A CASE STUDY OF TERRESTRIAL LASER SCANNING IN EROSION RESEARCH: CALCULATION OF ROUGHNESS AND VOLUME BALANCE AT A LOGGED FOREST SITE

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KEY WORDS: Forestry, Soil Erosion, Analysis, Measurement, DEM/DTM, High Resolution

ABSTRACT:

The microtopography of the soil surface (mm to dm range) is a crucial factor in understanding and monitoring soil erosion. It influences the dissipation of rain-drop energy, determines the hydraulics of surface runoff, and it is changed by transport and sedimentation of soil particles. We used a high-resolution terrestrial laser scanner to assess erosion risks due to mechanized logging with crawler harvesters on steep slopes. Four measuring fields of about 20 m² were scanned before and after the logging operation and after one year of exposure to the rain. To avoid shading, all soil vegetation and coarse litter was removed. The scans yielded approximately 50,000 irregularly distributed three-dimensional coordinates per m² and were interpolated to gridlike elevation models. The surface models and the balanced volumes revealed an overall compaction, track forming, and an increase of surface roughness by the logging operation. During one-year weather exposure a further weak volume loss occurred and sharp relief contrasts were partially smoothed. However, the surface models did not allow for the concluseion that soil erosion occurred. We attributed the volume loss during the weather exposure mainly to consolidation of loosened soil material. A calculated roughness index was highly variable in dependence of interpolation parameters. Therefore the interpretation of roughness indices requires the showing of the scale dependency, e.g. as fractal dimension. We conclude, that terrestrial laser scanning is very performant in assessing microtopography, but the problem of shading by soil vegetation complicate its general use in soil erosion monitoring.

KURZFASSUNG:

Die Mikrotopografie der Bodenoberfläche im Skalenbereich mm-dm ist ein entscheidender Faktor zum Verständnis der Bodenerosion durch Wasser. Sie beeinflusst den Energieverzehr auftreffender Regentropfen und bestimmt die Fließwege des Oberflächenabflusses und sie wird verändert durch Abtrag und Sedimentation von Bodenpartikeln. Mit Hilfe eines hochauflösenden terrestrischen Laserscanners sollten Erosionsrisiken bewertet werden, die durch mechanisierte Holzernte mit Raupenharvestern in Steillagen enstehen. 4 Messfelder mit ca. 20 m² Fläche wurden unmittelbar vor und nach der Holzernte sowie nach einem Jahr Witterungsexposition gescannt. Um Abschattungen zu vermeiden, wurde die gesamte Bodenvegatation und grobe Streu entfernt. Pro m² wurden ca. 50000 unregelmäßig verteilte 3-dimensionale Koordinaten erfasst, die dann zu Punktgittern interpoliert wurden. Die Oberflächenmodelle und die bilanzierten Volumina zeigten insgesamt eine Verdichtung der Flächen, Spurbildung und einen Anstieg der Rauhigkeit. Während der einjährigen Wettereinwirkung kam es zu einem weiteren leichten Volumenverlust und gleichzeitig zur Nivellierung scharfer Reliefgrenzen. Die Oberflächenmodelle gaben jedoch keine Hinweise auf Erosionsprozesse. Die Volumenverluste während der Wettereinwirkung haben wir hauptsächlich auf die Konsolidierung zuvor aufgelockerter Bodenbereiche zurückgeführt. Der berechnete Rauhigkeitsindex reagierte sehr empfindlich auf Änderugen der Gitterweite bei der Interpolation, seine Interpretation erfordert daher die Einbeziehung der Skalenabhängigkeit, z.B. als fraktale Dimension. Insgesamt hat sich der hochauflösende terrestrische Scanner als sehr leistungsfähig zur Erfassung der Mikrotopograpie erwiesen, das Problem der Abschattierung kann seinen Einsatz zur extensiven Erosionsüberwachung aber problematisch machen.

1. INTRODUCTION

Soil erosion by water is a major problem in soil protection. On-site the erosion process may cause loss of soil nutrients and humus as well as undesired changes of the surface relief , off-site deposition of sediments to sewerage systems, roads and reservoirs as well as eutrophication of streams by soil colloids are of great economical and environmental relevance. In contrast to tillage, closed forests generally have very low soil erosion rates. In most cases formation of surface runoff is inhibited by a litter layer and high infiltrability (Patric 1976). However, wild fires, clear cuts, and especially forest road construction may provoke erosion risks. Grace III (2003) attributes 90 % of sediments leaving forested watersheds in USA to creation and maintenance of forest roads and skid trails. On forest roads bare soil is exposed to rain action while infiltration capacity is drastically lowered by compaction. Forest roads may form long, steep ramps and natural drainage patterns can be interrupted which allows sediment- loaded surface runoff to access streams.

Until now erosion from forested areas did not cause major concern in Germany although historic erosion traces are obvious in many hilly and mountainous regions. This shows that an erosion potential is exists. Therefore, it is desirable to evaluate erosion risks when new harvesting concepts are introduced. This applies especially to the black forest in south west Germany, where the rain erosivity is higher than in most other regions of Germany (Sauerborn 1994) and even steep slopes are logged regularly.

Up to some years ago fully mechanized logging on slopes steeper than 30% was not possible. Newly developed harvesters with tiltable cabin on crawler chassis now may be used even on slopes steeper than even 60% (Schöttle et al. 1998), as long as transversal tilting of the chassis can be avoided. Therefore the logging lines have to be created strictly in the direction of maximum slope, which cause simultaneously the maximum erosion risk.

The microtopography of the soil surface is one crucial factor in understanding and modelling water erosion. It influences the energy impact of rain drops and determines the hydraulics of surface runoff. On the other hand, erosion itself changes the soil surface by forming rills or by sedimentation of soil material. The scale of the relevant surface structures, besides the general topography of the slope, are the diameter of the soil aggregates (mm) up to the typical width and depth of erosion rills, sediment cones, consolidated molehills, or stones (dm) (Roth 1996). Surveys of surface microtopography not only allow to be assessed erosion risks, but the tracing of its changes also allows erosion and sedimentation of soil material to be quantified. Common methods of measuring the surface topography with high spatial resolution include contact profile meters, where the surface is gaged with needles, flat-bed laser triangulation, or stereo-photogrammetric methods (Govers et al. 2000, Huang 1998). These methods have a limited performance when used on greater areas where resolution in the mm range is required. Triangulation laser scanning requires a very precise two-dimensional movement system, similar to flat-bed scanners, which must be positioned on the research area. Manual gaging and terrestrial stereo-photogrammetry may be laborious and time consuming, therefore, high resolution measurement of surface structure was thus restricted to small areas in most cases as a part of laboratory studies (e.g. Helming et al. 1998).

The new availability of three dimensional terrestrial laser scanners, first introduced in civil engineering, are a possible means of producing high resolution surveys of natural soil surfaces in erosion research. By subsequent scanning of the soil surface before and after logging and after exposure of the surface to the weather it should be possible to assess topography-linked changes of the erosion potential as well as volume losses due to erosion. The intention of this study is a) to test high resolution laser scanning of the soil surface as a new method in erosion research and b) to quantify the soil erosion risks as a consequence of crawler harveste use on a typical site in the black forest.

2. MATERIAL AND METHODS

2.1 Test area and treatment

The test site was a 50 year old stand of norway spruce (Picea abies L. Kast.) in the middle black forest (South West Germany) near St. Märgen (Table 1). Precipitation is approximately 1600 mm per year and mean temperature is 10,7°C. The estimated regional R- Factor of the USLE model is between 100 and 110 kJ m^{-2} mm h^{-1} (Sauerborn 1994)

Table 1: Site Description

geographical position	8° 9' 30" east 40° 0' 2" north
height above sea level	950 – 990 m
inclination and aspect	45 – 50 % to south-west
soil type (WRB)	dystric cambisol
soil forming substrate	periglacial gneiss deposits
soil texture	sandy loam, sceleton 20 -50 %
humus content of A horizon	15 %
humus form	moder

Thinning operations (Schmid 2004) were carried out by a crawler harvester "Königstiger" (30 t total mass, crawler width 60 cm, total width 3 m, Schöttle et al. 1998) in combination with cable logging. All mechanized operations were concentrated on lines with a distance of 30 m. These lines were passed twice by the crawler harvester and then were subject to pitching and dragging of the logs during cable logging. Branches remained on the lines.

2.3 Laser scanning

Before the first vehicle movement, four measuring fields each 7 m in length and 4 m in width were chosen on the planned logging lines. Six fixed points were anchored witch 80 cm concrete foundations around each measuring field, but outside the direct action sphere of the crawler chassis of the harvester. The fixed points were levelled with a total station.
For laser scanning a CYRAX 2500 Scanner (Cyra Technologies / Leica Geosystems) was used [1)]. The scanner allowed the aquirement of 1000 x 1000 polar coordinates with a maximum vertical and horizontal opening angle of 40°. Advertised accuracy was ± 4 mm of length and ± 60 µrad of angle. Absolute positioning was performed automatically with target marks attached to the fixed points.
In order to avoid shading by the surface roughness, the best position for the scanner would have been perpendicularly above the measurement field. However, this was not achievable. Therefore each measuring field was scanned from two to three positions and the point clouds were merged in post processing. After merging the data was available as a raw file for each field with 500,000 to 1,200,000 irregularly distributed carthesic coordinates with point density of 30,000 to 60,000 m^{-2}.

Each measuring field was scanned 3 times. The first scan was before the harvesting operation, the second directly after the harvesting operation without any further disturbance, and the third after one year of exposure to the natural precipitation. Before each scan, the soil surface was cleaned by removing branches, twigs, coarse litter and soil vegetation.

2.4 Data analysis

Data analysis was performed by using the open source GIS "GRASS" (Neteler and Mitasova 2002) and SAS Base Software (SAS Institute 1985). In the first step outliers, e.g. caused by flying insects, were identified and eliminated as extreme residuals of a two-dimensional linear regression model of the data. The portion of such outliers was < 0.01% In the next step the irregular data were interpolated to a regular grid by inverse-distance weighting of the nearest neighbours. Because the parameters of surface roughness are by nature sensitive to smoothing procedures, the interpolation parameters were varied between 5 and 10 mm grid width and with two and four neighbours included. Volume changes caused by the treatments were calculated by map algebra on interpolated raster maps.

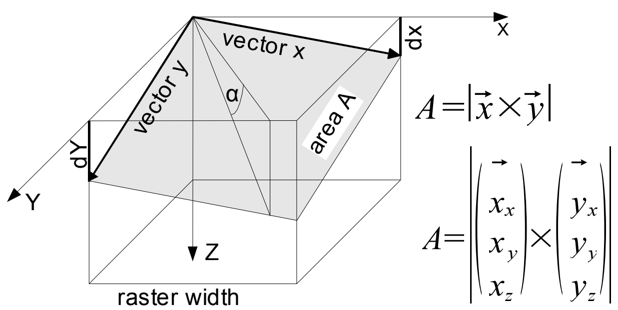

Figure 1: Calculation of the effective surface area of grid cells. The lines X, Y, and Z symbolize the axes of the carthesic coordinate system. The vectors x and y are calculated by the geographic information system. The area A is the outer product of the vectors.

1) by Scaning Ges. für dreidimensionale Objekterfassung und Ingenieurdienstleistungen mbH, Frankfurt a. M. , Germany

The relation between the surface area and the surface projection was calculated as an indicator of surface roughness. Because this indicator can be used as a deterministic parameter in the calculation of rain energy dissipation, it is particularly convenient in erosion research (Helming et al. 1993). The actual surface area of a raster cell depends on the grid width, the inclination, and the slope aspect in relation to the grid alignment. When the grid cell is inclined parallely to the the grid, the surface becomes a rectangle, whereas in all other cases the surface becomes a parallelogram. The surface can be calculated as the outer product of the vectors (Schmid 2004), illustrated in figure 1.

To supress the surface-increasing effect of the inclination of the terrain, we related the summed surface area of the raster cells to the area of the two-dimensional regression model (inclined plane), instead to the horizontal projection area.

3. RESULTS

In figure 2 the visualized surface of one measuring field before and directly after the harvesting operations is shown. The most obvious changes are the depressions and bulges created by the crawler tracks on the right side of the measuring field. On the left side, roughness seems to be increased by the operation, however, no apparent traces of the crawler movement can be seen. The one-year weather exposure did not cause obvious changes in the surface visualizations on any measuring field, therefore the respective surface models are not displayed.

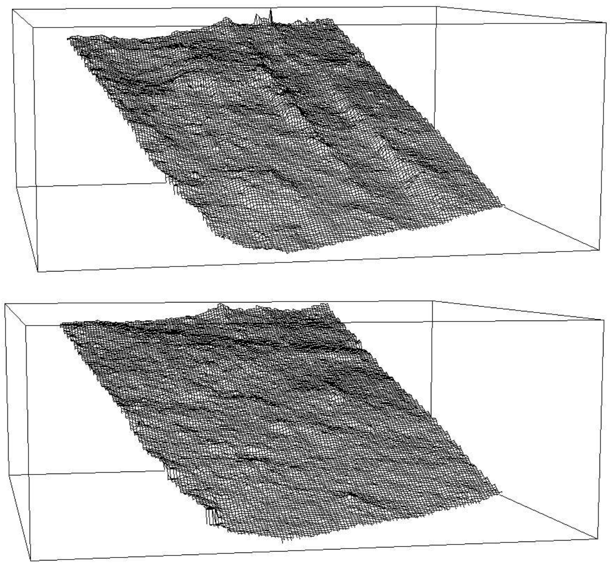

Figure 2: Visualized surface model of a measuring field before vehicle movement (above) and after the harvesting operation (below). The grid width represents 50 mm, the horizontal axes 7 m, the vertical axis 4 m.

The balanced volume changes during the one year weather exposure are displayed in figure 3. Noteable was the concentration of volume loss of the bulges formed by the crawler tracks. Figure 4 is shown a detailed view of a crawler track, where the molds of the crawler shoes, which cause a directional roughness perpendicular to the direction of movement can be seen. The logging operations and the weather exposure caused considerable local gains and losses in the soil volume (figure 5). In most cases the sum of losses exceeded the sum of gains. The overall height decrease of the measuring fields was between 1 and 10 mm. In no case were the volume losses by weather exposure higher than the volume gain by the vehicle movement.

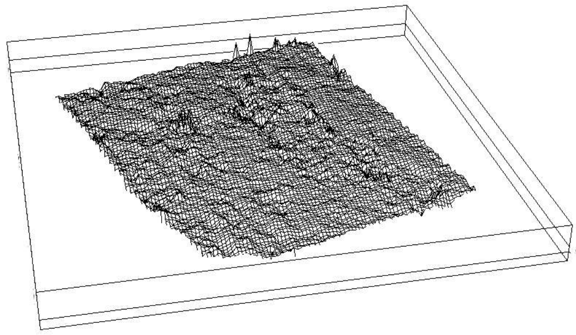

Figure 3: Visualization of the balanced volumes of measuring field 2 during the one-year weather exposure. The vertical axis represents approximately 50 cm. Depressions represent volume loss, peaks volume gain.

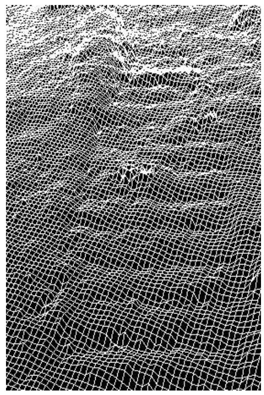

Figure 4: Detail of the surface model of a crawler track.

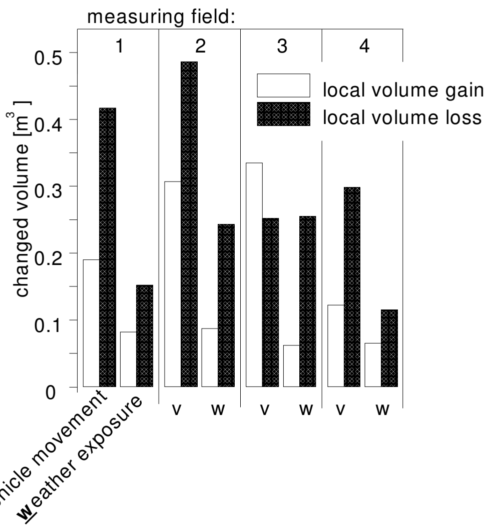

Figure 5: Changes of soil volume due to the harvesting operations and to the weather exposure as local volume gains (empty colums) and local volume losses (hatched columns). The balanced volume change is the difference of the two columns.

The volume losses were caused by relatively high vertical changes concentrated on a small part of the area. This can be seen in the spectrum analysis in figure 6. Depressions that can be attributed to the weather exposure greater than 30 mm caused 62 % of the volume change, but were concentrated on only 10% of the area.

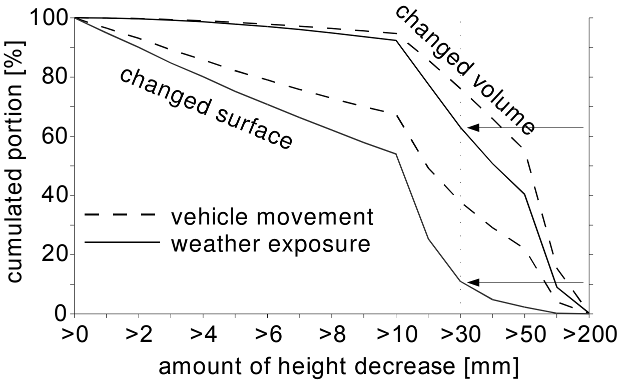

Figure 6: Spectral analysis of the height decreases causing volume losses. The curves represent the cumulated depressed area and volume loss of all measuring fields in relation to the amount of height decrease. The arrows refer to the example in the text.

The index of surface roughness and its changes are displayed in figure 7. The values are the relation between the modelled surface area and the projection area. The variation of the grid width had a dominating influence on the absolute values and its changes. The modelled surface increased by the factor two to three, when the grid width was decreased from 10 to 5 mm. In the 10 mm grid a treatment influence is visible. The logging operation increased the roughness, whereas the weather exposure smoothed the surface to roughness values near the initial state.

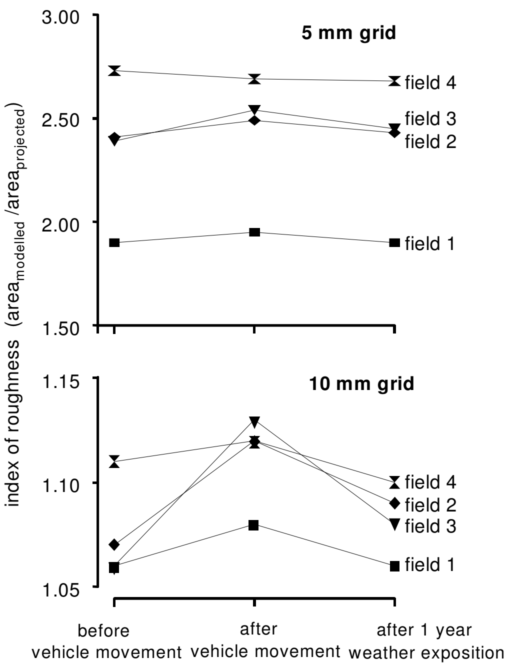

Figure 7: Surface roughness on the measuring fields. The 5 mm grid was interpolated with two inverse-distance weighted neighbours, the 10 mm grid with four neighbours.

4. DISCUSSION

One objective of this study was to test the applicability of terrestrial laser scanning in field research on soil erosion. The results are based on approximately 240 m^2 surface models with 5 mm spatial resolution. The equipment allowed the data of 60 to $80m^2$ within 1 day of field work to be aquired and postprocessing required approximately the same time. Compared to the methods of producing surface models documented by Govers et al. (2000) the laser scanning technique allowed a drastic increase in performance. The most critical point of use of the laser scanning technique in assessing the soil-surface structure, is the shading effect by soil vegetation, trees, stones, or branches. In this study, we completely removed all covering material. This work was laborious and furthermore it changed significantly the conditions controling soil erosion: By removing the surface cover, the susceptability of the surface to rain-drop impact and runoff generation is increased. But even a thorough removal of loose material does not guarantee that depressions can be scanned without shading. This applies especially for small structures with sharp edges. Therefore the laser scanning technique may under certain circumstances systematically underestimate the surface roughness.

Another critical point of the calculation of volume balances is the required degree of congruence of the surface models. This applies especially to the large scale monitoring of interrill erosion with e.g. an overall height decrease of only 1 mm standing for a significant soil loss of 10 to 15 t per ha. The foundation of fixed points with high precision may be too costly, if the laser scanning technique is to be used for general erosion monitoring.

What interpretations do the results from laser scanning concerning the erosion risks allow? The main change of relief was the action of the crawlers which formed compacted areas in the tracks and bulges at the sides, but also the cable logging had an impact on the surface structure when pitching logs caused displacement of soil. Depressed tracks with compacted soil may serve as preferred pathways for surface runoff. However, the cross bars of the crawler shoes as well as the small depressions caused by pitching logs retard the occurrence and decrease the flow velocity of surface runoff. During the one-year weather exposure a further weak volume loss occured. Interpretation of the visualized volume balances suggests that this volume loss did not occur in the tracks, where erosion was expected the soonest, but on the bulges and other formerly heightened areas. In no case did the volume loss during the weather exposure exceed the volume gain during the logging operation. This suggests, that the main cause of volume loss may have been the consolidation of loosened soil material e.g. in the bulges or the mounds formed by pitching logs. Local volume gains during the weather exposure may be attributed to the activity of soil animals and to filling of the formerly depressed areas by local soil displacement.
These interpretations imply an increase of roughness during the logging operation and a certain smoothing during the weather exposure. The roughness index calculated on the 10 mm grid reveals this phenomenon, but not the roughness index calculated on the 5 mm grid. Helming et al. (1993) reported a roughness index of 1.5 for a very rough seed bed in runoff experiments, which is between the range of our results in the 10 mm grid (1.05 to 1.12) and in the 5 mm grid (1.9 to 2.8). In their classification of roughness scales, Helming and Frielinghaus (1998) call the range between 2 and 100 mm “microtopography”. The strong scale dependence even in a the relatively small range of 5 to 10 mm in our results grid make it difficult to interpret the absolute values of the roughness index.

The soil aggregates of the seed bed investigated by Helming et al. (1993) had a relatively uniform diameter in the cm scale. The forest soil in our study was covered with needles with length/diameter relation of 15 to 1 with irregular voids between. This may explain the sharp decrease in surface roughness between 5 and 10 mm grid width and the complete masking of the treatment effect in the fine grid.

5. CONCLUSIONS

The use of hree-dimensional laser scanning to characterize soil surface changes was revealed to be a powerful tool in erosion research. However, the disturbance by shading structures above the soil surface such as soil vegetation and coarse litter complicates the use of this technique in practical erosion monitoring. The accuracy of this system seemed to be sufficient in detecting height decrease in the mm range, provided that congruence of the subsequent scans can be achieved by high-precision fixed points. However, in simple volume balances other relief-forming processes of natural soils like compaction by rain or loosening by soil animals can mask soil losses by erosion. By calculating flow-models of the surface models with geographic information systems, pathways of erosion may be detectable. The relation of the effective surface to the projection area as a roughness index revealed a high sensitivity to the grid width and the interpolation parameters. Instead of calculation of an absolute roughness index we recommend therefore to quantify the scale dependent function of soil roughness, e.g. as the fractal dimension (Huang 1998).

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ACKNOWLEDGEMENTS

The work was funded by the German Federal Ministry of Education and Research (BMBF .project n°0339767) .