The application of terrestrial laser scanner and SfM photogrammetry in measuring erosion and deposition processes in two opposite slopes in a humid badland area (Central Spanish Pyrenees)

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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~~ remote-sensing 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 3D 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~~Structure-from-Motion photogrammetry (SfM) techniques (Camera FUJIFILM, Finepix x100 and Software PhotoScan by AgiSoft), to evaluate erosion and deposition processes in two opposite slopes in a humid badland area in the Central Spanish Pyrenees. Results showed that TLS data sets and SfM 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 accuracy models, SfM photogrammetry was still a faster methodology in the field and precise at short distances. Both techniques present advantages and

disadvantages, and do not require direct contact with the soil and thus prevent the usual surface disturbance of traditional and invasive methods.

Keywords: badlands, ~~geomatic~~ remote sensing techniques, Terrestrial Laser Scanner, Structure-from-Motion p~~P~~hotogrammetry, geomorphological processes

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 (e.g. ~~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., ~~accepted~~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 mm yr^{-1}) due to the low frequency of rainfall. Lam (1977) obtained 17.36 mm yr^{-1} in the Hong Kong badlands. Higher 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, with erosion rates of over 30 mm 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 mm 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 (Figure 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.e.g. Nadal-Romero et al., 2008), seen by different authors as the best approach for measuring sediment transport (Walling, 19919). Remote sensing technologies (i.eee.g. Martínez-Casasnovas and Ramos, 2009), rainfall simulations (i.e.e.g. Martínez-Murillo et al., 2013) and erosion models (e.g.i.e. Mathys et al., 2003) were recorded in about 20 studies. Topographic surveys (e.g.i.e. Sirvent et al., 1997), runoff plots (e.gi.e. Gallart et al., 2013) and erosion pins (e.g.i.e. Vergari et al., 2013) were used a bit less often (approximately 15 studies each). On the other hand, dendrogeomorphological techniques (i.e.g. Ballesteros-Canovas et al., 2013), TLS data acquisition (i.e.g. Sáez et al., 2011; Vericat et al., 2014), radioisotopic measurements (e.gi.e. Sadiki et al., 2007) and bathymetric surveys (e.g.i.e. Grauso et al., 2008) have been sporadically applied in badland studies (Figure 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.e.g. remote sensing, TLS, SfM photogrammetry, aerial pictures). The annual evolution of the different methods is represented in Figure 2 (data from 1980, n = 164). Figure 2 indicates that (i) during the last 30 years, studies on soil erosion in badlands have increased (see also Gallart et al., 2013); (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 remote-sensing geomatic techniques: Terrestrial Laser Scanner and SfM pPhotogrammetry

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 and Crosby~~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~~, 3D 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~~ data already ~~conducted~~ obtained with TLS in badland areas (e.g.~~i.e~~. Lucía et al., 2011; López-Saez et al., 2011; Vericat et al., 2014) encourage its application in other study sites.

The digital photogrammetry has generated an improvement in topographic methods, due to a better accessibility to a wider variety of users, its low cost, and also ~~because~~due to the increased automation of the photogrammetric routines (Fonstad et al., 2013). Recently, Structure for Motion (SfM) techniques, developed by the computer vision community, were adapted to generate high resolution and quality DTMs. Classical (stereoscopic) photogrammetry is based on 3D reconstruction models by superimposing two images of the same area from different perspectives. SfM is based on the reconstruction of the 3-dimensional geometry from the matching of multiples images generated from different points of view. Pictures can be taken at different scales, and the position, orientation and distortion can be no-known. SfM differs from stereoscopic photogrammetry, because it uses image matching algorithms to recover randomly acquired images and to detect points ~~and~~in common elements.

The biggest difference between both methods is the need to use GCP for the 3D model resolution. In classical photogrammetry, the collinearity is solved after the introduction of the GCPs; in SfM, collinearity is solved from the common elements of the images. So, if there are errors in the measurements of the GCPs, they are propagated to the final result (Fonstad et al., 2013). Through SfM, the final quality of the point cloud is based on a high number of common points (> 1000) that have been automatically generated.

~~Structure from Motion photogrammetry is a remote sensing technology that obtains 3D 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 3D 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.g. the continuous development of processing algorithms) (Baltsavias, 1999). Several scientific fields, like geoarcheology and architecture, have already accepted photogrammetry as a useful tool (e.g. Cardenal Escarcena et al., 2011; Verhoeven et al., 2012; Martínez et al., 2015; Nadel et al., 2015~~Farenzena et al., 2008~~), and its advantages for geomorphological research have been long recognized (Castillo et al., 2012). ~~However, to~~In the last five years ~~date few~~different studies have taken advantage of the possibilities offered by geomorphology to generate terrain models using SfM photogrammetry (Gómez-Gutierrez et al., 2014, Kaiser et al., 2014, Michetti et al., 2015, Westoby et al., 2012).~~, 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~~Structure-from-Motion photogrammetry methods 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. Annual topographic changes will be evaluated and geomorphological processes will be spatially analyzed.

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 1,105 m, and it has a substantially large badland area, spreading over 25% of the catchment (Figure 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 1,000 mm annually, and the average temperature is 10 ºC.

Badlands occur on the Eocene marl of the Inner Pyrenean Depression (marls with interbedded decimeter-scale sandy layers). Nadal-Romero and Regüés (2010) demonstrated that the main causes of regolith development and weathering processes are the alternating freeze-thaw and wetting-drying cycles (being maximum in winter and summer).

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 (Figure 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 the surveyed areas and on the working distances for data acquisition with both methods (TLS and SfM)~~rom the TLS and SfM measurements were taken~~. The analyzed extension of the north and south slopes are ~~respectively~~ 3,200 m^2 and 560 m^2, respectively. 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 SfM 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 checking the technical characteristics of the TLS and the procedure used for scanning and for the post-processing information~~ can be checked~~).

Indirect registration (target-based registration) was used to merge the information from the different scan station~~s~~ 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. TLS automatically obtains 3D point clouds, but with a main limitation, we have only work from a single position due to time restrictions.

Once the formal steps were completed (e.g. 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, on the north-facing slope 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 0.027º. On the south-facing slope the resolution was~~on the north-facing slope~~, ~~and~~ 1,890 points/m^2 (0.023 m) and the angular scanning resolution was 0.054º~~ 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. Structure-from-Motion p~~P~~hotogrammetry

~~Close range~~Structure-from-Motion photogrammetry allows the creation of 3D models from multiple overlapping images taken at distinct triangulation angles. In this case, we used the FUJIFILM Finepix x 100 camera, with a focal length of 23 mm (equivalent to a fixed lens of 35 mm), with a resolution of 12 MP (4288 x 2848 pixels), which provided better 3D reconstruction than classical photogrammetry (James and Robson, 2012). In each survey, ~~in north-facing slopes~~ 17 pictures of the north-facing slope were taken at an approximate distance of 100-150 m; ~~in south facing slopes~~ 15 pictures of the south-facing slope were taken, at an approximate distance 40–60 m.~~ with a resolution of 12 MP (4288 x 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 3D point cloud of the study area. Differences in lighting can cause problems during data processing, and Agisoft software is a helpful tool to overcome this risk, as it estimates the ~~error~~ potential error and deletes questionable ~~photos~~pictures. 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. High resolution of original images would offer better texture and higher resolution to find keypoints in the photoset. Similarly, decreasing the distance between the camera and the feature of interest is related to increasing the spatial resolution of the photograph and would enhance the spatial density and resolution of the final point cloud (Westoby et al., 2012).

2.4.Data processing

In order to georeference both data sets (SfM 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~~ common coordinate system (which is named project 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; Prokop, 2008). Similarly, the point cloud obtained from SfM 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. Th~~is~~e ~~coordinates~~ transformation of the coordinates into a common coordinate system was ~~done~~carried out for the comparison of the information obtained with the two methods.

In both cases, the post-processing (comparing point clouds to determine the topographic differences between dates) was accomplished using CloudCompare software (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.

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

SfM photogrammetry. Monitoring intervals and rainfall data are presented in Table 1 and Figure 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 (Section 3.1), and then the results obtained on the south-facing slope are examined (Section 3.2). In both sections, spatial and temporal variability of topographic changes are described. Finally (Section 3.3), 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 Figures 5 and 6 (TLS and SfM 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 (Figures 5~~B~~ and 6~~B~~): -0.046 m and -0.051 m with TLS and SfM 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 m and -0.43 m with TLS and SfM 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 (Period 1, Figures 5~~A~~ and 6~~A~~). 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 (Figures 7~~B~~ and 8~~B~~, and Table 3): -0.037 m and -0.001 m (note the high standard deviation compared to the average difference in Table 1) with TLS and SfM 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 footslopes were recorded (see Figures 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 m and -0.032 m respectively, recorded using TLS point clouds (see Table 2 and 3). SfM photogrammetry yielded more moderate differences: -0.017 m 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 m and -0.453 m with TLS, and 0.48 m and -0.42 m with SfM photogrammetry); however, important differences were observed between the negative and positive absolute maximum values on north-facing slopes (0.250 m and -0.590 m with TLS, and 0.34 m and -0.46 m with SfM 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.

Figures 9 and 10 showed a direct comparison of DEMs between techniques considering LiDAR (TLS) as the reference. Differences have been calculated for the first and last acquisition dates (23/07/13 and 23/07/14). Big differences occurred in small areas, where small vegetation patches were present (almost all vegetation was eliminated from the point clouds, but some influence can be appreciated in the exterior limits of the selected slopes). Small differences were observed in "deep" concavities (yellow colours in the comparison figures), because in these areas the SfM was not able to accurately reproduce a precise topography. Other errors were usually located in ridges, and the areas behind them, from the TLS perspective, showing one of the main TLS limitations: with only one point of view, some areas are hidden. Average Ddifferences (Table 4) were higher in north-facing slopes (also the highest standard deviation were recorded in this slope) in both surveys because the increase on distance of data acquisition and the presence of shadows.(also the highest standard deviation were recorded).

4. Discussion

4.1. Geomorphological dynamics

Both techniques can produce high-resolution topographic models with centimeter 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 Table 2 and 3). The detailed analysis of the point clouds showed the geomorphological dynamics of these severely eroded areas. The results indicated that the geomorphological dynamics on north-facing slopes are were 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 (e.g.i.e. Calvo-Cases and Harvey, 1996; Descroix and Olivry, 2002; Pulice et al., 2013).

The values presented in Table 2 and 3 also showed 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 did 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 (Figures 9 and 10), showing the importance of climate and topographic factors in badlands development. 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 SfM 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 SfM photogrammetry point clouds with annual values of 17 mm yr^{-1} and 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 38 mm for north-facing and 56 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~~ 5 presents the advantages and disadvantages of both methods.

Both methods allow fast and automatic image processing. Nevertheless, SfM 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 SfM photogrammetry is relatively cheap and easy to use. Castillo et al. (2012) calculated the cost of TLS at 10 times the cost of 3D photogrammetry.

The comparison between both methods (Figures 9 and 10 and Table 4) showed that results were similar in both cases, although significant differences can be observed in small points, especially in the presence of shadows and vegetation.

Our study demonstrated that SfM delivers good accuracy and is really useful for field application in geomorphological and soil erosion studies, for observing changes in the centimeter scale (depending on the working distance). In our case, the quality of the images should be improved in order to obtain better accuracy, paying especial attention to illumination changes during the acquisition of the images, which have been observed as an important error-causing interference. The number of pictures could be a problem to be solved together with the computer memory (a large memory is needed to process a large number of high quality pictures). 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). Micheletti et al. (2015) carried out an analyses in similar areas and at the same scale, and they obtained good and valid models with 13 pictures.

TLS shows better performance in differentiating small displacement of terrain (resolution of surface models) (e.g. rills development). However, due to time restrictions we have worked with one single scan position causing the shadowing effect of terrain (the so-called sight shadowing), which do not enable to retrieve data from different areas of the site originating missing information. This missing information due to terrain curvature observed in some areas with the TLS (north-slope), is avoided with SfM photogrammetry because different points of view of the study area were easily acquired (see differences in Figures 9 and 10). Nevertheless, in the presented analyses, and annual erosion rates ~~and also in the images that show point cloud differences,~~ these shadow areas have been removed in SfM photogrammetry to consider exactly the same area with both methods.

SfM p~~P~~hotogrammetry 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 of surface models. Indeed, the high number of points obtained for low distances to the TLS in comparison to these obtained for large distances, is one limitation for these devices. This has encouraged minimizing scan distances when possible (Heritage and Hetherington, 2007). In the contrary, SfM technique, does not show this high dependence on distance due to the multiple points of view of the surveyed area (Smith and Vericat, 2015) being this one of the main advantages when we compare to TLS.

TLS and SfM 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 SfM photogrammetry is the method that produces the best approximation to the TLS~~, with differences less than 3 cm~~. They also suggested that traditional methods (2D 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.

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. During the new surveys a higher number of pictures will be taken, and TLS surveys will be taken from two single points. With this information we will check some of the observed limitations of both methodologies. The next stages of the project will focus also on the analysis and comparison of TLS and SfM 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 SfM photogrammetry (non-intrusive methods) show high precision and obtain high-resolution topographic information. We used the combination of TLS and SfM photogrammetry to maximize their advantages while minimizing the disadvantages of each technique.

The results show that TLS and SfM photogrammetry data sets provide ~~new~~ opportunities in the study of topographic change of very erosion-prone landscapes (e.g.~~i.e.~~ badlands) where the use of conventional, invasive topographic technologies is limited. SfM p~~P~~hotogrammetry 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~~ should be solved using a camera with higher resolution, or a higher number of pictures. In that way, we could consider that SfM photogrammetry would be a good opportunity in geomorphological ~~in~~ ~~short distance~~ studies when carried out taking ~~the~~ pictures at short distances.

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.

Acknowledgment

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	Monitoring interval	Number of days	Total rainfall (mm)	Max. daily rainfall (mm)	Max. rainfall 5-min intensity (mm h^{-1})
Period 1	23 July 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 July 2014	119	198	30.2	33.6
Annual period	23 July 2013-23 July 2014	365	841.6	77.2	148.8

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

North-facing slope		Period 1	Period 2	Period 3	July 2013-July 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**

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

South-facing slope		Period 1	Period 2	Period 3	July 2013-July 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**

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

	24/07/2013	24/07/2014
North-facing slopes (TLS-SfM) [m]	**-0.013 ± 0.0308**	**-0.0201± 0.0326**
South- facing slope (TLS-SfM) [m]	**-0.002 ± 0.0202**	**-0.006 ± 0.0141**

Table 4. Mean differences and standard deviation of point clouds obtained with both methods calculated for the first and last acquisition dates (23/07/13 and 23/07/14).

	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 • sight shadowing
Photogrammetry	• non-invasive • low costs • small format: low weight • reduce data collection time by ~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

Table 45. Advantages and disadvantages of Terrestrial Laser Scanner (TLS) and Photogrammetry methodologies for studying geomorphological processes in badland areas.

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

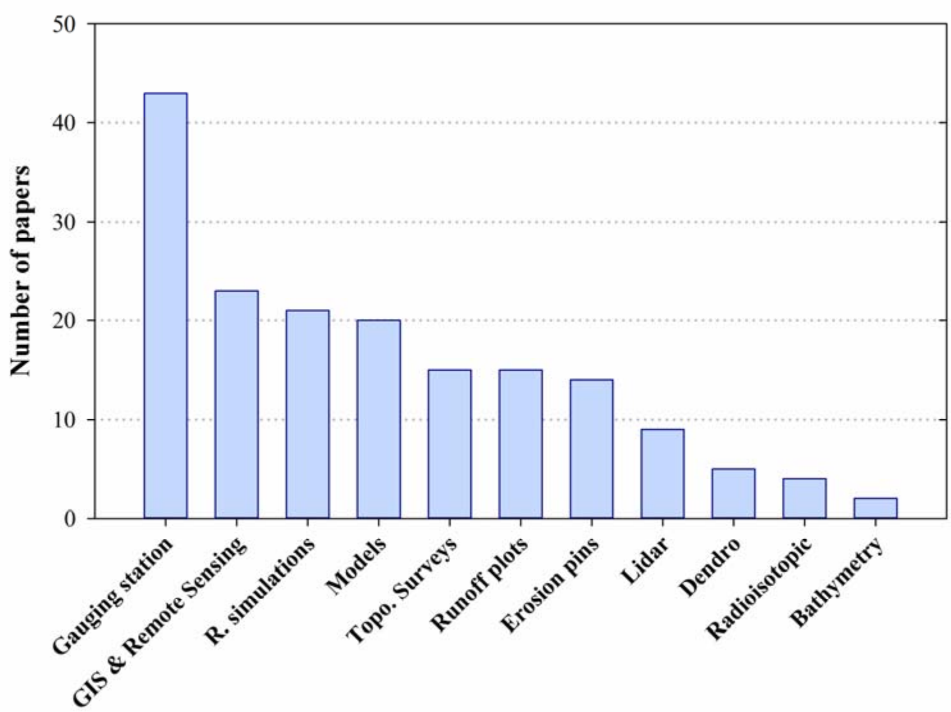


Figure 2. Evolution of different methodologies and difference between invasive and non-invasive methods

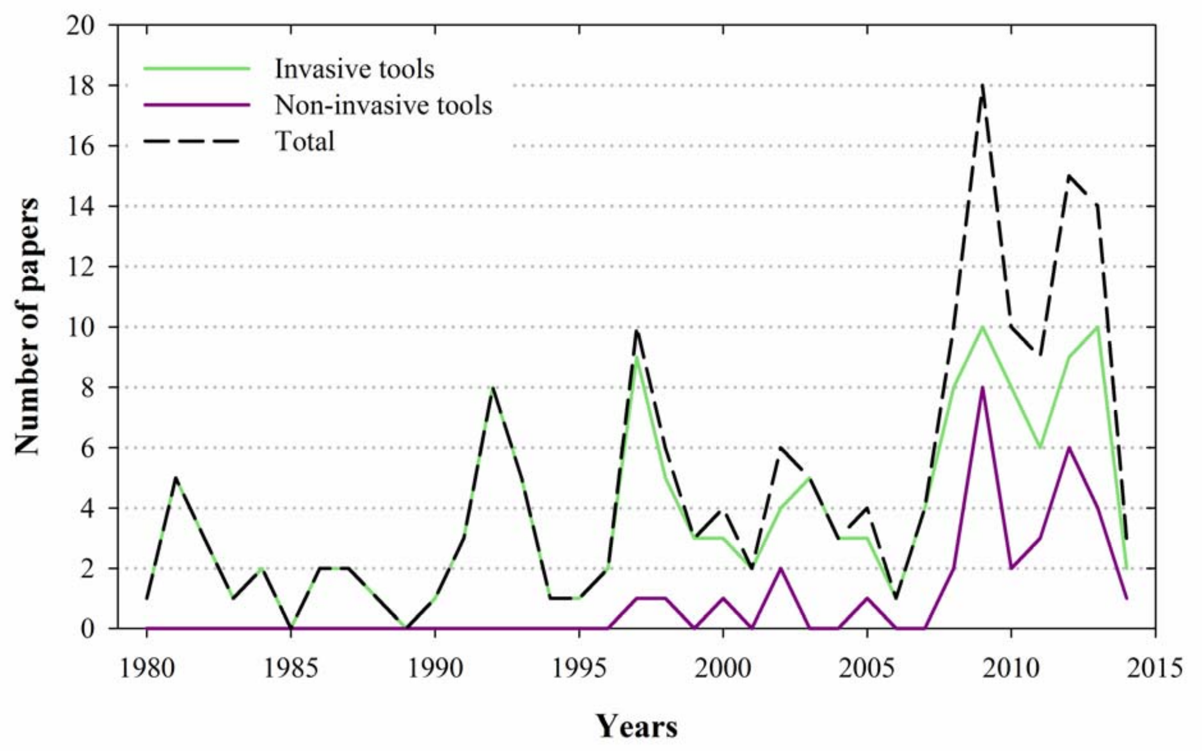


Figure 3. Field site location, Araguás catchment. Detailed image of both selected slopes

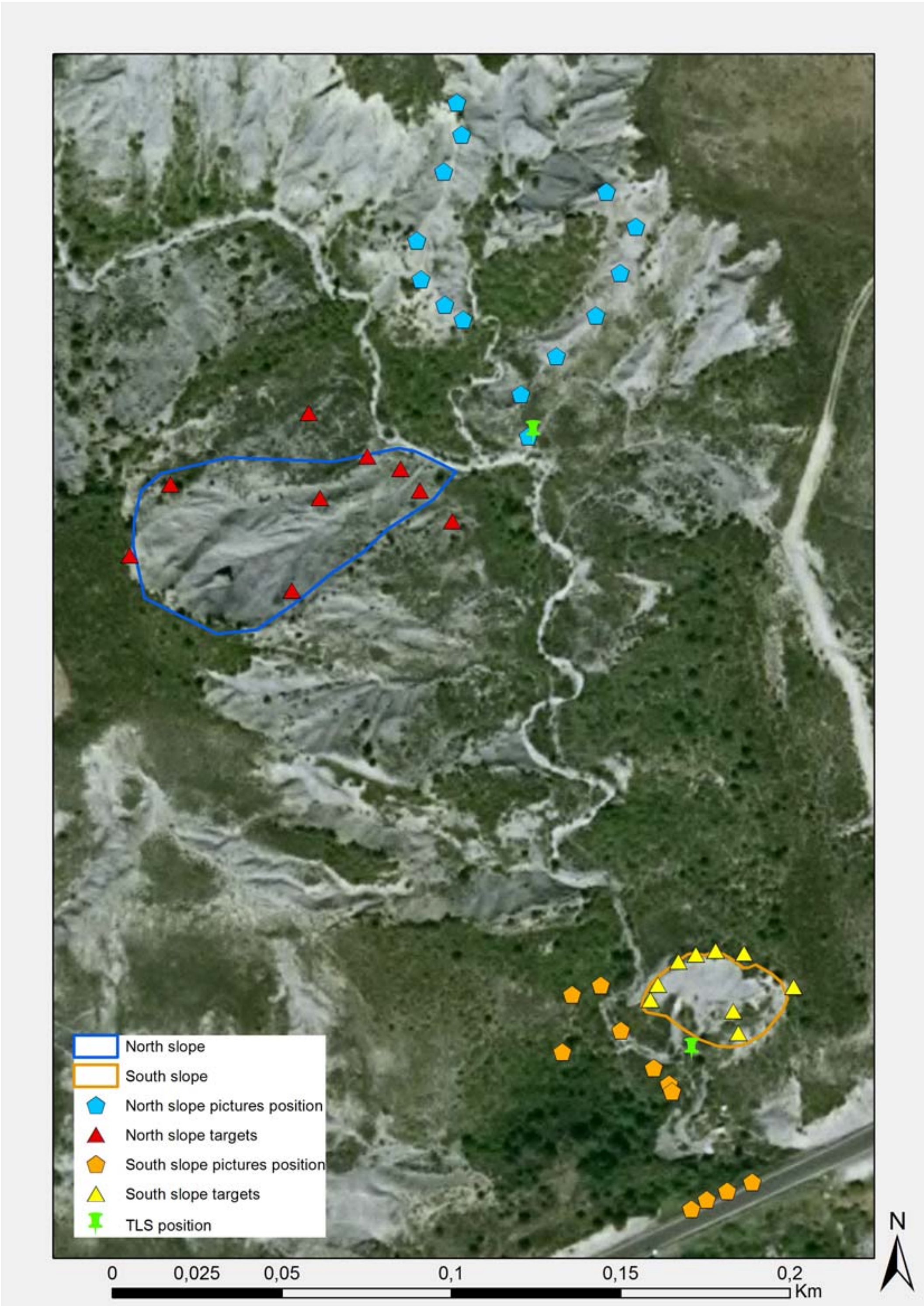


Figure 4. Daily rainfall and accumulated rainfall during the survey period (July 2013–July 2014).

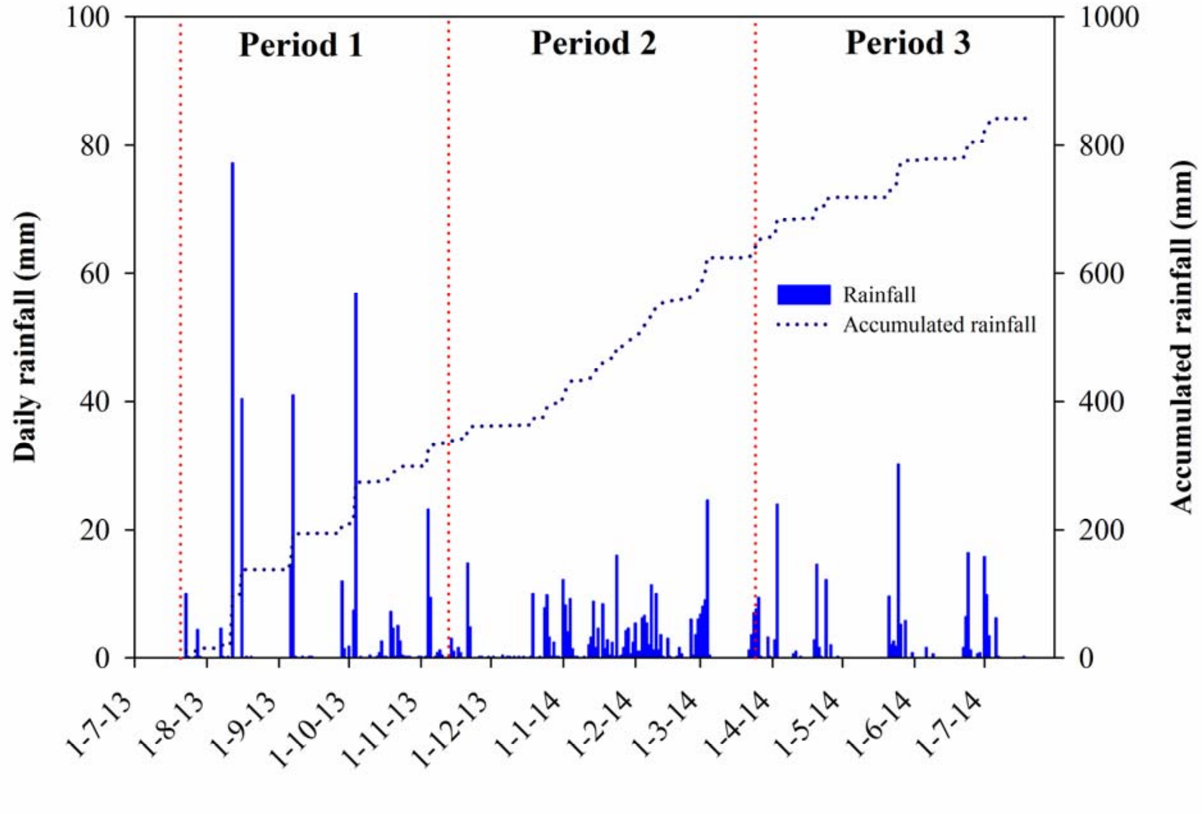


Figure 5. Topographic changes observed at the monitoring intervals and at annual scale obtained with TLS on north-facing slopes (cloud compare software).

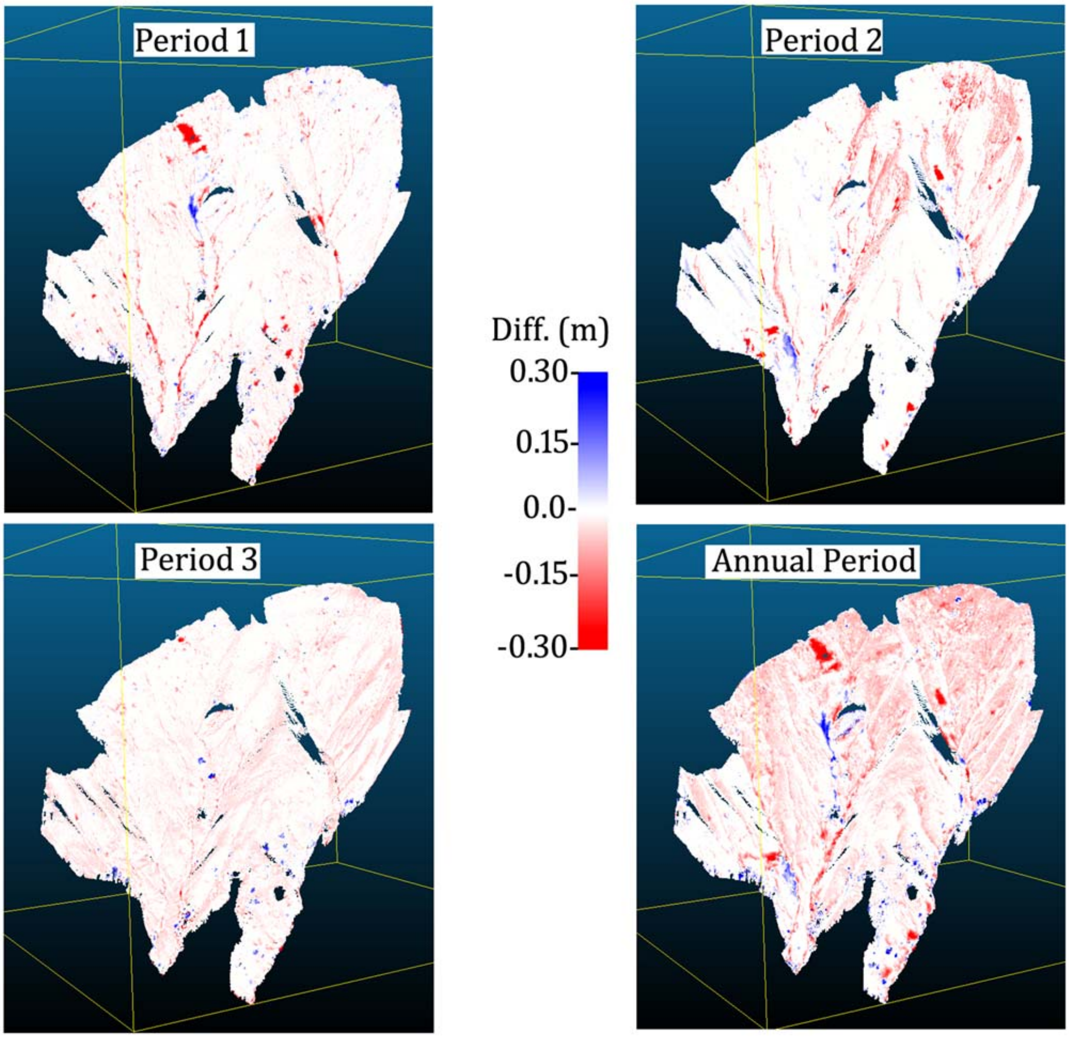


Figure 6. Topographic changes observed at the monitoring intervals and at annual scale obtained with photogrammetry on north-facing slopes (cloud compare software).

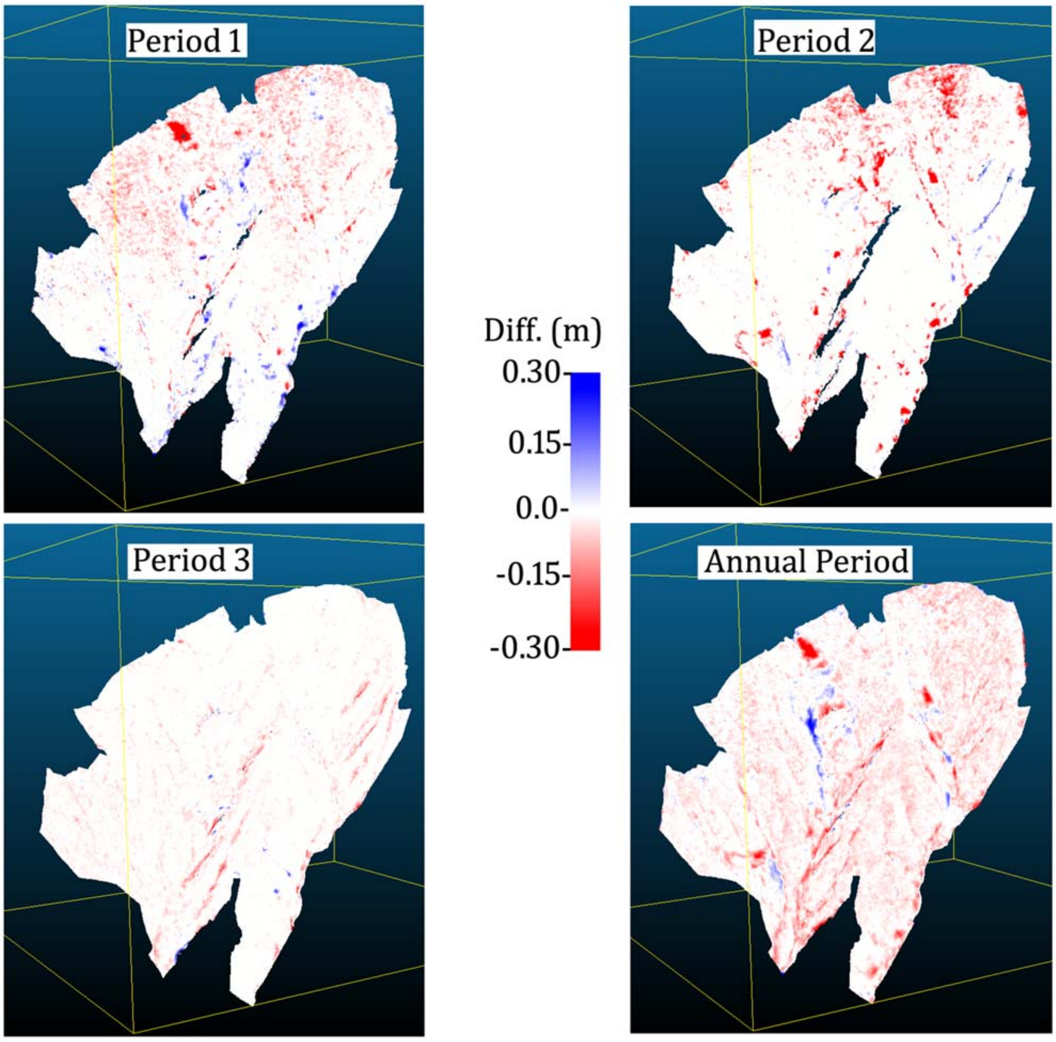


Figure 7. Topographic changes observed at the monitoring intervals and at annual scale obtained with TLS on south-facing slopes (cloud compare software).

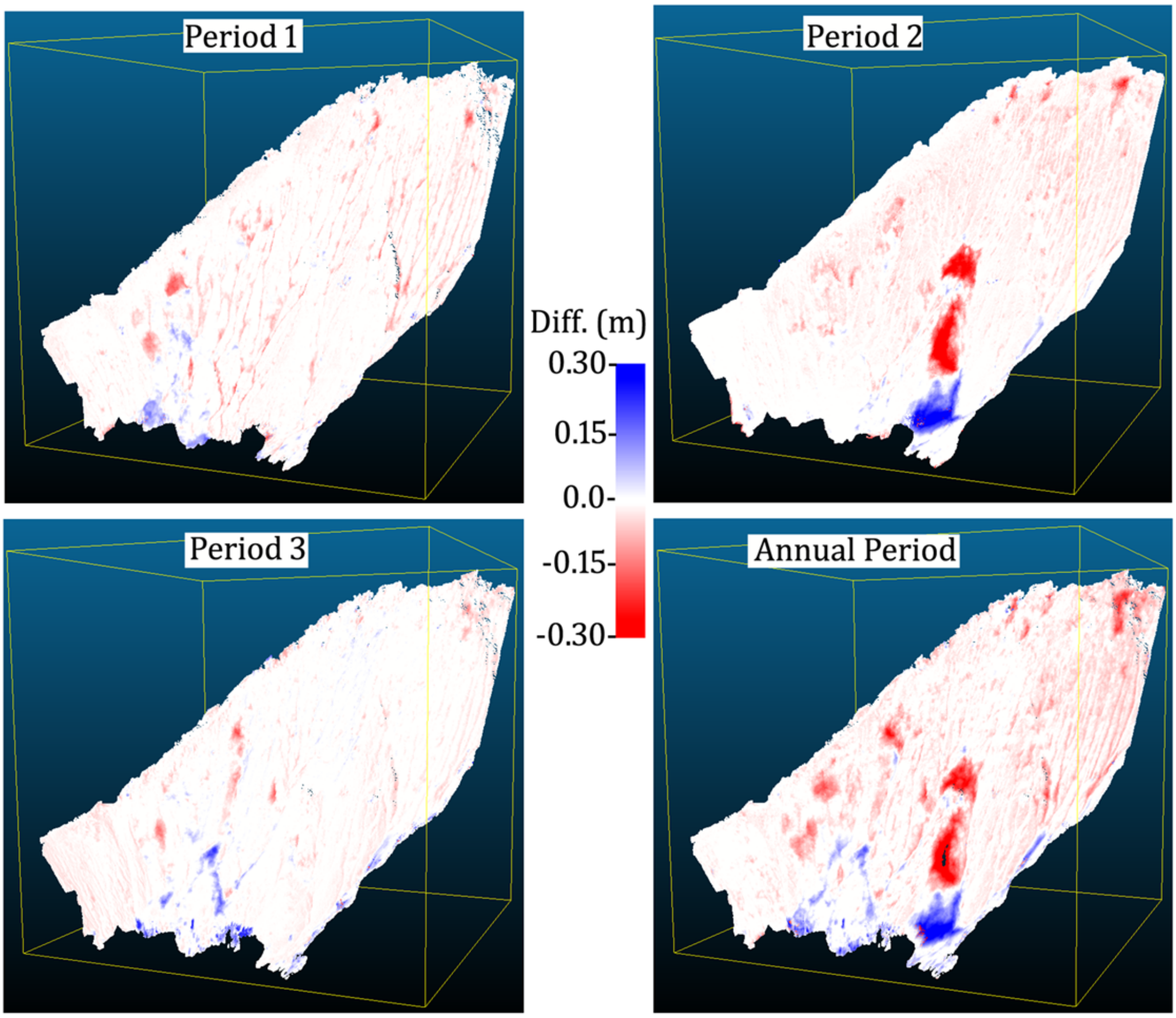


Figure 8. Topographic changes observed at the monitoring intervals and at annual scale obtained with SfM on south-facing slopes (cloud compare software).

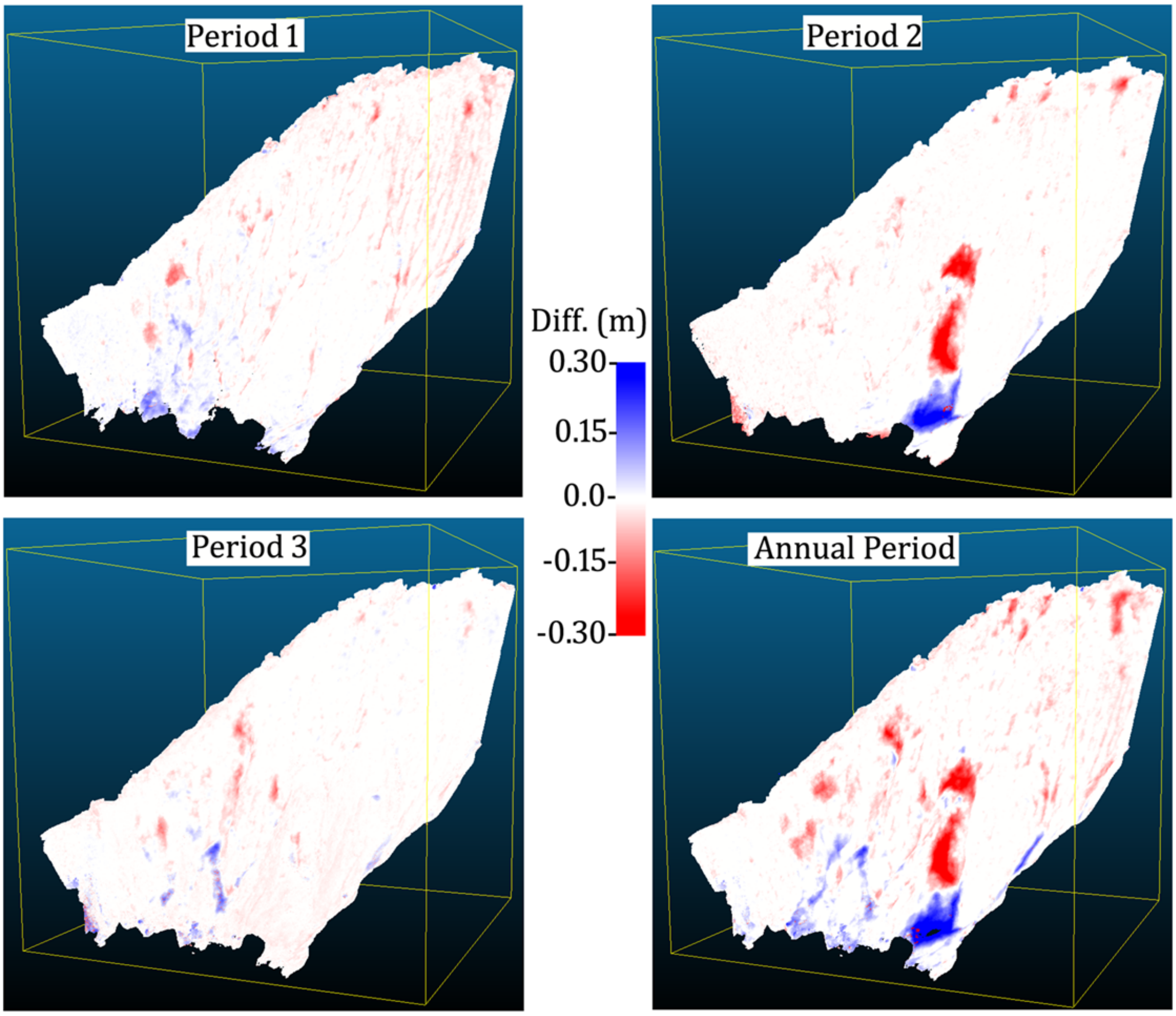


Figure 9. Comparison of DEMs between techniques, considering TLS as the reference, on north-facing slopes. Differences have been calculated for the first and last acquisition dates (23/07/13 and 23/07/14) (cloud compare software). A RGB colored points images is added in right panel as an overview of the north-facing slopes

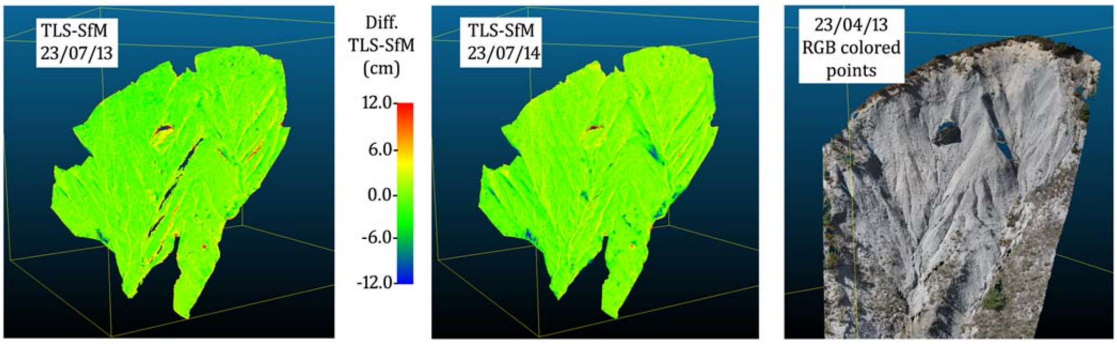
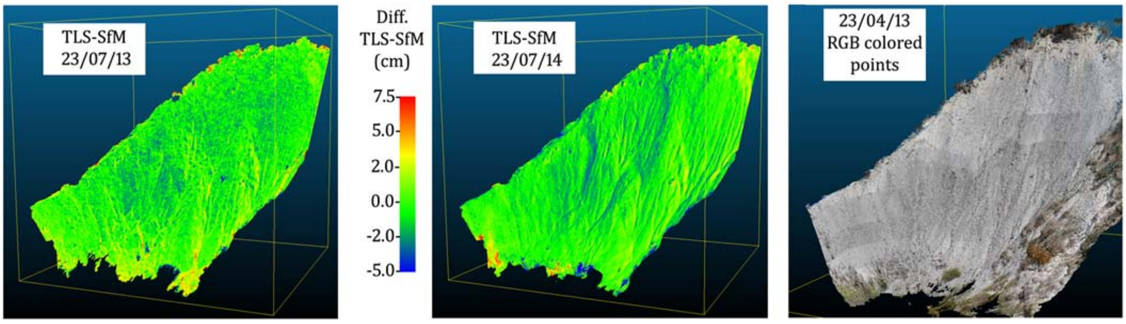


Figure 10. Comparison of DEMs between techniques, considering TLS as the reference, on south-facing slopes. Differences have been calculated for the first and last acquisition dates (23/07/13 and 23/07/14) (cloud compare software). A RGB colored points images is added in right panel as an overview of the south-facing slopes



Interactive comment on "The application of terrestrial laser scanner and SfM photogrammetry in measuring erosion and deposition processes two opposite slopes in a humid badlands in the Central Spanish Pyrenees" by E. Nadal-Romero et al.

Dear editor, dear reviewers,

We are pleased to submit a revised version of the manuscript. First of all we want to thank for your effort in improving the work. Recommendations about the methodology, and about the form to transmit the main ideas of the paper have resulted extremely useful. We have followed by far the majority of them, and we think that they helped to prepare a better manuscript, easier to be read and more robust from a methodological point of view. Below, we provide a point-by-point answer to all the comments raised from the review, and the changes that we have introduced in this revised version. Despite it is required a separate answer to both reviews, we provide the same document to both reviewers to facilitate them a fast assessment of all changes introduced in the manuscript.

Looking forward to hear your kind reply,

Estela Nadal-Romero and co-authors.

Anonymous Referee 1

General Comments

1. Photoreconstruction survey and its error assessment

Concerning this comment, these new paragraphs have been included in the introduction section (1.3. New remote-sensing techniques: Terrestrial Laser Scanner and SfM photogrametry):

"The digital photogrammetry has generated an improvement in topographic methods, due to a better accessibility to a wider variety of users, its low cost, and also because the increased automation of the photogrammetric routines (Fonstad et al., 2013). Recently, Structure for Motion (SfM) techniques, developed by the computer vision community, were adapted to generate high resolution and quality DTM. Classical (Stereoscopic) photogrammetry is based on 3D reconstruction models by superimposing two images of the same area from different perspectives. SfM is based on the reconstruction of the 3-dimensional geometry from the matching of multiples images generated from different points of view. Pictures can be taken at different scales, and the position, orientation and distortion can be no-known. SfM differs from stereoscopic photogrammetry, because it uses image matching algorithms to recover randomly acquired images and to detect points in common elements.

The biggest difference between both methods is the need to use GCP for the 3D model resolution. In classical photogrammetry, the collinearity is solved after the introduction of the GCPs; in SfM, collinearity is solved from the common elements of the images. So, if there are errors in the measurement s of the GCPs, they are propagated to the final result (Fonstad et al., 2013). Through SfM, the final quality of the point cloud is based on a high number of common points (> 1000) that have been automatically generated."

2. Comparison between both techniques taking the LiDAR survey as the reference.

It has been the main concern in our manuscript. We are conscious that it was a weak point in our manuscript. So we have carried out a new analysis including the comparison of the methods. Two new comparison figures have been included together with a point cloud with RGB colours (real colours from the camera coupled in the TLS) of the slopes in the different survey days (Figures 9 and 10 and Table 4). Thereby, in section 3.3. Joint analysis these lines have been added:

"Figures 9 and 10 showed a direct comparison of DEMs between techniques considering LiDAR (TLS) as the reference. Differences have been calculated for the first and last acquisition dates (23/07/13 and 23/07/14). Big differences occurred in small areas, where small vegetation patches were present (almost all vegetation was eliminated from the point clouds, but some influence can be appreciated in the exterior limits of the selected slopes). Small differences were observed in "deep" concavities (yellow colours in the comparison figures), because in these areas the SfM was not able to accurately reproduce a precise topography. Other errors were usually located in ridges, and the areas behind them, from the TLS perspective, showing one of the main TLS limitations: with only one point of view, some areas are hidden. Differences were bigger in north-facing slopes in both surveys (also the highest standard deviation were recorded)."

Specific comments:

3. Tittle. We have changed the tittle. The application of terrestrial laser scanner and SfM photogrammetry in measuring erosion and deposition processes in two opposite slopes in a humid badland areas (in the Central Spanish Pyrenees)

4. Abstract. We have changed in the abstract and in the manuscript "geomatic" and we have used "remote sensing techniques".

1.2. Review, line 26: Gauging stations. We consider that gauging stations are invasive in most of the case, due to the construction of the gauging station and due to the building of the different canals to measure the water level. In the case of the deployment of ground control points in our study case, these points are outside (in the limit) of the study area, so we are not disturbing the different slopes.

1.3. Page 341, Line 27: term "Photogrammetry". The different reviewers coincided in that the term photogrammetry is not correct, so we have deleted it and we have used Structure for Motion photogrammetry (SfM).

1.3. page 342, line 10:We have made a wide revision in SfM photogrammetry and LiDAR studies. Different references have been included in the text (see the end of the comments and manuscript (last lines in 1.3 section))

1.3. page 342, line 11:Previous photogrammetric studies in badland areas have been included in these lines.

2.2. page 344, line 13:*TLS does not enable a consistent distribution of the acquired information.* Yes. It is a limitation for all remote sensing techniques. But we want to remark that for the TLS it is an important issue. Indeed, the high number of points obtained for low distances to the TLS in comparison to these obtained for large distances, is one limitation for these devices. This has encouraged minimizing scan distances when possible (Heritage and Hetherington, 2007). In the contrary, SfM technique, does not show this high dependence on distance due to the multiple points of view of the surveyed area (Smith and Vericat, 2015) being this one of the main advantages when we compare to TLS.

2.3. page 344, line 22: We have changed these sentences to avoid a misunderstanding:

"Structure-from-Motion photogrammetry allows the creation of 3D models from multiple overlapping images taken at distinct triangulation angles. In this case, we used the FUJIFILM Finepix x 100 camera, with a focal length of 23 mm (equivalent to a fixed lens of 35 mm), with a resolution of 12 MP (4288 x 2848 pixels), which provided better 3D reconstruction than classical photogrammetry (James and Robson, 2012)."

2.3. page 344, line 23: The number of pictures could be a problem in our study case. However, we consider that the increase in the number of pictures could induce different problems as the lighting of the different pictures. This way, in different point cloud generation tests in Agisoft software, when considering a higher number of pictures, large errors were observed in some areas (topographic features that did not exist as very abrupt peaks or sinks), which were related to illumination changes. Also we know that distance is a problem. So in future fieldwork, we will try to take into account the distance and the picture number as a factor.

We consider that is really important to obtain different images from all possible point of views. However, the number of pictures necessary could vary in each study, and we consider that it is really difficult to determine a minimum number of pictures (3 would be the minimum to generate a 3D model). So we consider that the number will depend on the occlusion, topography (complexity) and scale. A number between 10 and 100 is adequate to medium and high scales, when the study area was well represented in the image geometry.

A different point that should be addressed is the constraint of computer memory. In our analyses it was a big problem because we cannot analysed a big number of pictures. We have used the software Agisoft and our computer only have a memory of 12 Gb. However, there are different studies (e.g. Micheletti, Chandler and Lane, 2015b) that have carried out the analyses in similar areas and at the same scale, and they have obtained good models with 13 pictures.

2.3. page 345, line 6: In SfM, the resolution does not depend so importantly on the measuring distance as in TLS; the point distribution within the area does not vary significantly and in general is quite similar for the whole study site. Concerning this issue, these lines have been included in 2.3. section:

"High resolution of original images offers better texture and resolution to find keypoints in the photoset. Similarly, decreasing the distance between the camera and the feature of interest is related to increasing the spatial resolution of the photograph and will enhance the spatial density and resolution of the final point cloud (Westoby et al. 2012)."

2.4. page 345. Direct comparison of DEMs between techniques. As we said before, we have carried out a direct comparison of DEMs between techniques considering LiDAR as the reference (Figures 9 and 10 and Table 4). Comparison of 3D cloud is the best way to generate DEMs of difference to quantify volumetric change in temporal frequencies between successive topographic surveys (Williams, RD, 2012). In such a way, two new figures, one for north-facing slope and one for the south-facing slope, have been included. In these figures, considering as reference the LiDAR DEM, differences have been calculated for the first and last acquisition dates (23/07/13 and 23/07/14). The observed differences between DEMs are (new Table 4):

	24/07/2013	**24/07/2014**
North-facing slopes (TLS-SfM) [m]	**-0.013 ± 0.0308**	**-0.0201± 0.0326**
South- facing slope (TLS-SfM) [m]	**-0.002 ± 0.0202**	**-0.006 ± 0.0141**

These results showed the differences that existed between both methods. Additionally, when considering the figures that show these differences (the two new figures), it is possible to observe that larger differences occur in limit areas, where small vegetation patches were present (most of the vegetation was eliminated from the point clouds). Lower errors were observed in "deep" concavities (yellow colours in the comparison figures), because in these areas the SfM was not able to accurately reproduce a precise topography. Other errors were usually located in ridges and these areas behind them from the TLS perspective, showing one of the main TLS limitations; with one point of view, some areas were hidden. Thereby in the limits of these ridges we observed deviations between SfM and the DEM originated with the TLS.

Considering the Std Dev in these comparisons and also the standard deviation obtained in the calculations of the transformation matrixes from the targets coordinates (data processing section), which ranged between 0.025 m and 0.015 m, the colour scales of the erosion maps was set with a “zero band” (white colour) around zero ± 0.025 m.

3.1. We think that we cannot provide a sediment yield estimation for the slope as the balance of positive or negative differences. We have estimated an erosion rate for the slope areas for one year (according with the topographic differences). We consider centimetre differences significant due to the intense and fast geomorphological dynamic in these humid badlands. The precision should be enough for centimetre precision. We have installed again a new turbidimeter at the outlet of the catchment so in near future studies we can compare both methodologies in different study periods with higher precision (assuming the turbidimeter error assessment too).

3.3. page 348. We have carried out the comparison between both techniques, as explained before. Thereby, those differences could be explained due to the difficulty of SfM to detect small erosion processes (in our opinion and experience). This is especially evident for Period 3, the less active period in both slopes. In this period the small amount of total rainfall and low rainfall intensities were registered (Table 1), and small differences were observed in the north-facing slope. Additionally, in the erosion maps no big landslides or rills formation were observed during this period. Thereby, Period 3 differences represent an example of such deviation with erosion processes in the centrimetric scale.

Nevertheless, some deviations were observed in the south-facing slope in mean differences from the expected behaviour for the low “erosive” period. In this case, for Period 3, the observed positive differences may explain erosion processes, no detected by SfM neither by the TLS, but with an accumulation in the lower part of the surveyed area, properly observed.

Probably, the deviation in the north-facing slope with a higher importance was the one observed for the annual period. Considering the mean deviation obtained in the DEM comparison between TLS and SfM, this error may be understood. Despite the difference deviations observed, clearly erosion maps of both techniques present quite good agreement in the eroded areas, accumulation areas and even more important in the order of magnitude observed in both of them. This encourages considering both techniques applicable in such kind of studies with the advantages and disadvantages presented in this manuscript. Hereby, it could be concluded that both techniques were not precise enough to observe small differences that happened in periods with moderate erosions processes, but they show enough precision to describe erosion processes on small study areas at annual scale in really high dynamics humid badlands.

4.1. Page 348. Line 15. We have changed “subcentimeter accuracy”. We have considered centimetre accuracy.

4.1. page 349, line 9: Yes, we completely agree with the reviewer opinion, and such assertion has been included in the final manuscript version in the discussion section.

4.2. Page 350. Line 26. We have added more literature about the accuracy of SfM in different studies, and also new results have been included in this section

4.3. page 351, line 1: The dependence of the 3-D model from SfM, firstly depends on the software reconstruction mode, if low-resolution modes are selected, poor 3D models are created. When high-resolution mode is selected, the spatial resolution is improved. We have not analysed the number of points for a given cell, because we have not worked with rasterized information. Working and comparing only 3D point clouds ensure that the resolution of the obtained clouds is not lost, because otherwise, in some areas (closer to the acquisition points) we would have lost some information. In spite of that, a small number of pictures have been used for generating the point clouds, as can be observed in Figure 3, and considering the sharp topography of the study site which makes extremely difficult photo acquisition, perspectives diverge at least 90º (between extreme positions).

As can be appreciated in the new figures, included in the manuscript, we have only compared these areas without vegetation presence, to avoid such influence. Additionally (and fortunately for our analysis) in the slopes, due to the high geomorphological dynamics vegetation cannot growth.

Also the referred above lines, now states:

“The comparison between both methods (Figures 9 and 10 and table 4) showed that results were similar in both cases, although significant differences can be observed in small points.

Our study demonstrated that SfM delivers good accuracy and is really useful for field application in geomorphological and soil erosion studies, for observing changes in the centimeter scale (depending on the working distance)In our case, the quality of the images should be improved in order to obtain better accuracy, paying especial attention to illumination changes during the acquisition of the images, which have been observed as an important error-causing interference. The number of pictures could be a problem to be solved together with the computer memory (a large memory is needed to process a large number of high quality pictures). 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). Micheletti et al. (2015) carried out an analyses in similar areas and at the same scale, and they obtained good and valid models with 13 pictures."

4.3. page 351, line 16: We have included in Table 4 (now Table 5) and in the text brief information on the cost and time-requirements of both technologies in this study area.

5. page 352, line 20: We could obtain higher resolution pictures making photos at lower distance in small areas and then adding them to the dataset. However, for the present study we don't have it, but we can consider that in future study. Nevertheless, this statement makes reference to a general possibility of reducing errors that could be accomplished by using higher resolution cameras or making pictures at closer distances.

Table 3: We consider relevant centimetre differences. We are conscious that millimetre differences are really difficult to analyse. We have realize that changes in the month or 3-months scale are quite difficult to observe, unless erosion processes (mudflows, landslides, rill or gully development…) are big enough (above several cm of difference) to ensure that are captured by the techniques.

Table 4. We have included detail data about the cost and times of both methods.

Figure 1. We have considered GIS and remote sensing together. LiDAR was separated because its novelty in recent years.

FIGURES 5-8. We have improved the quality of these figures, with letters and explanations for each figure (dates, software). We have improved the legend and labels. We have used the common colour scale for such kind of maps as suggested by reviewers, (blue, and red with white transition). We have not consider to include arrows in the figure because we think that it could be difficult the reading. However, we have added two new figures with the comparison of both methods at annual scale, and we have included coloured point clouds of the slopes for one of the acquisition dates to provide more information on the study site characteristics to potential readers.

Figures captions (new figure captions): Figure 5 (6,7,8): Erosion maps for the analysed periods in North (South)-facing slope for TLS (SfM) technique. Differences have been calculated with Cloud Compare software.

Technical corrections.

4.2. pag. 351, line 1: We have changed lighting conditions.

References. We have included additional references as reviewers have mentioned in the different points.

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Smith, M.W., and Vericat, D.: From experimental plots to experimental landscapes: topography, erosion and deposition in sub-humid badlands from Structure-from-Motion photogrammetry. Earth Surf. Process. Landforms, 2015.

Prokop, A.: Assessing the applicability of terrestrial laser scanning for spatial snow depth measurements, Cold Regions Science and Technology ,54, 155–163, 2008.

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Anonymous Referee 2

First of all, we would like to thank the reviewer the first comment on our paper and the comment about the difficulties to apply this kind of methods in such dynamics humid badlands. Thank you very much.

We have improved the manuscript in this new version. We have carried out additional analysis to improve error assessment. As suggested by reviewers, we have included a comparison of both methods. And finally we have included a wider literature review on SfM photogrammetry in geomorphology.

Specific comments

1. We have changed in the manuscript the term "photogrammetry". We use Structure for Motion photogrammetry (SfM).
2. p 341 L 2-4: It is true that due to the increased digitalization of literature, these data could be confused. However we think that badland studies have increased in the last decades. You can check the review carried out in 2013 by Gallart et al. and published in Catena. They indicated, after the analysis of a list of about 450 texts written since 1982 (when the important book Badlands Erosion and Piping, Bryan and Yair), that badland researches have increased in Scientific literature.
3. p 341 L 16-17: Yes, you are right, so we have removed the word "mesh".
4. p 341 L 23-26: We have changed surveys by "…data already obtained with TLS…
5. Section 1.3: We have included a large number of references (See list at the end of

comments 1), also improving the whole section, including an explanation between SfM and traditional photograpetric methods as follows:

"The digital photogrammetry has generated an improvement in topographic methods, due to a better accessibility to a wider variety of users, its low cost, and also because the increased automation of the photogrammetric routines (Fonstad et al., 2013). Recently, Structure for Motion (SfM) techniques, developed by the computer vision community, were adapted to generate high resolution and quality DTM. Classical (Stereoscopic) photogrammetry is based on 3D reconstruction models by superimposing two images of the same area from different perspectives. SfM is based on the reconstruction of the 3-dimensional geometry from the matching of multiples images generated from different points of view. Pictures can be taken at different scales, and the position, orientation and distortion can be no-known. SfM differs from stereoscopic photogrammetry, because it uses image matching algorithms to recover randomly acquired images and to detect points in common elements.

The biggest difference between both methods is the need to use GCP for the 3D model resolution. In classical photogrammetry, the collinearity is solved after the introduction of the GCPs; in SfM, collinearity is solved from the common elements of the images. So, if there are errors in the measurement s of the GCPs, they are propagated to the final result (Fonstad et al., 2013). Through SfM, the final quality of the point cloud is based on a high number of common points (> 1000) that have been automatically generated."

6. Section2.1. We have included more details of the substrate in the study area.
7. Page 343. L. 14. We have improved the sentence and now it states: "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 the surveyed areas and on the working distances for data acquisition with both methods (TLS and SfM)."
8. Page 343. Line 22-23. We have improved the sentence. Now it states: "The device used in the present study is a long-range TLS (RIEGL LPM-321) (see Revuelto et al., 2014 for checking the technical characteristics of the TLS and the procedure used for scanning and for the post-processing information)."
9. Page 344. Lines 8-10. We have changed these sentences. Now it states: "In this study, for the north-facing slope 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 0.027º.

On the south-facing slope the resolution was, 1,890 points/m^2 (0.023 m) and the angular scanning resolution was 0.054º."

10. Section 2.3. We have slightly improved the explanation of the SfM photogrammetry method. Nevertheless we do not want to do a deep analysis of the generation process. We consider that are technical details which are high dependent on the software considered. Thereby we have introduced the details on the software only as users. Additionally, in the section which we consider more interesting for erosion community, the setup characteristics for the image acquisition is deeply described (Figure 3).
11. Page 344. L. 22. We have changed this sentence. Now it states: "which provided better 3D reconstruction than classical photogrammetry (James and Robson, 2012)"
12. Page 344. L. 22-24. We have changed this sentence following the reviewer's recommendations of plurals. .
13. Page 344. L. 25. We have changed this sentence following the recommendation.
14. Page 344. Lines 23-24. Yes, we have taken always the same number of photos and in the same positions. Why? We consider that is really important to obtain different images from all possible point of views. However, the number of pictures necessary could vary in each study, and we consider that it is really difficult to determine a minimum number of pictures (3 would be the minimum to generate a 3D model). So we consider that the number will depend on the occlusion, topography (complexity) and scale. A number between 10 and 100 is adequate to medium and high scales, when the study area was well represented in the image geometry.

    A different point that should be addressed is the constraint of computer memory. In our analyses it was a big problem because we cannot analysed a big number of pictures. We have used the software Agisoft and our computer only have a memory of 12 Gb. However, there are different studies (e.g. Micheletti, Chandler and Lane, 2015b) that have carried out the analyses in similar areas and at the same scale, and they have obtained good models with 13 pictures.

    Due to your comments and the results in future surveys we will try to increase the number of images and in this way we can test the results and check if the models improve due to the number of images.
15. Page 345. Line 5-6. Yes. Thank you very much for your comment. We will try to improve the resolution and number of images and distance in future studies. Also this sentence now states:

    "…decreasing the distance between the camera and the feature of interest is related to increasing the spatial resolution of the photograph and will enhance the spatial density and resolution of the final point cloud (Westoby et al., 2012)."

16. Page 345. Line 13. Measuring ground control points with a DGPS or a total station, being quite accurate methods, increase uncertainties too. The expected errors on a global coordinate acquisition must be considered in the coordinate transformation process, which in planimetry may reach 10 cm. Hereby, in order to not include these possible deviations, no global coordinates have been considered. In such a way, the coordinates of ground control points in the coordinate system of TLS (not absolute coordinates, because the TLS do not has integrated GPS antenna) have been used for giving values to SfM point clouds. Reflectors placed in ground control points were selected in Agisoft software and their coordinates, directly obtained from the TLS, were introduced in this software. This way, the text now states:

"Based on the target coordinates, a transformation matrix to a common coordinate system (which is named project coordinate system)using Riprofile 1.6.2 software is generated for the TLS point cloud. [….], the point cloud obtained from SfM 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.

17. Page 345. Line 16. We have included new references about TLS errors with same device (Prokop, 2008). We consider this is important, even if one of the co-authors of this manuscript is cited, because this demonstrates, that this aspect is in accordance to other studies.

18. Page 345. Line 19. This value is the standard deviation in target coordinates positions when applying the translation-rotation matrix that transforms point cloud generated in Agisoft to the coordinate system of the TLS. Please, see response 15 to reviewer 1. In this point, it is discussed this error put in contrast to differences observed between DEM comparison of TLS and SfM.

19. Section 3. We have analysed the differences between the TLS and SfM model for the initial and final period. Two new figures have been created and added to the manuscript. Please, see response 3.3. page 348. to *reviewer 1* and the new figures (Figures 8 and 9) added in the manuscript.

20. Section 4. We absolutely agree with reviewer opinion in this point: errors reported (standard deviations through the paper) in tables 2 and 3, makes that the absolute accuracies, needed to support such mean differences, are not enough. Thereby, we

consider these differences as a tendency about what it happens in the slopes. For us, after the revision of our work, it is clear that both techniques are suitable for observing and measuring differences above two-three cm, but for smaller differences, the uncertainties of the method, are really difficult to measure. The error mentioned by the reviewer about old figure 7, was due to a deviation in the colour scale selection. We agree in this point with the reviewer, it seemed a systematic offset error. It has been corrected in the new TLS south-facing slope figure in the final manuscript version, with the improved blue-red colour scale.

21. Page 348. Line 15. We have changed “subcentimetre” accuracy to centimetre accuracy, which fits better with the obtained results.

22. Section 3 and 4. We have improved the processes presented and discussed, considering these suggestion. We have also added some photos to provide more information on the study sites characteristics. Rill development is better observed in the south-facing slope due to the topographic characteristic of the selected slope. However, in the north-facing slope rill development is also observed (as you can see in the TLS figures).

23. Page 349. Line 28 and Page 350 line 1. These numbers are doing reference to the values presented on Table 2 and 3, and are correct (also the units).

24. Page 350. We consider that these erosion rates data have to be included. First in the introduction showing the high erosion rates recorded in badland areas and second in the discussion where we showed our data in comparison with other erosion rates recorded with different methods.

25. Page 350. Line 26-27. With the new analysis and new data we consider that we have provided more analysis to support this statement. Additionally this sentence now states: “Our study demonstrated that SfM delivers good accuracy and is really useful for field application in geomorphological and soil erosion studies, for observing changes in the centimeter scale (depending on the working distance).”

26. Page 350. Line 28. Page 351. Line 4.

In SfM the highest number of photographs is desired for obtaining a higher point cloud resolution or quality of the generated DEM. This higher quality would be directly related with the capacity of the method for observing little differences in the terrain. It would be interesting too, to obtain pictures at different distances, to test if the distance is a really important factor in SfM, and in that case our models could be improved. In our study, due to illumination problems (terrain shadowing effects and also clouds presence or not in the different image acquisitions), large errors were observed in the point cloud generation process when considering pictures with different illumination. This made compulsory to discard these pictures and finally only consider these with the same illumination. This originated the relatively low number of images considered in this study.

27. P 351 L 5-6 and L 15: We have checked this sentence. We mean the surface model computed from the TLS point clouds, not images of course. This has been corrected in the text.

28. Page 351. Lines 6-11. This is maybe the main limitation of TLS application and hereby has been included in method sections this sentence:

TLS automatically obtains 3D point clouds, but with a main limitation, we have only work from a single scan position; if other scanning positions are not defined, it is quite expensive in time, problems in the sight shadowing would be present.

"….However due to time restrictions we have worked with one single scan position causing the shadowing effect of terrain (the so-called sight shadowing), which do not enable to retrieve data from different areas of the site originating missing information. This missing information due to terrain curvature observed in some areas with the TLS (north-slope), is avoided with SfM photogrammetry because different points of view of the study area were easily acquired (see differences in Figures 9 and 10). Nevertheless, in the presented analyses, and data and also in the images that show point cloud differences, these shadow areas have been removed in SfM photogrammetry to consider exactly the same area with both methods.

29. Page 351. Line 20. We have deleted this statement to avoid misunderstanding.

30. Page 352. Line 19-20. It is a subjunctive tense. We consider that if we increased the images resolution our model would be improved too.

31. Page 352. Line 22. We have changed this sentence.

32. Figure 3. We have checked and improved these small mistakes.

33. Figure 5-8. We have improved the figures, changes the legend and labels

Figures have been changed as suggested by reviewers, and a new scale more appropriate for such kind of maps has been included. Nevertheless some resolution has been lost, because we have realize that a transition band around zero (± 2.5cm). Please see comment 15 of reviewer 1, where these figures have been explained. Unfortunately the software used in the study does not enable to change the background colour. Nevertheless, we consider that with the colour bar between red and blue with a white transition these accumulation areas are appropriately recognized.

34. Technical corrections

a. We have changed i.e. for e.g.
b. Page 340. Line 17. We have corrected the year for Walling.
c. Page 341. Line 11. We have changed and corrected Barnhat and Crosby.
d. Page 343. Line 16. We have changed this sentence.
e. Table 1. Caption. We have changed "periods".
f. Figure 1. We have changed the names in the X axis.

Anonymous Referee 3

We are really thankful to the nice comments and suggestion from anonymous reviewer 3. Most of them coincide with these suggested by the other reviewers and thereby in the previous response can be found most of these changes.

The paper now exploits better the obtained information, having been improved results and discussion sections being included new relevant references. A new comparison between both methods has been included for the annual period in the two slopes, doing the manuscript more robust, especially in the comparison between the two techniques.

1. We have included more references to discuss the advantages of the different techniques for this specific application. We have remarked the characteristics of humid badland areas topography to show the differences with other environments where these techniques have been applied.

2. Following the reviewer recommendation, we have changed the abstract to focus the study.

3. We have changed the term photogrammetry using Structure from Motion photogrammetry (SfM). Also we have differentiated between "traditional" photogrammetry and SfM to highlight new opportunities in data acquisition of SfM,

4. We have changed the sentence from previous manuscript version "P345 L6" . After Reading different literature we have checked that distance is really important. However, we consider that the effect of distance is higher using TLS. So now it states:

"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. High resolution of original images offered better texture and resolution to find keypoints in the photoset. Similarly, decreasing the distance between the camera and the feature of interest is related to increasing the spatial resolution of the photograph and will enhance the spatial density and resolution of the final point cloud (Westoby et al., 2012)."

5. We have included the comparison between both techniques. Please see 3.3 Joint analysis section and the new figures included. Now it is stated:

"Figures 9 and 10 showed a direct comparison of DEMs between techniques considering LiDAR (TLS) as the reference. Differences have been calculated for the first and last acquisition dates (23/07/13 and 23/07/14). Big differences occurred in small areas, where small vegetation patches were present (almost all vegetation was eliminated from the point clouds, but some influence can be appreciated in the exterior limits of the selected slopes). Small differences were observed in "deep" concavities (yellow colours in the comparison figures), because in these areas the SfM was not able to accurately reproduce a precise topography. Other errors were usually located in ridges, and the areas behind them, from the TLS perspective, showing one of the main TLS limitations: with only one point of view, some areas are hidden. Average differences (Table 4) were bigger in north-facing slopes in both surveys (also the highest standard deviation were recorded)."6. Figures 5-8. We have improved the figures, labels and legend following reviewers recommendations.

We have tried to improve and go much into the analysis of geomorphological process understanding.

Finally, we remain at the disposal of the Managing Editor and the Anonymous Referees in terms of making additional changes and improvements to the manuscript. Thank you for your assistance and advice on how to improve our manuscript.

Yours faithfully, Estela Nadal-Romero and co-authors