Geomorphology 245 (2015) 243–254

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Accuracy constraints of terrestrial Lidar data for soil erosion measurement: Application to a Mediterranean field plot

A. Eltner [a,*], P. Baumgart [b]

[a] Institute of Photogrammetry and Remote Sensing, Technical University Dresden, Helmholtzstr. 10, 01069 Dresden, Germany
[b] Institute of Geography, Technical University Dresden, Helmholtzstr. 10, 01069 Dresden, Germany

ARTICLE INFO

Article history:
Received 18 September 2014
Received in revised form 26 May 2015
Accepted 4 June 2015
Available online 6 June 2015

Keywords:
Terrestrial laser scanning (TLS)
Multi-temporal referencing
Scan geometry
Soil erosion
Hillslope scale
Mediterranean

ABSTRACT

Applications of terrestrial laser scanning (TLS) to measure soil erosion are yet limited, although this topographic mapping method allows for large area coverage with high resolution and reliable precision. However, restricting factors are accurate and stable references for multi-temporal change detection and adverse scanning geometries. At agricultural fields the plot is usually situated on gentle slopes provoking low viewing angles of the scanning device onto the surface, which inherits the risk of high data noise. In this study, TLS is exploited from a high tripod to measure soil erosion at an Andalusian hillslope (2×1000 m^2). In the Mediterranean sediment yield reveals discontinuous pattern and TLS is a promising method to quantify these surface changes. A stable reference system is defined, resulting in multi-temporal registration accuracy better than 7 mm. Further, an mm-accurate calibration plot (60 m^2) is designed to evaluate scan geometry and radiometry (i.e. incidence angle, footprint, and intensity) in dependence of distance related errors. A lookup table is determined to correct systematic errors of the field data. The Andalusian field plot is captured during a winter season and during single precipitation events. Estimated erosion rates amount 10 and 2.4 t ha^{-1}, respectively. Surface changes with magnitudes larger 1.5 cm are reliably measured. TLS can be implemented to estimate soil erosion with cm-resolution if errors are carefully accounted for.

1. Introduction

Terrestrial laser scanning (TLS) is a method for high resolution topographic survey mapping, which is widely recognised in geosciences (Shan and Toth, 2008; Heritage and Large, 2009; Vosselman and Maas, 2010). A great advantage is the measurement of large areas up to several hectares without disturbance of the investigated object, for instance due to instrument installations, which is beneficial for area based soil surface change detection. However, applications in soil erosion studies are yet limited and surveys are mostly conducted under restricted conditions. Erosion measurements with TLS are either performed on steep slopes with almost vertical viewing direction, on very small plots, or at locations where erosion magnitudes are very high.

Schmid and Hildebrand (2004) are one of the firsts to test TLS for soil erosion. They conduct field surveys on a small plot at a logged forest site and reveal the difficulty to clearly distinguish soil erosion from consolidation. However, they state, if a very precise reference could be setup, mm-accuracy is possible. On small plots of a few square metres different investigations are conducted to measure soil surface roughness to estimate its influence on soil erosion (Haubrock et al., 2009; Eitel et al., 2011; Smith et al., 2011; Vericat et al., 2014). In contrast, Hancock et al. (2008) are the first to measure rill erosion on a larger plot (60 m long) from further distance at a steep slope. Rills are detected broadly and thus high underestimation of rill erosion is assumed. At larger study areas erosion forms of larger magnitudes – i.e. gullies – are usually measured (Perroy et al., 2010; Lucía et al., 2011; Höfle et al., 2013). Recent studies on actively agriculturally utilised areas are performed by Ouédraogo et al. (2014), who generate digital surface models (DSMs) with m^2-resolution at watershed scale, and by Barneveld et al. (2013), who calculate high resolution models of soil surfaces for different plots at field scale. However, the mentioned studies on larger plots have not yet conducted multi-temporal measurements, which entail the need for a precise reference system.

Soil erosion – especially interrill erosion – usually occurs with low magnitudes. If event-based soil surface changes are to be measured at larger field plots, stable references need to be defined and data acquisition has to be performed with very high accuracy as well as resolution. These requirements have already been demonstrated for different geomorphic surveys using TLS — e.g. change detection of rock slopes (Abellán et al., 2009), coastal cliffs (Rosser et al., 2005), river bluffs (Day et al., 2013), or sand dunes (Feagin et al., 2014). Lague et al. (2013) further highlight the importance of accuracy consideration for multi-temporal geomorphic change measurement with TLS.

However, it is difficult to achieve high data resolution and accuracy for soil erosion studies at cultivated fields because agriculturally

* Corresponding author.
E-mail address: Anette.Eltner@tu-dresden.de (A. Eltner).

http://dx.doi.org/10.1016/j.geomorph.2015.06.008

utilisation is common at gentle rather than steep slopes, which results in unfavourable scanning geometry due to low viewing angles. The resulting data noise increases with increasing distance to the scanning device. Soudarissanane et al. (2011) show the importance of scan geometry, i.e. incidence angle and range, on point precision. Also, Schürch et al. (2011) highlight difficulties emerging from sub-horizontal surface measurement of complex topographies. Possibilities to correct errors, which evolve from TLS, are self-calibration algorithms (e.g. Lichti, 2007; Schneider and Maas, 2007). Thereby, adjustment is performed to estimate different parameters (e.g. scanner orientation and position as well as internal scanner geometry) of a geometric model that describes the TLS system. Approximate values for the adjustment are derived either from distinct points or from flat target observations. Object related errors can be included into the adjustment as additional parameters to account for effects due to TLS beam geometry. Dorninger et al. (2008) use planar features at the area of interest to calibrate the scanner. However, this is not possible for soil surfaces due to their rough morphology. But the detection of errors, e.g. along a plane calibration plot, can be performed offsite and correction values subsequently assigned to the field data. Hodge et al. (2009) tested TLS data for errors under laboratory conditions and subsequently applied the results to the field data of fluvial sediments.

Soil erosion is a severe issue in the vulnerable Mediterranean landscape. Beside lithogenic backgrounds, high potentials in relief energy, and intense agriculture cultivations, water is the main factor influencing soil erosion (e.g. Poesen and Hooke, 1997; Faust and Schmidt, 2009). Torrential precipitations (high intensity and short duration) are typical (Poesen and Hooke, 1997) and very effective at eroding soil (Bracken and Kirkby, 2005). Low organic matter content as well as slow soil formation rate and thus shallow soil profiles are typical for the Mediterranean (Poesen and Hooke, 1997; Cantón et al., 2011). Hence, runoff and consequently sediment yield respond fast to precipitation due to high rainfall intensity and low soil infiltration capacity (Poesen and Hooke, 1997). The long history of human activity in the Mediterranean is another factor promoting soil vulnerability (García-Ruiz et al., 2013).

The Mediterranean is one of the worldwide erosion hotspots (Boardman, 2006), which depicts unique runoff and sediment yield pattern. Hydrological connectivity is discontinuous at the hillslope scale, particularly when vegetation is present (Calvo-Cases et al., 2003; Puigdefábregas, 2005), due to the short duration of erosive-effective precipitation events (Yair and Raz-Yassif, 2004) and soil physical thresholds (Cammeraat, 2002). Open or closed plots are current methods for measuring soil erosion in the Mediterranean, which declare erosion volumes or weights per area, although local relocation information is needed (Boardman, 2006) to asses these source – sink – patterns. TLS can help to qualify and quantify non-linear interaction of erosion factors at different spatial scales (Boix-Fayos et al., 2006; Lesschen et al., 2009). In the Mediterranean highest portion of total sediment yield per year occurs due to one or two precipitation events (López-Bermúdez et al., 1998; De Santiesteban et al., 2006; González-Hidalgo et al., 2007). At inter-annual scale this erosion variability amplifies when long-term erosion rates are dominated by large scale events of low frequency (Martinez-Mena et al., 2001; Ollescch and Vacca, 2002). However, low magnitude events are also relevant for long-term rates due to their high frequency (Romero-Díaz et al., 1988). The temporal and spatial complex soil erosion characteristics in the Mediterranean, i.e. sediment yield connectivity and variability, highlight the necessity to assess area-based surface changes with high resolution.

In this study, scan geometry is investigated for low incidence angles, which is inevitable for soil erosion measurements with TLS on agricultural utilised fields that are commonly situated at gentle slopes. The influence on point accuracy is studied for a calibration plot and field data. A method is introduced, which detects systematic errors and subsequently assigns corresponding correction values. At a large field plot in Andalusia (Spain) the corrected data are tested for its suitability to detect soil surface changes of different magnitudes. In this regard, the definition of a stable reference system for multi-temporal change detection with TLS is illustrated. Soil erosion is measured with cm-accuracy after a semi-annual and a monthly period, which allows for analysing complex erosion pattern typical for the Mediterranean landscape.

2. Study area

The study area is located in a Mediterranean landscape in the south of Alcalá de Guadaíra in Andalusia, Spain (Fig. 1). The location of the investigated field plot is chosen because detailed studies on soil erosion are missing in the region. Although, the landscape exhibits a high morphodynamic, which is investigated for the marl landscape in the south of the study area (Faust, 1995; Faust and Schmidt, 2009), where soil conditions are different but climatic circumstances are similar. Moreover, communication with the local farmer indicates that the selected hillslope is erosion-prone because frequent observations of distinct erosion rills are made, which was confirmed during field work. The field plot is situated in an area dominated by Tertiary calcareous sandstone. Hence, the soil is very rich in calcium carbonate. However, only remnants of originally in-situ formed soils are abundant at a few preserved locations due to long cultivation and erosion history of that area. Recent tillage is mostly performed on colluvial deposits or lithogenic background material. For an estimation of the composition of the tillage horizon, 40–50% of substrate is lost via decalcification and prior to the granulometry measurement. The remaining grain sizes contain 10–15% clay, 5–10% silt and 20–30% sand. Surfaces are expected to have a high runoff threshold because of the abundance of sand and a corresponding elevated infiltration capacity. Soil type is addressed as colluvium, which is indicated by present brick fragments. The hydrological conditions of the selected field plot are common for the Mediterranean. Thus, precipitation occurs from October until May with two small peaks in spring and autumn and exhibits high inter-annual variability (Renschler et al., 1999; García-Ruiz et al., 2013). In western Andalusia the highest erosive precipitation events occur in October (Renschler et al., 1999), which are significant for soil erosion after a dry summer leading to dry soils (Faust, 1995; Romero-Díaz et al., 1999).

The field plot has a size of 40×50 m^2 but is divided into eastern and western parts, which are observed separately (Fig. 1). Two different temporal scales are considered. The eastern part has been studied from Sep. 06, 2012 until Mar. 03, 2013 to capture the rainy winter season. Cumulative precipitation totalled 468 mm, with a maximum daily value of 61 mm. The western part of the field plot has been investigated from Sep. 11, 2013 until Oct. 30, 2013. This time three precipitation intervals in total amounting 112 mm are observed. The highest daily value conducts 31 mm. The field plot is a straight slope with an average inclination of 8°. Conservation tillage, which leaves significant amount of crop residue at the soil surface to reduce erosion susceptibility, is the common agricultural preparation practice. However, during this study the surface has been freshly harrowed and rolled before the investigation of each plot site.

3. Methods

3.1. Data acquisition

The field plot is captured with a terrestrial laser scanner (Riegl LMS Z420i) utilising time-of-flight principle for distance estimation. The TLS is installed on a 4-m high tripod to compensate for unfavourable scan geometry due to a low viewing angle onto the field plot (Fig. 2). The TLS is situated around the plot with at least one scan position at each plot side to guarantee a sufficient coverage of the area of interest. Scan positions can be compared to each other for accuracy assessment