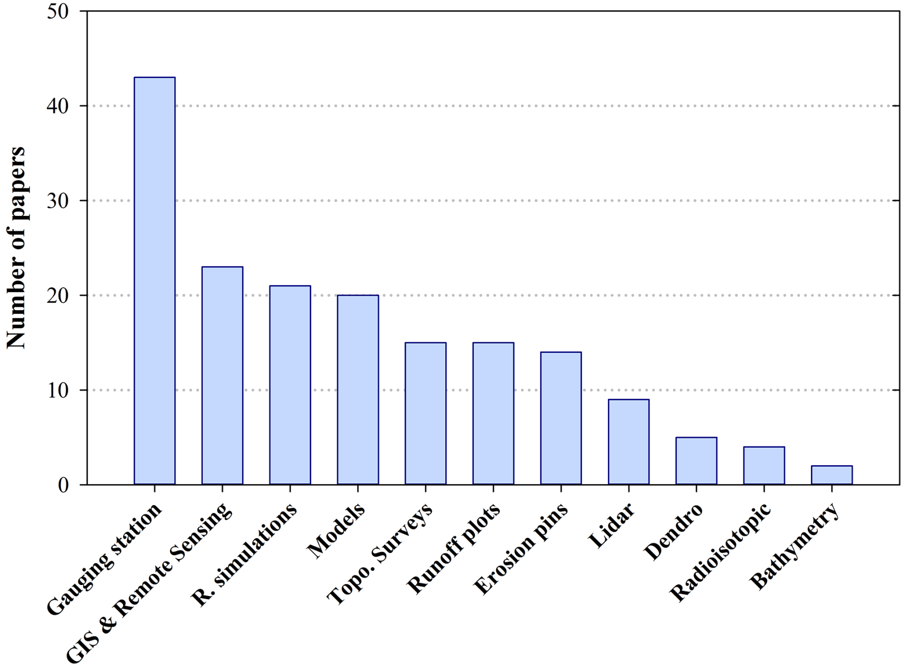

Figure 1. Distribution of soil erosion studies in badland areas according to different methodologies.

SOILD
2, 337–369, 2015

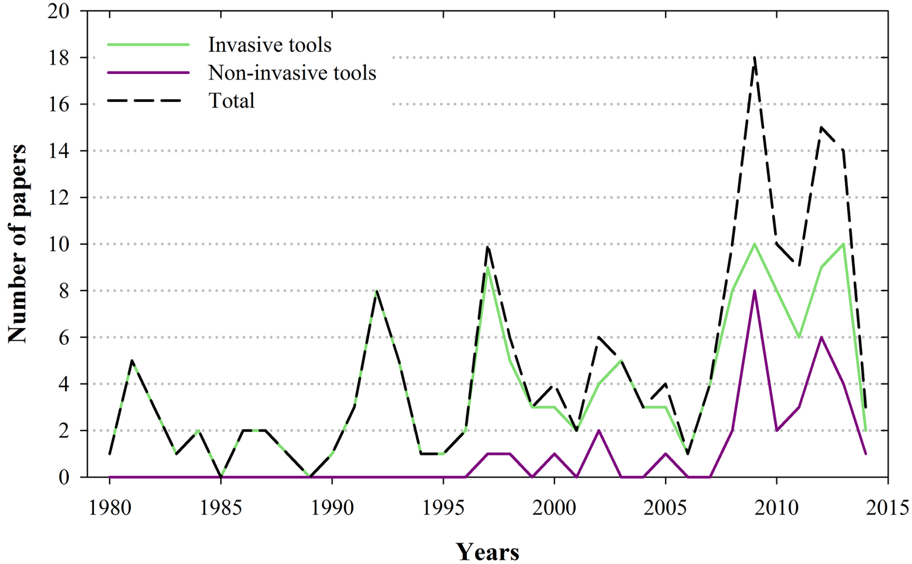

Figure 2. Evolution of different methodologies and difference between invasive and non-invasive methods.

SOILD
2, 337–369, 2015

The application of terrestrial laser scanner and photogrammetry in geomorphology

E. Nadal-Romero et al.

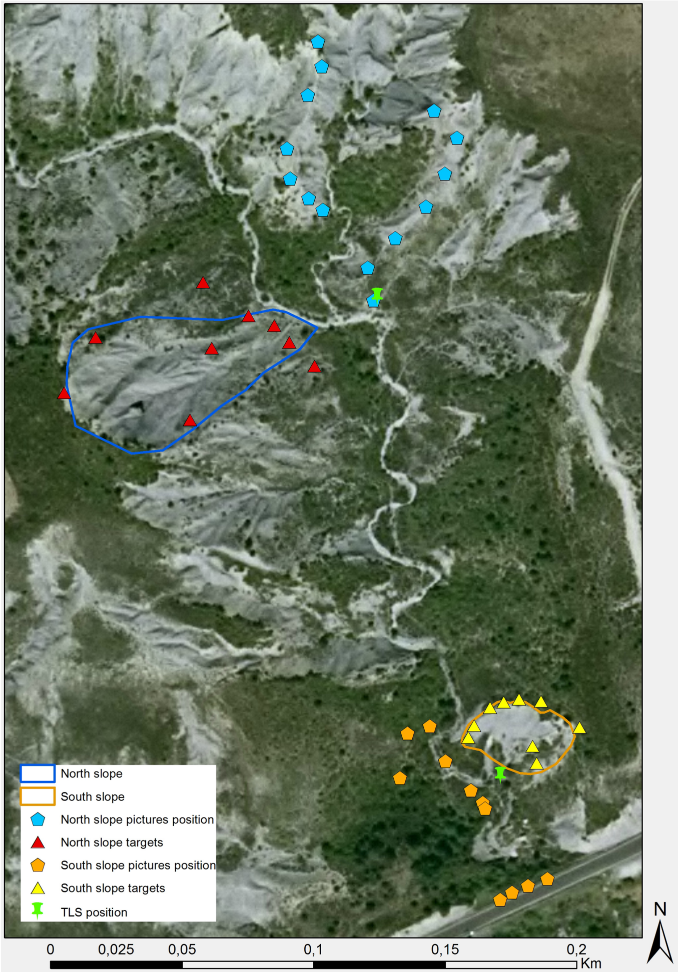

Figure 3. Field site location, Araguás catchment. Detailed image of both selected slopes.

SOILD
2, 337–369, 2015

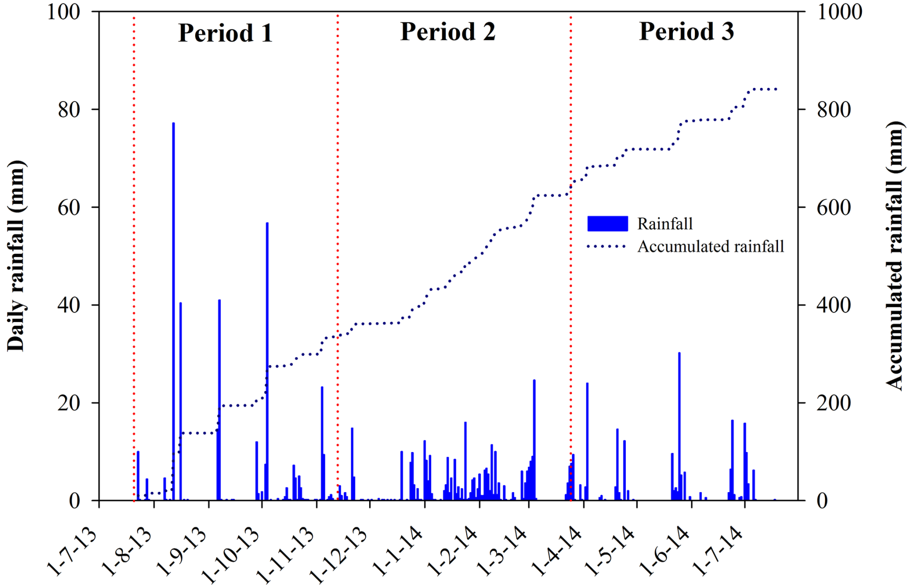

Figure 4. Daily rainfall and accumulated rainfall during the survey period (July 2013–July 2014).

SOILD
2, 337–369, 2015

The application of terrestrial laser scanner and photogrammetry in geomorphology

E. Nadal-Romero et al.

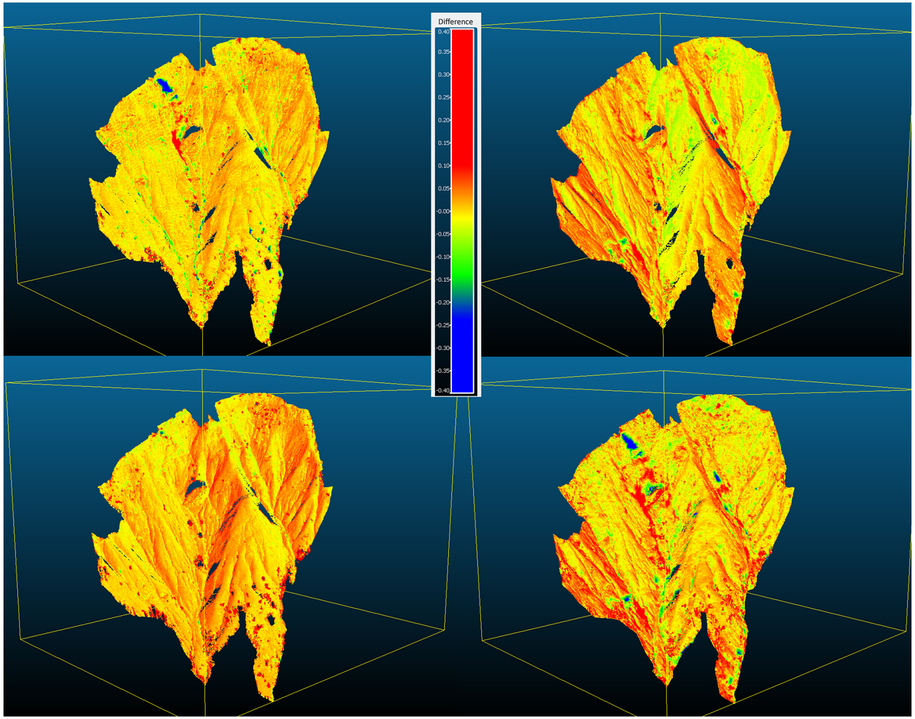

Figure 5. Topographic changes observed at the monitoring intervals and at annual scale obtained with TLS on north-facing slopes.

SOILD
2, 337–369, 2015

The application of terrestrial laser scanner and photogrammetry in geomorphology

E. Nadal-Romero et al.

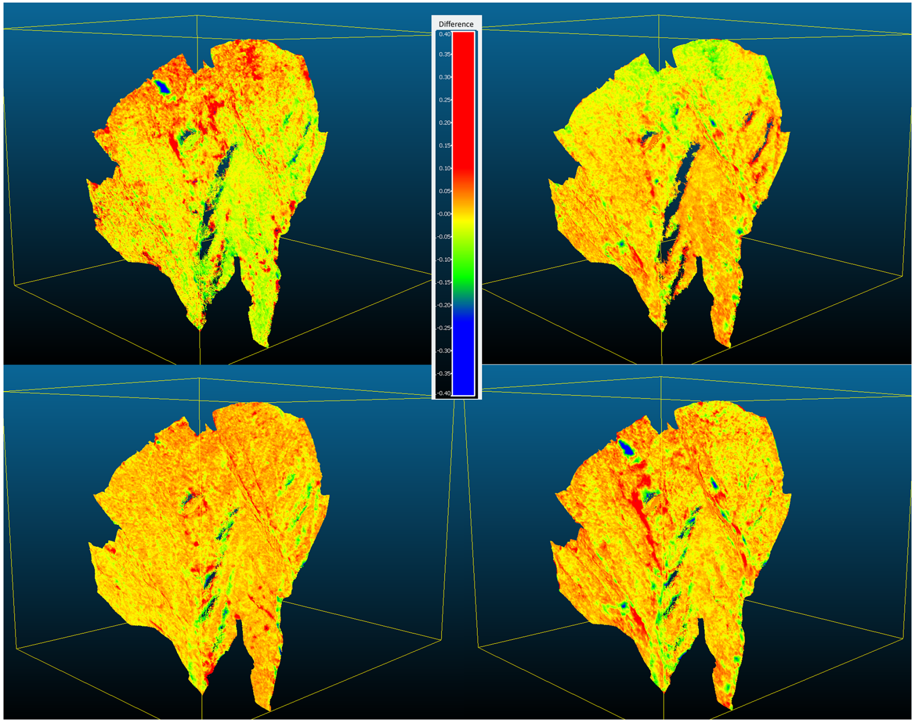

Figure 6. Topographic changes observed at the monitoring intervals and at annual scale obtained with photogrammetry on north-facing slopes.

SOILD
2, 337–369, 2015

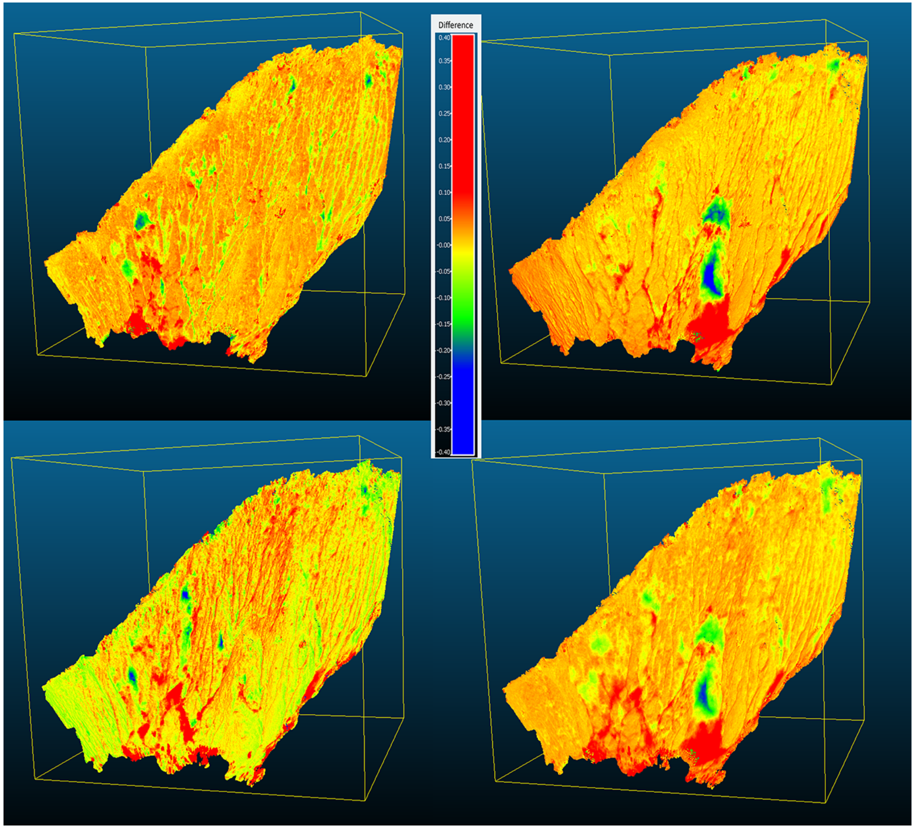

Figure 7. Topographic changes observed at the monitoring intervals and at annual scale obtained with TLS on south-facing slopes

SOILD
2, 337–369, 2015

The application of terrestrial laser scanner and photogrammetry in geomorphology

E. Nadal-Romero et al.

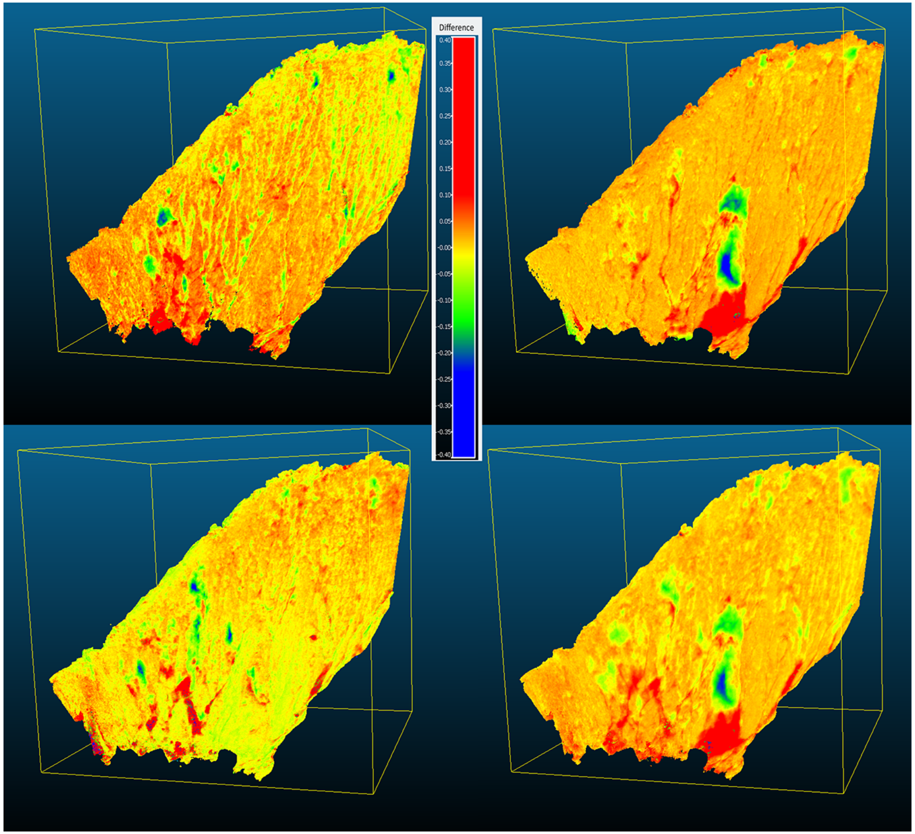

Figure 8. Topographic changes observed at the monitoring intervals and at annual scale obtained with photogrammetry on south-facing slopes.

SOILD
2, 337–369, 2015

The application of terrestrial laser scanner and photogrammetry in geomorphology

E. Nadal-Romero et al.