Please cite this manuscript as: Aleksandra M. Tomczyk, Marek Ewertowski, Quantifying short-term surface changes on recreational trails: The use of topographic surveys and 'digital elevation models of differences' (DODs), *Geomorphology*, Volume 183, 1 February 2013, Pages 58-72, ISSN 0169-555X, http://dx.doi.org/10.1016/j.geomorph.2012.08.005.
(http://www.sciencedirect.com/science/article/pii/S0169555X1200387X)

Quantifying Short-Term Surface Changes on Recreational Trails: The Use of Topographic Surveys and 'Digital Elevation Models of Differences' (DODs)

Aleksandra M. Tomczyk[a,1]; Marek Ewertowski[2,1]

1. Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, ul. Dzięgielowa 27, 61-680 Poznań, Poland. E-mail addresses: alto@amu.edu.pl; marek.ewertowski@gmail.com
2. Department of Geography, Durham University, Science Laboratories, South Road, Durham, DH1 3LE, UK

[a] Corresponding author:

Aleksandra Tomczyk

Institute of Geoecology and Geoinformation

Faculty of Geographical and Geological Sciences

Adam Mickiewicz Univeristy

Ul. Dzięgielowa 27

61-680 Poznań

Poland

Tel: +48-61 829 6203

Abstract

This study applied a new method for detailed surveys of short-term dynamics in the surface of recreational trails. The main objectives of this study were: (1) to analyse the spatial aspect of surface changes in microscale; (2) to quantify precisely the short-term rate of soil loss and deposition. Measurements were taken in 12 test fields, located in two protected natural areas in the south of Poland: the Gorce National Park and Poprad Landscape Park. The measuring places were located on trails characterized by different slopes, types of vegetation, and types of use. Each of the test fields was established by four special marks, firmly dug into the ground. The use of precise elevation data provided by the electronic total station and digital elevation models (DEMs) of difference allowed us to assess the sediment budget of the surface changes.

The proposed method allowed for obtaining information not only for profile lines but also for specified areas. In such a way, the spatial and temporal dynamics of geomorphologic processes influencing the trail tread could be studied. During a two-year period (2008-2010), soil loss dominated within 10 test fields, while a predominance of deposition was recorded for the remaining two. The average net volumetric change of the trail surface varied from –0.035 m^3 m^{-2} per year to +0.005 m^3 m^{-2} per year. The short-term dynamics was high and several test fields had a positive balance (predominance of deposition) in one period and negative balance (predominance of soil loss) in the next period. Local geomorphic conditions, morphology of the trail tread and soil properties seemed to be the most important factors contributing to the relief transformation. No connection was

demonstrated between the amount of use (i.e. number of visitors) or type of use and the amount of soil loss or deposition.

Keywords: soil loss; erosion; recreational trail; Poland; GIS; DEM; trail impact; protected natural areas; footpath erosion

1. Introduction

Recreational trails are one of the key infrastructure elements which enable visitors to enjoy many of the Protected Natural Areas (PNAs) of the world. On one hand, trails provide an easy access to certain places of interest that usually are not spatially concentrated. On the other hand, they limit recreational penetration to designated routes and prevent the scattering of visitors. In this way, areas which, for environmental reasons, should be excluded from direct human impact, can be isolated.

However, the restriction of visitor traffic to certain sites (trails or campsites) brings them far more deterioration through wear and tear than the adjacent areas (e.g. Coleman, 1981; Marion et al., 1993; Hammitt and Cole, 1998; Leung and Marion, 2000; Olive and Marion, 2009). This topic has been the subject of numerous studies, with an extensive overview having been provided by several publications (e.g. Leung and Marion, 1996, 2000; Sun and Walsh, 1998; Orams, 2002; Cole, 2004; Davenport and Davenport, 2006; Pstrocka and Rak, 2006; Pickering et al., 2010; Monz et al., 2010).

Negative changes in the natural environment resulting from the use of recreational trails include: destruction of vegetation cover, changes in plant communities, weakening the vitality of plants, changing the physico-chemical properties of soils, trail braiding and broadening, the accelerated outflow of water, and the formation of muddy sections (e.g. Cole, 1993; Hammitt and Cole, 1998; Sun and Walsh, 1998; Leung and Marion, 2000).

The tread of a recreational trail, which is devoid of vegetation cover, makes it highly susceptible to the effects of geomorphological processes. Trail surfaces can be incised evenly or unevenly. Within the trail tread, a number of microforms (erosional or depositional) can be created: erosion rills and gullies, small plunge pools, deflation pavements, depositional lobes, etc. As a result of lowering the surface, the roots of trees and rocks of the substrate may be exposed. If the trail tread is so incised that it becomes difficult to use, visitors will walk alongside it, leading to an expansion of the path (Bayfield, 1971, 1973; Wimpey and Marion, 2010).

From the perspective of visitors, extensive damage to trails reduces the aesthetic value of tourist areas (Roggenbuck et al., 1993; Vaske et al., 1993). In addition, crossing deep ruts and muddy places can cause great difficulty and can even be dangerous for the safety of visitors. In turn, from the perspective of managers of PNAs, soil loss is one of the main undesirable trail impacts, because it is hard to recover a destroyed trail (Olive and Marion, 2009). Degradation of recreational trails is associated with large financial and material outlays for repairs and rehabilitation of trails.

The size of incision in recreational trails has been studied using mainly three methods. The Cross-Sectional Area (CSA) method is based on measurement along the rigid links across the trail, the depth of which is measured at regular intervals, e.g. every 10 cm (e.g. Cole, 1983; Whinam and Comfort, 1996; Hammitt and Cole, 1998; Yoda and Watanabe, 2000; Kasprzak, 2005; Wałdykowski, 2006a). Instead of fixed intervals, measurements can be carried out at characteristic points of the trail surface – as in the Variable Interval

Cross-Sectional Area (Variable CSA) method (Olive and Marion, 2009). An alternative to the two aforementioned methods is measurement only at the point of maximum incision to the trail. Depth is measured from the initial level of the surface, which is determined by pulling across the trail measuring tape, sticks or a folding staff, such a car antenna (Dixon et al., 2004; Cakir, 2005; Hawes et al., 2006).

Repeated surveys in cross-sections have been used to determine the dynamics of deepening in recreational trails and forest roads (e.g. Whinam and Comfort, 1996; Yoda and Watanabe, 2000; Wałdykowski, 2006a; Rojan, 2009). However, the location of these transects is usually limited to a few sites. Moreover, when performing a cyclic sampling, it is essential to stabilize the line profile, which is often a large problem, especially in mountainous areas where markers can be moved as a result of slope processes. Several measurement devices have been used by various authors. These include measurement tape, scaled sticks/antennas, and laser rangefinders (e.g. Cole, 1983; Yoda and Watanabe, 2000; Kasprzak, 2005; Rojan, 2009). Based on a review of the literature, repeated surveys with total station have not been used for studying soil loss at recreational trails. However, they were applied to the quantification of surface changes within other environments, for example, glacial (c.f. Kjær and Krüger, 2001; Schomacker and Kjær, 2008) and fluvial (c.f. Keim et al., 1999; Wheaton et al., 2010).

In this paper, we propose a new workflow (comprising stages of preparation, surveys, data processing and analysis) which allows us to study the spatial and temporal aspects of trail degradation. The main objectives of this study are:

- to apply a new method for studying recreational trail transformation
- to compare our method with results of the transect-based measurements
- to analyse the spatial and temporal aspect of surface changes in microscale,

- to quantify precisely the short-term rate of soil loss and deposition

2. Regional setting

The study setting for this research is two protected natural areas: the Gorce National Park (GNP) and Poprad Landscape Park (PLP), located in south-central Poland (Fig. 1).

The GNP encompasses 70.3 km^2 and receives 70,000 visitors annually (CSO, 2010). The park's main attractions are mountainous, forested landscape and glades. The park is also protected in the framework of the NATURA 2000 network. The Gorce Mountains belong to the outer Carpathians mountain system and they are composed of the Carpathian flysch. Mountain ridges stretch from the highest central point – Mount Turbacz (1,311 m a.s.l.) in many directions. The typical features are cupola-like culminations reaching an elevation of 1,100-1,300 m a.s.l., surrounded by more-or-less flat ridges, usually 300-400 m below the culminations. The mean annual precipitation varies from 700 mm in the foothills to 1,200 mm at the highest points (Miczyński, 2006). Forest is the main type of land cover (94%) (Ruciński and Tomasiewicz, 2006).

Although the GNP has official protected status, some parts of the land are privately owned (6% of the park area). Also, the Park Service conducts forestry to some extent. Hence, the network of forest roads is fairly dense in those areas. Recreational trails are for single - or multi-use. The most popular types of use at the GNP are hiking (96-98%) and cycling (2-4%) (Popko-Tomasiewicz, 2006). Some trails are also subjected to a small amount of motorized use (4-wheel vehicles), mainly related to forestry. A series of detailed maps with trail degradation has been shown in Tomczyk and Ewertowski (2011). Moreover, Tomczyk (2011) has presented a simplified theoretical model of environmental sensitivity, suggesting that some parts of the GNP are much more vulnerable to trail impact than others.

The Poprad Landscape Park (PLP) was set up in 1987 to preserve the natural and cultural sites of the Sądecczyzna region. It covers an area of 540 km^2, with a buffer zone of 250 km^2, making it one of the largest landscape parks in Poland (CSO, 2010). Field studies were conducted in the western part of the PLP, including the Radziejowa Range. The Radziejowa Range is separated from the Gorce Mountains by the Dunajec river valley, and is also composed of the Carpathian flysch, dominated by thick sandstone strata. The range has a wide ridge shape, heavily dissected from the north and south by steep river valleys (up to 500-600 m deep). The highest peak is Radziejowa (1,162 m a.s.l.). The average annual level of precipitation is from 800 mm in the valleys of the Dunajec and Poprad to 1,100 mm in parts of Radziejowa peak. The maximum daily rainfall (over 100 mm) occurs in June and July, while the lowest is in March, September and October. The period of snow cover increases with the elevation a.s.l. and averages from 63 to 154 days (Brzeźniak and Czeremda, 2000). 70% of the PLP is covered by forests. The largest and most dense forest complex covers the Radziejowa Range where it is strongly dominated by the lower forest floor, extending from 550 (600) m to 1,080 (1,100) m a.s.l.

Similar to the GNP, recreational trails in the PLP are also for single- or multi- use. There are no quantitative data about visitor numbers. However, based on some reliable observations, a qualitative classification of the use of selected trails was created. Forestry use of roads is more common in the PLP than in the GNP. However, forest roads are usually well prepared. The number of trail users in both parks is not very high compared to other mountainous protected natural areas in Poland, but their impact is relatively important.

The soils in both parks are developed mainly from the decaying flysch rocks. The soils' distribution and properties are determined mainly by the kind of bedrock and topography. The main types of soils found in the parks are: lithogenic, autogenic, semihydrogenic, hydrogenic, and alluvial. The dominant type is autogenic soils (cambisols, district cambisols, eutric cambisols) (Sikorska and Tomasiewicz, 2006). The main feature of vegetation cover is vertical zonation into the lower montane zone (from 550-600 m a.s.l. to 1,150-1,200 m) with coniferous and other trees, while the upper montane zone (from 1,150-1,200 to 1,311 m a.s.l.) is dominated by spruce forest. Two communities most common in the lower montane zone are: spruce-fir forest and mixed forest with a greater share of beech on larger areas (i.e. "Carpathian beech forest"). The Norwegian spruce association is typical for the upper montane zone. Semi-natural meadows and pastures belong to the most common non-forest vegetation: mountain meadows rich in species, species-poor plant community with mat-grass, sedge mires with cotton-grass (Medwecka-Kornaś, 2006).

3. Materials and methods

3.1. Precise measurements of elevation

To gather precise and objective elevation data, a Topcon electronic total station was used. Because of the need to maintain a high accuracy of measurement, we used a mini-prism mounted on a pole at a height of 0.2 m. This minimizes reading errors and errors resulting from deviations of the pole from upright.

3.1.1. Designation and characteristic of the test fields

Twelve segments of four trails with a similar amount of use (i.e. similar number of visitors), were selected for the precise measurement of elevation, so as to ensure representation from different types of use, slopes, exposure, and vegetation cover in the vicinity of the route. Test field dimensions were about 5 m in length and from 3 to 4 m in width - depending on the width of the trail. Each test field covered a trail tread and its surroundings.

Six test fields were installed on the trails in the GNP (Fig. 2A; Table 1), and the other six within the Radziejowa Range in the PLP (Fig. 2B, Table 1). We were not able to calculate precisely the number of visitors for each trail; however, we managed to qualitatively determine the amount of use from interviewing experienced park managers. This was done in a way similar to Olive and Marion (2009) and Wimpey and Marion (2010). All the test fields receive a similar amount of use. Based on field surveys and park managers' experience, we can estimate the daily number of visitors during high season (from the end of June to the end of August). This number varied from 10 to 140 people per day. The maximum number of visitors is usually seen during weekends (Friday to Sunday). The type of use observed on the test fields also varied. Five of them are used only by hikers, six by hikers and cyclists, and one is used also as a forest road for motorized vehicles. The mean slope of trail tread (trail grade) varied from 6 to 23^{o}. Trails mainly follow ridges, after climbing from valleys, however different aspects of trail tread and local morphological settings were also taken into account. The altitude was generally between 1,100 and 1,250 m a.s.l. Six of the test fields are located on meadows (glades) covered by European Blueberry (*vaccinium myrtillus*) communities (sometimes with the addition of spruce - *pices abies* - secondary communities). The other six are located in the forest: mixed forest of fir, spruce and beech (transitional communities *Abieti-Piceetum / Plagiotecio-Piceetum)*; mixed forest with a greater share of beech (i.e. "Carpathian beech forest", *Dentario glandulosae-Fagetum typicum*) or the Norwegian spruce association (*Plagiothecio-Piceetum*). Soils are different types of sandy loams, sandy clay loams or clay loams.

3.1.2. Establishing the benchmarks of the test fields

Four geodetic marks were mounted in the surroundings of each of the selected test fields. They are composed of a metal rod with a length of 0.5 m, which is surrounded by a plastic coating with protruding "spikes" to maintain stability. Photographs was taken and a description of the topography, indicating the distance from at least three landmarks in the vicinity (boulders, characteristic trees, etc.), was made for each of the points. It was necessary to re-establish the precise location of each test field for each measurement occasion. All the elevation measurements performed were referenced to the local refernce system (based on geodetic marks), which allowed the determination of volume changes.
(served as local points of a geodetic control network)

3.1.3. Performing the elevation measurements

Each of the measurement sessions consisted of surveys of pickets in scattered points around the test field, taking into account the characteristics of microforms. The density of surveyed points was about 80 pickets m^{-2}. Moreover, additional surveys along fixed profile lines were carried out – with 5 cm resolution. At the end of each measurement session, 30 random checkpoints were surveyed – these would be used to check the accuracy of surveys in later stages.

Five measurement sessions were carried out for each test field: August/September 2008, June 2009, August/September 2009, June 2010, August/September 2010. Photographic monitoring was also carried out at these dates. Figure 3 presents data on precipitation, together with the timing of test field surveys.

3.2. Analysis of the microrelief transformation

3.2.1. The development of digital elevation models

A total of five digital elevation models (DEMs) using inverse distance interpolation methods and cell size 1 x 1 cm were created for each test field. Checkpoints, which were not used when creating the models, were used to assess the accuracy of the DEMs. The root mean square error (RMSE) for each set of checkpoints was used to measure the accuracy of mapping relief within each model. The RMSE for the DEMs was less than 1 cm.

3.2.2. Calculation of short-term surface changes

Generated DEMs were subtracted from each other, enabling us to obtain a spatial picture of the loss or deposition of soil in each cell of the model from one survey session to another. The subtraction of DEMs from subsequent time periods (DEMs of Differences – DoDs – e.g. Wheaton et al., 2010) gave the amount of soil which was transported within the test fields and showed the spatial distribution of earth-surface changes as well.

4. Results and Discussion

Section 4 presents the results of surveys over changes in the relief of recreational trails and their surroundings. By soil loss, we understood the reduction in the volume of material, jointly caused by erosion and compaction. Prefix (G) and (P) relate to GNP and PLP respectively.

4.1. Transformation of the trail surfaces

4.1.1. An example of the results

We show the detailed results for the test field (P)ZLOMISTY as an example of the analysis that was carried out for each of the test fields. Field test (P)ZLOMISTY is located within the Radziejowa Range in the PLP (Fig. 2B) on a trail that is used heavily. The route is used by hikers and cyclists. Local settings of the trail are young spruces and dense undergrowth consisting of bilberries (Fig. 4). The width of the trail tread in September 2008 was 1.0 - 1.35 m.

The surveys were performed on: 11 SEP 2008; 25 JUN 2009; 31 AUG 2009; 02 JUL 2010 and 30 AUG 2010. The area of the test field is 10.58 m^2. On average, 96 elevation points per 1 m^2 were recorded. Figure 5 presents the digital elevation models constructed on the basis of data from subsequent survey sessions.

Changes between 11 September 2008 and 31 August 2009

The surface of the test field (P)ZLOMISTY was unevenly lowered during this period (Fig. 6). More than 135,000 cm^3 of soil was lost. The amount of loss in just two summer months (JUN09-AUG09) was about the same as in the remaining period of the year (SEP08-JUN09). Changes covered an area that made up 41% of the test field, concentrating on an area devoid of vegetation cover. The largest deepening, by up to 17.2 cm, was in plunge pools. The amount of deposition was slightly less than 5,900 cm^3 per year.

Changes between 31 August 2009 and 30 August 2010

Between 31 August 2009 and 30 August 2010, the direction of change was similar to the previous year. However, the changes were slightly larger and predominant in the period from SEP09 to JUN10, and to a lesser extent during the two summer months of JUN10-SEP10.

Soil loss occurred in 44% of the test field area. The loss of a total of 145,000 cm^3 of soil locally lowered the trail surface by 11.9 cm (Fig. 6). The amount of deposition was 19,900 cm^3 of material and the maximum increase in the elevation of the trail tread surface was 14.9 cm. Deposition concerned 6% of the test field area. The material was deposited mainly in the plunge pools.

Changes in a two-year period: between 11 September 2008 and 30 August 2010

Within two years of observation, considerable lowering of the trail surface was recorded – on the entire surface of the trail tread (57% of the test field; Fig. 6). 285,000 cm^3 of soil was lost. There was a reduction in the uneven surface of the trail, leading to the cutting of a rill parallel to the route. The study area was lowered locally by 14.0 cm.

Soil deposition took place in a limited area - less than 5% of the test field area – mainly within the plunge pools and their vicinity, where the material was then washed out (Fig. 4). Locally, the surface was raised by 5.5 cm. In the period from 2008 to 2010, there was a widening of a part of the trail by 0.4 - 0.5 m. In 2010, the maximum width of the trail within the test field reached 1.8 m.

4.1.2. Overview of the spatial aspects of changes in other test fields

The spatial distributions of transformations in the remaining test fields over the two-year period (between AUG/SEP08 and AUG/SEP10) is shown in supplementary material. The further significance of these results is discussed in sections 4.2 and 4.3. Selected profiles perpendicular to the trail tread are shown for comparison (Fig. 7).

4.2. Differentiation in the transformations of the test fields

The transformation of the trail surface within the test field occurred unevenly in time and space. The average annual change in elevation between August/September 2008 and August/September 2010 ranged from -3.7 cm for a test field (P)ROW to +0.7 cm for fields (G)KB (Fig. 8). One can distinguish the fields in which the magnitude of change in two consecutive years was similar (e.g. (P)ZLOMISTY, (P)DROGA, (G)KA02) and those where the magnitude of change in the second year far exceeded the transformations observed between August/September 2008 and August/September 2009 (e.g. (P)ROW,

(P)SKALKA, (G)KC, (G)TURBACZ, (P)MECH). (P)CZERWONY and (G)KB are cases substantially diverging from the other test fields.

Within two years, the maximum amount of local reduction of trail tread surfaces within the test field ranged from -25 cm for the field test (P)ROW to -4 cm for the test field (G)KA01 (Fig. 9). However, next to the places where there was a substantial soil loss, parts with deposition of material were observed. The maximum values of local deposition within a two-year period ranged from 3 cm for (G)KA02 and (P)DROGA to 18 cm for the test fields (G)KB.

In addition to the alteration of the relief within the test fields, changes in the width of recreational trails were also examined (Table 2). Among these, we can distinguish those whose width in a two-year period:

- has not changed – (G)KB, (G)KC, (G)LAS, (P)SKALKA;
- has increased slightly (to 0.25 m) – (P)MECH, (P)ROW;
- has increased considerably (to at least 0.5 m) – (G)KA01, (G)KA02, (G)TURBACZ, (P)ZLOMISTY, (P)CZERWONY, (P)DROGA.

The examined test fields differ in dimensions. To compare them with each other, we used standardized data - the total change in volume of the soil (the loss of soil + deposition) in a given field divided by its surface (Table 3). The analyzed test fields are characterized by great diversity. There were test fields in which the soil loss in two years was greater than 25,000 cm^3 m^{-2} (0,025 m^3 m^{-2}). There were also those where the volume of material removed and deposited was either similar or the deposition slightly dominated (Fig. 10). (P)CZERWONY was the only field where in two consecutive years, the direction of change was radically different; in the first year a large quantity of material was deposited, in the second year significant loss of material was recorded. The examined test fields were divided into four groups depending on the amount of soil loss or deposition (Fig. 10, sec. 4.2.1. - 4.2.4.).

4.2.1. A – Test fields with a substantial soil loss

For three test fields, the amount of soil removed within two years from an area of 1 m^2 exceeded 25,000 cm^3, reaching as much as 37,000 cm^3 m^{-2}. For fields (P)ROW and (P)SKALKA, major changes occurred in the period August/September 2009 to August/September 2010, while for the field (P)ZLOMISTY changes in the two consecutive years were similar. The main factors contributing to the substantial soil loss are the following:

- Test fields (P)ROW and (P)ZLOMISTY are located in a specific geomorphological situation, which is probably the cause of such significant erosion. Analysis of their location on the topographic map shows that these two fields are located near a ridge (watershed lines). They are situated near the pass at the foot of the Złomisty Peak. The trail, which runs from the summit of Złomisty Peak to both of these fields, is steep and characterized by a relatively small but distinct incision (up to 30 cm) in relation to the land surface next to it and has no drainage facilities. All of this means that during heavy rainfall, it turns into a trough of a rushing stream. Large quantities of water flowing down to the test fields cause erosion of the material, which earlier under the pressure of visitors, had been loosened and prepared for transportation. An important factor is also the soil, which is made up of a high content of sand, and the very uneven surface of the trail tread, thereby contributing to the destruction and loss of soil particles via trampling by hiking boots.

- Test field (P)SKALKA is located on a very steep segment of the trail (at 23^o). Moreover, the position at the upper part of the local hillside; compact clay soil (which becomes malleable after rain and susceptible to compaction and displacement); uneven trail surface; and the presence of rock fragments (which were removed from the ground by trampling) - all contributed to significant erosion.

4.2.2. B - Test fields with a moderate soil loss

On the test fields (G)KC, (G)TURBACZ, (P)DROGA, (G)KA02, (P)MECH, erosion was considerably greater than deposition, and the volume of soil loss for four of them ranged from 10,000 $cm^3\ m^{-2}$ to 20,000 $cm^3\ m^{-2}$. On the fields (G)KC and (G)TURBACZ, soil loss in the second year of measurement (August/September 2009 - August/September 2010) was significantly greater than a year earlier. On the fields (P)DROGA and (G)KA02, the volumes of soil loss in both years were similar. Somewhat different surface modifications were observed for the test field (P)MECH: in the first year of measuring, a small amount of deposition was recorded, while in another, a distinct soil loss happened. The factors influencing the prevalence of soil loss within these fields are the following:

- Field (G)KC is located on the upper part of a steep slope (also the trail grade is high – 16^o). A rill (10-20 cm deep) in the trail tread caused channelling of rainwater and erosion; moreover, banks of the rill were cut and trampled upon by hikers and cyclists.

- Field (G)TURBACZ is located on a local recess of the hill-slope, which causes significant trail grade (16^o). Also, the presence of fragments of rock in the ground that are removed by pressure from shoes plus the channelling of water in two rills favour erosion.
- Field (G)KA02 is located on a local recess of slope (gradient 8^o), which is susceptible to cutting and trampling upon by boots or bicycle tires. Moreover, small convex morphological features of trail tread, partially covered with plants, are susceptible to shear.
- Field (P)DROGA - deepening and widening of erosional furrows running parallel to the trail tread cause canalization of the rainwater flow from the upper part of the trail. Moreover, this section of trail is also used by motorized vehicles doing forestry work.
- Field (P)MECH is overgrown with tree roots, which to some extent strengthen the substrate. The predominance of deposition in the first year corresponds to the supply of material from the upper part of the slope, which was deposited on a small flattened, upper part of the test field. In addition, there is a rill located in the middle of the trail, which is uncomfortable to walk on, so tourists tended to move along the trailside, trampling the vegetation cover. This contributed to an increase in soil loss during the second year of measurement.

4.2.3. C – Test fields with low relief transformation

Two of the surveyed fields showed only a minor degree of surface transformation. The total change in volume did not exceed 2,500 $cm^3\ m^{-2}$ in two years. (G)KA01 test field is located in a meadow in the section of the trail with a slope of 8^o. The test field (G)LAS is located in the forest, and is inclined at an angle of 10^o. These two fields receive a similar number of visitors to the other ones (Table 1). However, they are characterized by low transformation of relief, which is caused mainly by the following factors:

- Field (G)KA01 - the presence of several parallel tracks separated by narrow strips of vegetation that slow down the processes of erosion. Moreover, the sizable width of the trail favours the dispersion of visitors, which causes the creation of additional paths rather than an accelerated soil loss.
- Field (G)LAS - the presence of large quantities of fragments of rock in the ground naturally leads to a strengthening of the trail tread.

4.2.4. D – Test fields on which unusual phenomena occurred

Within two test fields, unusual phenomena were observed, which largely affected the normal balance of surface changes. The featured test fields are located in forest, on trails with slopes of 7^o to 9^o. Events that affected the size of the transformation in each of the fields may be mentioned as follows:

- Field (P)CZERWONY - a tree fell over at the centre of the field, which resulted in a significant deposition of material during the first year of measurement. During the second year of measurement (after the tree was removed), previously deposited material was compacted and eroded.
- Field (G)KB - it is located in a deep erosional gully (about 1 m deep). In the past, it was a place of significant erosion processes. Now, the gully is more developed; at its base there are numerous rock fragments that can reduce the velocity of the flowing water and contribute to the deposition of material. Deposition was not only of fine material, but included a few large rock fragments. In addition, a big

spruce fell to the trailside, and some of its needles were deposited within the borders of the test field.

4.3. Factors contributing to the transformation of recreational trails' surface

Sections of the studied trails were located in slightly different managerial and environmental conditions (Table 1). In this section, we provide our interpretation over the influence of selected factors on the dynamics of soil loss.

The amount of use was similar on all of the test fields (Table 1). Despite this, the amount of soil loss varied significantly (see section 4.2.), which confirms some other observations suggesting that the dynamic of soil loss or deposition is independent of visitor numbers (e.g. Cole, 1983; Farrell and Marion, 2002; Dixon et al., 2004; Olive and Marion, 2009).

For the studied test fields there is no observable relationship between the type of use and amount of soil erosion (Fig. 11A). However, the type of use has mainly influenced the way in which direct human impact occurs on trails. Hikers trampled on vegetation and caused soil compaction, especially in flat segments of trail tread. However, in muddy conditions (especially in soils containing lots of clay) or for uneven trail tread containing many sharp microforms, hikers' boots can slide and relocate soil particles. Moreover, trekking sticks contribute to loosening of the soil, and in this way also prepare material to be transported. The influence of bikers is slightly different. Tyres generate higher pressure on the soil than boots, and often, especially on steep sections, cause soil to loosen and relocate. It suggests that park managers can effectively control soil loss by choosing the appropriate type of use rather than limiting the number of visitors.

Trail slopes (i.e. grade of the test fields) show no clear connection to the amount of soil loss (Fig. 11B). Generally, it is true that a a gradient of the trail of more than 15^{o} favours soil loss (cf. Hesselbarth et al., 2007; Olive and Marion, 2009). On the other hand, fields with gentler trail gradient (6 to 10^{o}) are characterized by a rather variable volume of displaced material and are present in all four distinguished groups. Comparing the amount of soil loss with several other factors, it is hard to see any regularity (Fig. 11C, D).

In our opinion, soil properties (Fig. 11E) (cf. McHugh, 2007), morphology of the trails (Fig. 11F) (cf. Bryan, 1977; Cakir, 2005) and local geomorphological conditions (especially slope length above the test field) are factors which have the greatest influence on the amount of soil loss. These three factors are often linked together. The examined sections of the trails, whose surfaces are overgrown by tree roots - (P)CZERWONY - or are covered with numerous rock fragments - (G)LAS, (G)KB - show the least transformation. Roots act as sediment traps and cause the deposition of fine grained material. Similarly, rocks can also protect the soil against excessive water erosion. When the trail tread is even, the pressure of hikers' boots causes soil compaction, which makes water erosion difficult. An uneven trail tread can affect trail development in two ways. First, when the trail is hard to walk on, visitors start to bypass the deteriorated section which leads to trail widening. Moreover, a rough trail tread also favours significant soil erosion - (P)SKALKA, (P)ROW, (P)ZLOMISTY. For an uneven tread, hikers destroy microforms and cause soil to loosen, and in such a way facilitate water erosion and transport. Accelerated soil erosion is also facilitated by location in the bottom part of the local slope - (P)ZLOMISTY, (P)ROW. In such cases, the volume of flowing water after rain is high, which provides greater erosional and transportational power. The effect of soil is also variable and depends on other factors. A clay soil texture is homogeneous and compacts tightly which ensures that in dry conditions it is more resistant to trampling. However, in the case of rain, such textures cause greater runoff on steep sections and creation of muddy puddles on gentle sections. Moreover, in humid conditions, boots and tyres easily slide and relocate soil particles. Soils with coarser grains and generally a wider range of particle sizes are more prone to soil erosion. However, in case of light rains, due to greater permeability, they are less prone to creation of muddiness.

Analyzing the temporal dynamics of transformation, it can be seen that generally surfaces of the test fields (except for two cases) are being lowered. There is a group of test fields within which larger transformations are taking place during summer - (P)ROW, (P)ZLOMISTY, (G)TURBACZ. The direct reason for the greater soil loss during the second year of measurement (between August/September 2009 and August/September 2010) can be related to meteorological conditions. During May 2010, there were heavy rainfalls (Fig. 3) – the overall amount of precipitation was 326 mm and, which is also important, the rain was very intense (6.5 hours of rain with the intensity higher than 25 mm h^{-1}) and long-lasting (116 hours of rain during the month). Hence, the major transformations recorded in the second season of research could be the result of rain effects (both duration and intensity).

Recreational trails and forest roads can be equated with periodic flows in the context of soil loss, transport and deposition (e.g. Froelich and Słupik, 1986). In such a context, trail dynamics should be investigated in terms of sedimentary balance. Three sections can be distinguished on the trail: erosional, transportational, and depositional. Localisation of these three sections varies through space and time. It means that the same section of trail can be a source of material (i.e. erosional section) or the place for material to be deposited (i.e. depositional section). Switching between these sections, and consequently between dominating processes, depends on the local geomorphic properties and meteorological seasons and conditions.

4.4. Comparison with transect-based measurements

This study applied a new workflow for assessing the dynamics of transformation of recreational trails. It incorporates precise topographic surveys and digital elevation modelling to quantify soil loss or deposition from specified areas, and not only profiles (transects). The proposed method was applied to 12 test fields in two PNAs and provided an efficient procedure for assessing soil dynamics on recreational trails.

For ten of the test fields, we compared the volume of soil loss/deposition obtained from area-based measurements with results from the transect-based measurements. Volumes of soil loss/deposition calculated from transect-based measurements were from 4% to 183% of the volumes calculated from area-based measurements (Fig. 12). Moreover, area-based measurements within test fields reflect very well the spatial variation in micro-topographic transformation of recreational trails, which cannot be captured using transect-based measurements alone. Even the location of transects, in close proximity to each other (profile lines for most of the test fields were located at intervals of about 1 m), allows only for an approximate determination of spatial and temporal trends. Moreover, the main advantage of the proposed method is that from the DEM or DOD we can generate as many cross-sections as desired.

In comparison to previous studies employing measurements only in profile lines (Cole, 1983; Whinam and Comfort, 1996; Hammitt and Cole, 1998; Yoda and Watanabe, 2000;

Kasprzak, 2005; Wałdykowski, 2006a; Olive and Marion, 2009), our method made it possible to obtain and analyse precise information about the spatial and temporal dynamics of soil loss or deposition. In this way, geomorphic processes transforming recreational trails can be studied in detail. Various standardized measures (mean soil loss/deposition, volume per square metre, percentage changes) can also be derived for making objective comparison of soil loss across use-types, trails, morphological settings, or protected areas.

4.5. Comparison with other areas

We are aware of no other studies that have used area-based methods for calculating the volume of soil loss/deposition, so that direct comparisons to other protected areas are not possible. However, to partially evaluate our results, we compared our transect-based measurements for GNP and PPK with transect-based measurements obtained in other studies for several mountain ranges with similar climatic conditions in Central Europe (Table 4). As both sampling and time covered differed, the mean value of surface lowering or raising was used for comparison.

Results of this study indicate that the mean value for the deepening of cross-sections located in the GNP within a two-year period was 1.6 cm, and for PLP 2.5 cm. The mean dynamics of 32 cross-sections were similar to observations by Słupik and Froehlich (1986) for 30 cross-sections installed on forest roads in Beskid Sadecki Mts., i.e. 1.7 cm. The values obtained for the studied segments of trails in GNP and PLP are consistent with the mean rate of deepening on the trail in Karkonosze Mts., where Parzóch (2001) noted 1 to 2 cm of deepening per year. A similar order of magnitude surface lowering was estimated by Kasprzak (2005) for erosion cuts on hiking trails in Karkonosze: 1.1 cm (range of changes from 0.2 cm to 2.1 cm). However, it should be noted that these values were averaged over periods of several years. Significantly higher values for the average lowering of the surface of recreational trail for the Pilsko region were presented by Łajczak (1996). Within the eight months of research (from May to November 1993), the analyzed trails deepened on average by 5 cm. Measurements on the intensively used forest roads for the area of Turbacz in Gorce Mts. (Wałdykowski, 2006a, b) and the Slovak Tatra Mts (Rojan, 2009) showed a very high rate of surface lowering - up to 20 cm. These values are much higher than those obtained in this study, which probably results from the location of these cross sections in segments not used extensively by motor vehicles.

6. Conclusions

The main conclusions that can be drawn from this study are the following:

- A key objective of this research is the development and application of a more precise method for calculating soil loss/deposition and assessing the dynamics of surface transformation in recreational trails. Developed workflow incorporates precise topographic surveys and digital elevation modelling to quantify soil loss or deposition from specified areas, and not only profiles. Digital elevation models of differences (DODs) were found to provide a useful representation of microrelief features and their transformations. The proposed method was applied to 12 test fields in two PNAs and provided an efficient procedure for assessing soil dynamics on recreational trails. Such data support enhances the understanding of trail degradation. In comparison with transect-based measurements, the main advantages are twofold; we obtain spatial distribution of topographic changes, and that from the DEMs or DODs as many cross-sections as desired can be generated.

- The magnitude of recreational trail transformation for the studied PNAs can be quite considerable. The amount of soil loss was even up to 37,000 $cm^3 m^{-2}$ (0.037 $m^3 m^{-2}$) per two-year period. This amount of soil loss may be visualized as the equivalent of a half-full average garden wheelbarrow removed from each square metre.
- The spatial and temporal distributions of soil loss or deposition are diverse and for the most part related to local geomorphic conditions (e.g. location within specified part of slope, drainage condition). Moreover, those most prone to significant soil erosion are trails with an uneven tread surface. It is also important that soil loss is not simply linearly-related to the amount of use (i.e. number of visitors) – and for the same number of visitors the mean amount of soil loss/deposition per square metre per year can vary even up to 400%.
- Soil deposition occurs primarily due to the presence of obstacles on the trail tread (i.e. tree roots, fragments of rocks, etc.). It suggests that to slow down the rate of soil erosion from steep sections of the trails, the most effective tool is to construct drainage features (for example berms) perpendicular to the trails.
- The proposed workflow of the survey can be applied to determine accurately the dynamics of transformation in trails and to assess their spatial and temporal variations. In this way, it can be useful for monitoring changes of magnitude of soil loss or deposition, so that managers of protected areas can respond effectively to deterioration in the environment.

Acknowledgements

This manuscript greatly benefited from suggestions and comments from Ian Evans. The work was supported by the Polish Ministry of Science and Higher Education, project: N N305 362533 and Polish National Science Centre project: N N305 066940. The Marek Ewertowski fellowship at Durham was founded by the Polish Ministry of Science and Higher Education in the frame of the "Mobility Plus" programme. We are grateful to Margaret O'Donnell for language proofreading of the manuscript. The manuscript benefitted considerably from the incisive comments of the reviewers, which were much appreciated.

References

Bayfield, N.G., 1971. A simple method for detecting variations in walker pressure laterally across paths. Journal of Applied Ecology 8, 533-535.

Bayfield, N.G., 1973. Use and deterioration of some Scottish hill paths. Journal of Applied Ecology 10, 635-644.

Bryan, R. B., 1977. The influence of soil properties on degradation of mountain hiking trails at Grövelsjön. Geografiska Annaler. Series A, Physical Geography 59, 49-65.

Brzeźniak, E., Czereda, A., 2000. Klimat. In: Staszkiewicz, J. (Ed.), Przyroda Popradzkiego Parku Krajobrazowego, PPK, Stary Sącz, pp. 37-46.

Cakir, J.F. 2005. Modeling Trail Degradation Using Field and GIS Methodologies: A Comparative Study. University of North Carolina State University, PhD Thesis, 166 pp.

Central Statistical Office (CSO), 2010. Environment statistical information and elaborations. Warszawa, Poland., Central Statistical Office, 609 pp.

Cole, D.N., 1983. Assessing and monitoring backcountry trail conditions. Research Paper INT-303. Ogden, UT: United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, 10 pp.

Cole, D.N., 1993. Minimizing conflict between recreation and nature conservation. In: : Smith, D. S.; Hellmund, P. C. (Eds.), Ecology of greenways: design and function of linear conservation areas. University of Minnesota Press, Minneapolis, MN, pp. 105-122.

Cole, D.N., 2004. Environmental impacts of outdoor recreation in wildlands. In: Manfredo, M.J., Vaske, J.J., Bruyere, B.L., Field, D.R., Brown, P.J. (Eds.), Society and Resource Management: A Summary of Knowledge, Modern Litho, Jefferson City, MO, pp. 107-116.

Coleman, R., 1981. Footpath erosion in the English Lake District. Applied Geography 1, 121-131.

Davenport, J., Davenport, J. L., 2006. The impact of tourism and personal leisure transport on coastal environments: A review. Estuarine, Coastal and Shelf Science 67, 280-292.

Dixon, G., Hawes, M., McPherson, G., 2004. Monitoring and modelling walking track impacts in the Tasmanian Wilderness World Heritage Area, Australia. Journal of Environmental Management 71, 305-320.

Farrell, T.A., Marion, J.L., 2002. Trail impacts and trail impact management related to visitation at Torres del Paine National Park, Chile. Leisure/Loisir 26, 31-59.

Froehlich, W., Słupik J., 1986. Rola dróg w kształtowaniu spływu i erozji w karpackich zlewniach fliszowych. Przegląd Geograficzny 58, 67-87.

Hammitt, W.E., Cole, D.N., 1998. Wildland recreation: ecology and management, Wiley, New York, 376 pp.

Hawes, M., Candy S., Dixon G., 2006. A method for surveying the condition of extensive walking track systems. Landscape and urban planning 78, 275-287.

Hesselbarth, W., Vachowski, B., Davies, M. 2007. Trail construction and maintenance notebook 2007 edition. USDA Forest Service, Missoula Technology and Development Center, Missoula, MT, 178 pp.

Kasprzak, M., 2005. Tempo degradacji powierzchni dróg and sciezek turystycznych w Karkonoszach Wschodnich. Opera Corcontica 41, 17-30.

Keim, R.F., Skaugset, A.E., Bateman, D.S., 1999. Digital terrain modeling of small stream channels with a total-station theodolite. Advances in Water Resources 23, 41-48.

Kjær, K.H., Krüger, J., 2001. The final phase of dead-ice moraine development: processes and sediment architecture, Kötlujökull, Iceland. Sedimentology 48, 935-952.

Łajczak A., 1996. Wpływ narciarstwa i turystyki pieszej na erozje gleby w obszarze podszczytowym Pilska. In: Łajczak, A., Michalik, S., Witkowski, Z. (Eds.), Wpływ narciarstwa i turystyki pieszej na przyrode masywu Pilska. Studia Naturae, Seria A, PAN 41, 131–159.

Leung, Y.F., Marion, J.L., 1996. Trail degradation as influenced by environmental factors: A state-of-the-knowledge review. Journal of Soil and Water Conservation 51, 130-136.

Leung, Y.F., Marion, J.L. 2000. Recreation impacts and management in wilderness: A state-of-knowledge review. In: Cole, D.N., McCool, S.F., Borrie, W.T., O'Loughlin, J., (Eds.), Wilderness science in a time of change conference. Proceedings RMRS-P-15-Vol-5. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 23-48.

Marion, J.L., Roggenbuck, J.W. , Manning R.E., 1993. Problems and practices in backcountry recreation management: a survey of National Park Service Managers. Natural Resources Report NPS/NRVT/NRR-93/12. USDI National Park Service, Denver, CO., 48 pp.

McHugh, M., 2007. Short-term changes in upland soil erosion in England and Wales: 1999 to 2002. Geomorphology 86, 204-213.

Medwecka-Kornaś, A., 2006. Szata roślinna. In: Różański, W. (Ed.), Gorczański Park Narodowy - 25 lat ochrony dziedzictwa przyrodniczego and kulturowego Gorców [The Gorce National Park - 25 years of nature and cultural heritage protection in the Gorce Mts], GPN, Poręba Wielka, pp. 65-84.

Miczyński, J., 2006. Klimat. In: Różański, W. (Ed.), Gorczański Park Narodowy - 25 lat ochrony dziedzictwa przyrodniczego and kulturowego Gorców [The Gorce National Park

- 25 years of nature and cultural heritage protection in the Gorce Mts], GPN, Poręba Wielka, pp. 33-57.

Monz, C.A., Cole, D.N., Leung, Y.F., Marion, J.L., 2010. Sustaining visitor use in protected areas: future opportunities in recreation ecology research based on the USA experience. Environmental Management 45, 551-562.

Olive, N.D., Marion, J.L., 2009. The influence of use-related, environmental, and managerial factors on soil loss from recreational trails. Journal of Environmental Management 90, 1483-1493.

Orams, M.B., 2002, Feeding wildlife as a tourism attraction: a review of issues and impacts. Tourism Management 23, 281-293.

Parzóch K., 2001. Erozja rynnowa na stokach wylesionych w Karkonoszach. Zeszyty Studiów Zachodnich 4, 171–180.

Pickering, C.M., Hill, W., Newsome, D. Leung, Y.-F., 2010, Comparing hiking, mountain biking and horse riding impacts on vegetation and soils in Australia and the United States of America. Journal of Environmental Management 91, 551-562,

Popko-Tomasiewicz, K., 2006. Turystyka. In: Różański, W. (Ed.), Gorczański Park Narodowy - 25 lat ochrony dziedzictwa przyrodniczego and kulturowego Gorców [The Gorce National Park - 25 years of nature and cultural heritage protection in the Gorce Mts], GPN, Poręba Wielka, pp. 237-243.

Pstrocka, M., Rak G., 2006. Wpływ wybranych form turystyki na środowisko przyrodnicze – przegląd literatury polskiej and zagranicznej. Problemy Turystyki 29, 59-72.

Roggenbuck, J.W., Williams, D.R., Watson, A.E., 1993. Defining acceptable conditions in wilderness. Environmental Management 17, 187-197.

Rojan, E., 2009. Morphological changes within road incision forms in the blowdown area in the Slovak Tatra Mountains after termination of intensive forest works. Landform Analysis 10, 117-123.

Ruciński, M., Tomasiewicz, J., 2006. Gorczański Park Narodowy w liczbach. In: Różański, W. (Ed.), Gorczański Park Narodowy - 25 lat ochrony dziedzictwa przyrodniczego and kulturowego Gorców [The Gorce National Park - 25 years of nature and cultural heritage protection in the Gorce Mts], GPN, Poręba Wielka, pp. 33-57.

Schomacker, A., Kjær, K.H., 2008. Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier Holmströmbreen, Svalbard. Boreas 37, 211-225.

Sikorska, E., Tomasiewicz, J., 2006. Gleby. In: Różański, W. (Ed.), Gorczański Park Narodowy - 25 lat ochrony dziedzictwa przyrodniczego and kulturowego Gorców [The Gorce National Park - 25 years of nature and cultural heritage protection in the Gorce Mts], GPN, Poręba Wielka, pp. 50-54.

Sun, D., Walsh D., 1998. Review of studies on environmental impacts of recreation and tourism in Australia. Journal of Environmental Management 53, 323-338.

Tomczyk, A.M., 2011. A GIS assessment and modelling of environmental sensitivity of recreational trails: The case of Gorce National Park, Poland. Applied Geography 31, 339-351.

Tomczyk, A.M., Ewertowski, M., 2011. Degradation of recreational trails, Gorce National Park, Poland. Journal of Maps 2011, 507-518, 10.4113/jom.2011.1195.

Vaske, J.J., Donnelly, M.P., Shelby B., 1993. Establishing management standards: Selected examples of the normative approach. Environmental Management 17, 629-643.

Wałdykowski, P., 2006a. Wpływ dróg górskich na dynamikę procesów morfogenetycznych w rejonie Turbacza. Ochrona Beskidów Zachodnich 1, 67-79.

Wałdykowski P., 2006b. Rzeźbotwórcze skutki rozwoju sieci dróg gruntowych w Beskidach na przykładzie Gorców. In: Latocha, A., Traczyk A. (Eds.), Zapis działalności człowieka w środowisku przyrodniczym. Metody badan i studia przypadków, GAJT, Wrocław, pp. 64–76.

Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A., 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surface Processes and Landforms 35, 136-156.

Whinam, J., Comfort M., 1996. The impact of commercial horse riding on sub-alpine environments at Cradle Mountain, Tasmania, Australia. Journal of Environmental Management 47, 61-70.

Wimpey, J.F., Marion, J.L., 2010. The influence of use, environmental and managerial factors on the width of recreational trails. Journal of environmental management 91, 2028-2037.

Yoda, A., Watanabe, T., 2000. Erosion of mountain hiking trail over a seven-year period in Daisetsuzan National Park, Central Hokkaido, Japan. In: Proceedings of the National Wilderness Research Conference, RMRS-P-15-VOL-5. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, pp. 1172-1178.

List of figures

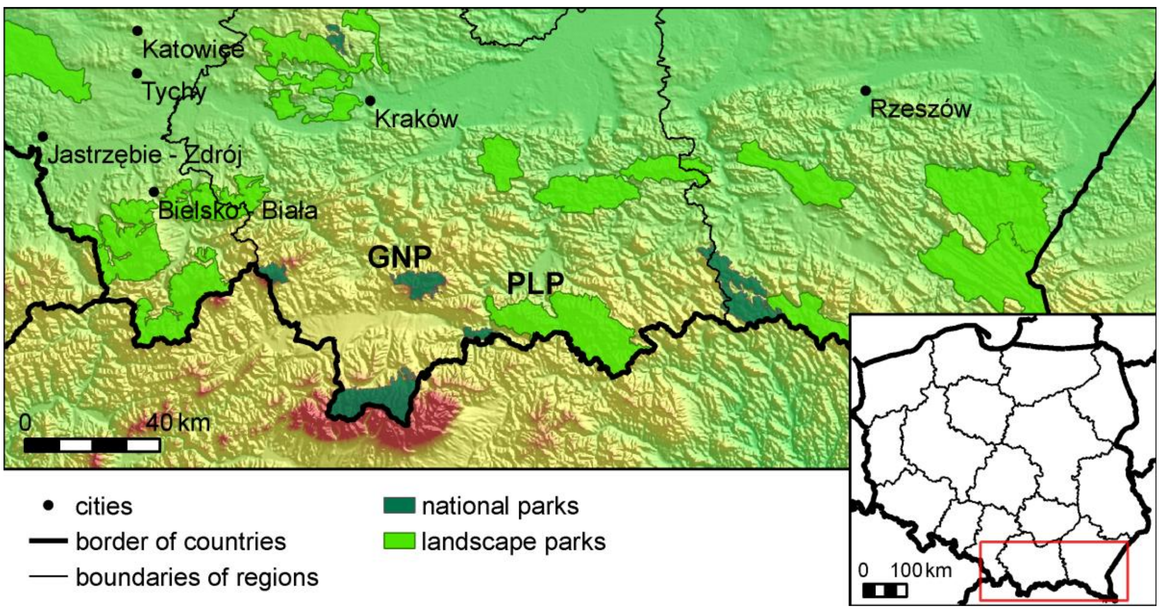

Fig. 1. Location of the study area, modified from Tomczyk (2011), Applied Geography Vol. 31, Copyright, permission from Elsevier.

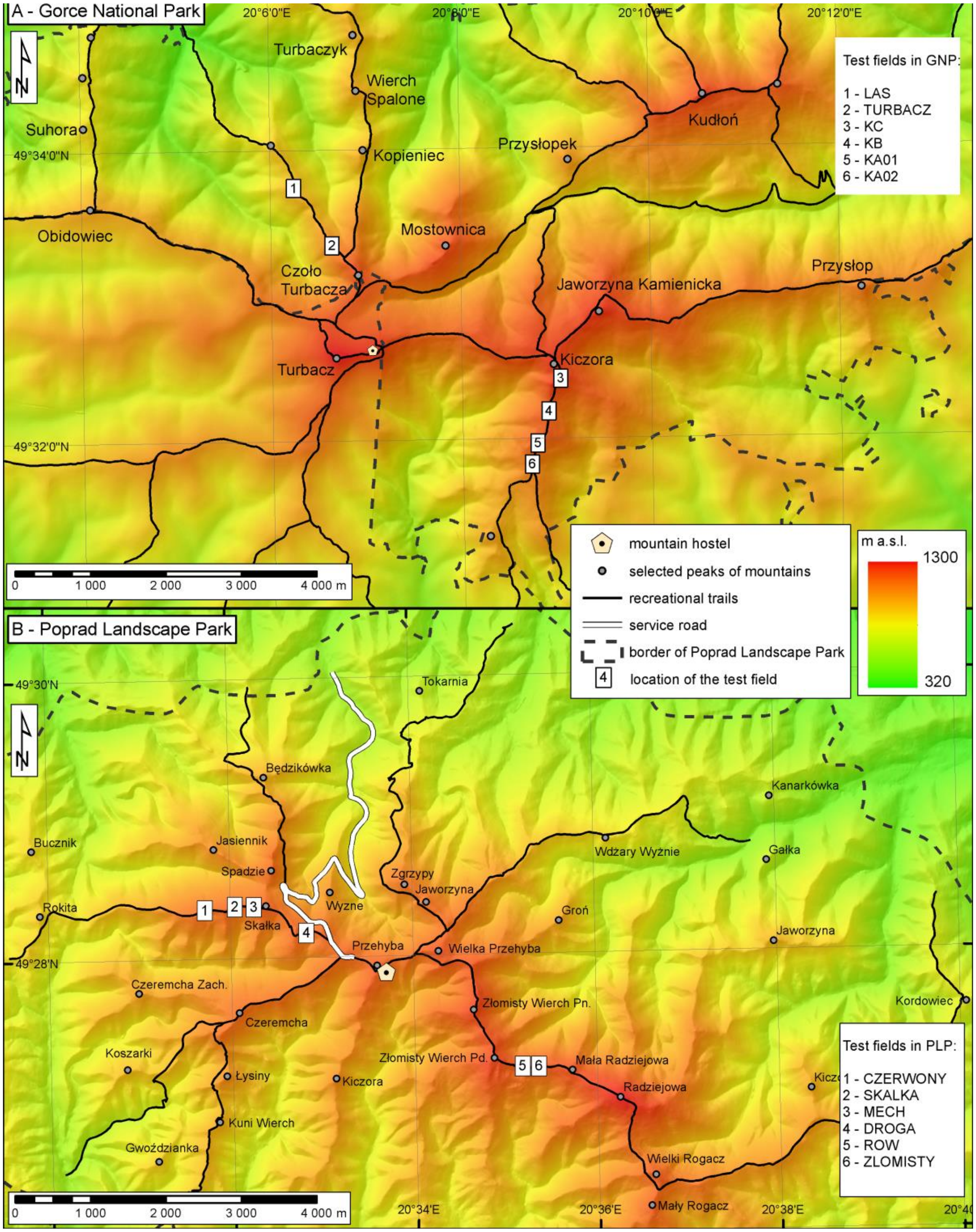

Fig. 2. Location of the test fields. A - Gorce National Park, Poland; B – Poprad Landscape Park, Poland.

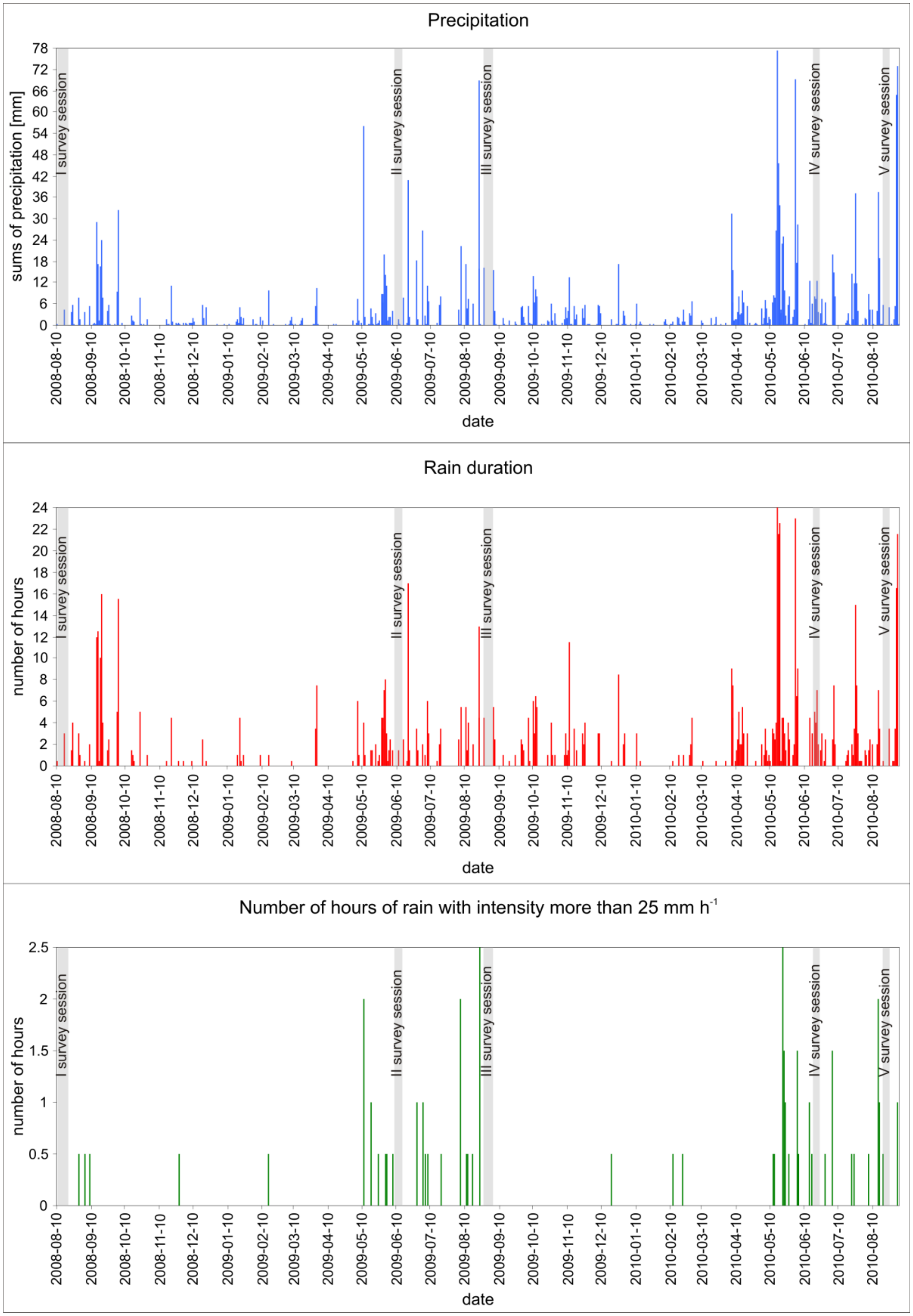

Fig. 3. Sums of precipitation, rain duration, and intensity of 25 mm h^{-1} of rain. Survey dates are marked in grey (data from the meteorological station at Suhora)

Fig. 4. The state of the trail and its surroundings for the selected dates – test field (P)ZLOMISTY. Notice the small plunge pools filled in with material and subsequently eroded

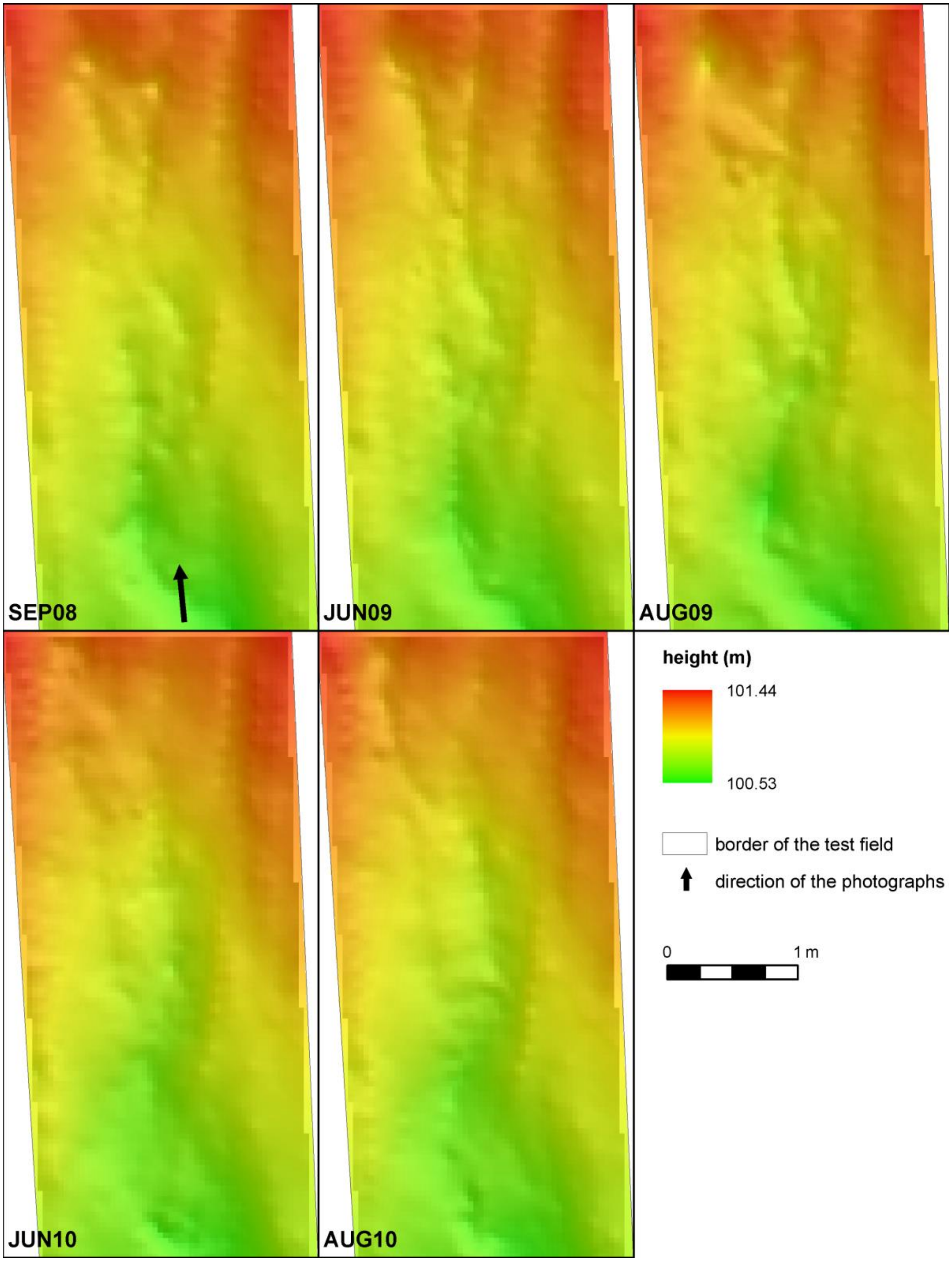

Fig. 5. Digital elevation models of the test field (P)ZLOMISTY

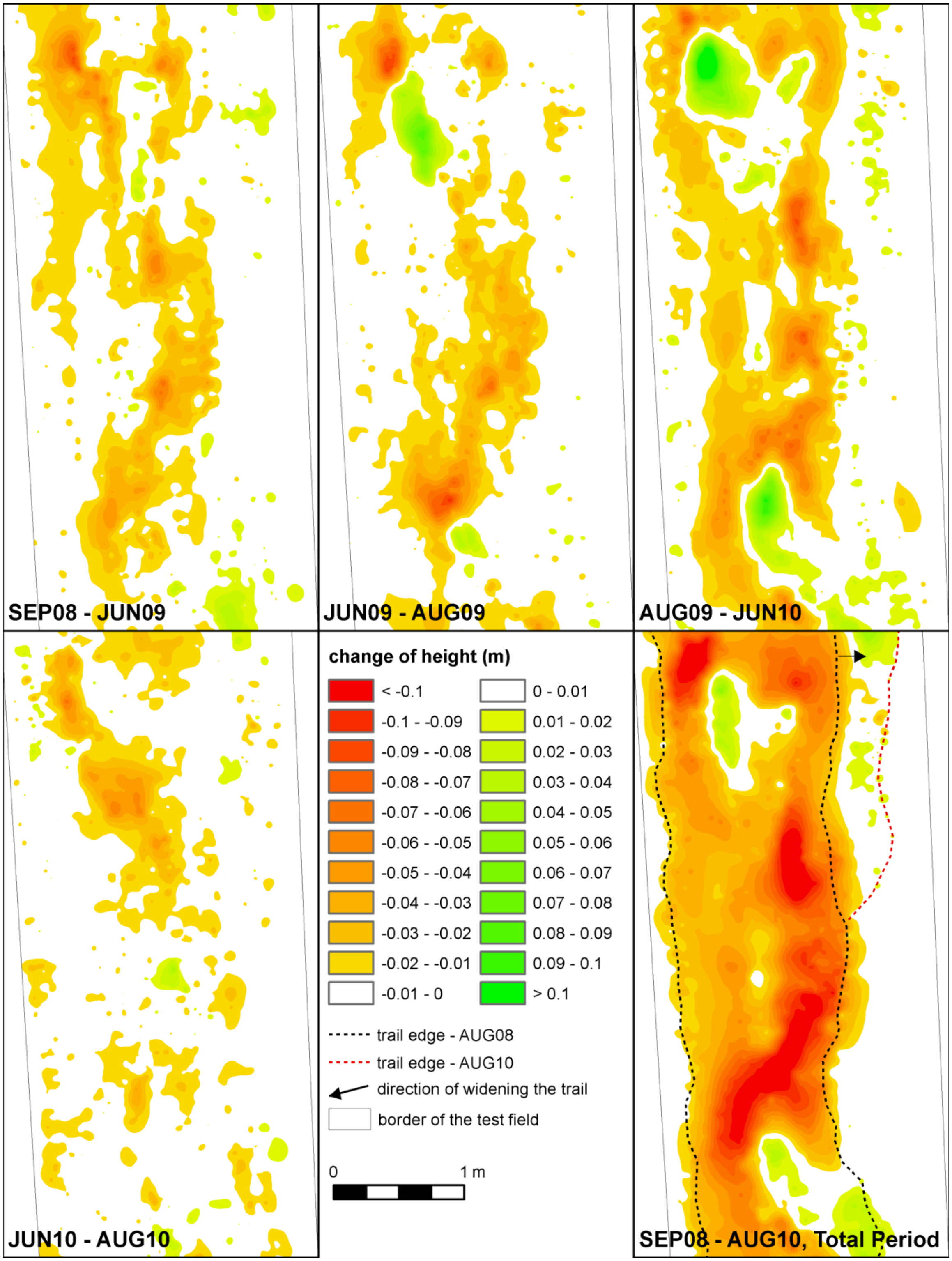

Fig. 6. DEMs of Differences (DODs) showing the spatial distribution of surface transformations – test field (P)ZLOMISTY

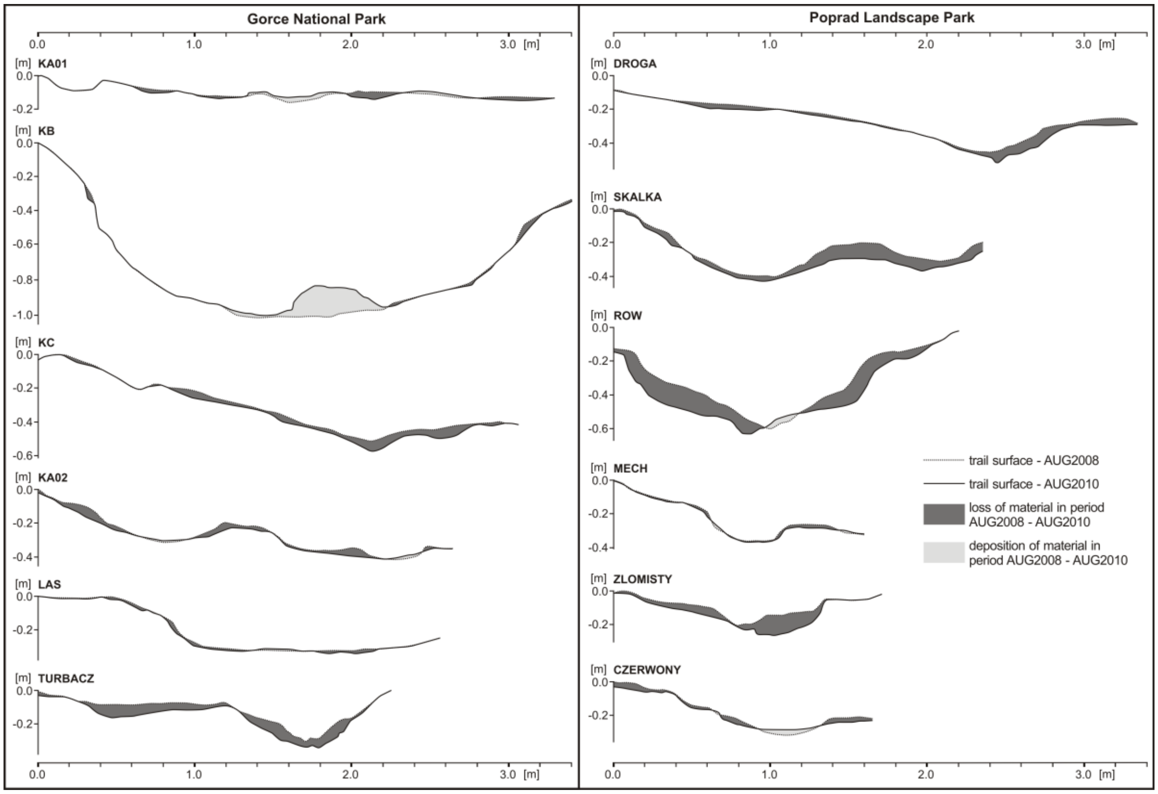

Fig. 7. Examples of elevation profiles perpendicular to the trail tread. Changes in elevation between August/September 2008 and August/September 2010 are marked in dark (soil loss) or light grey (deposition)

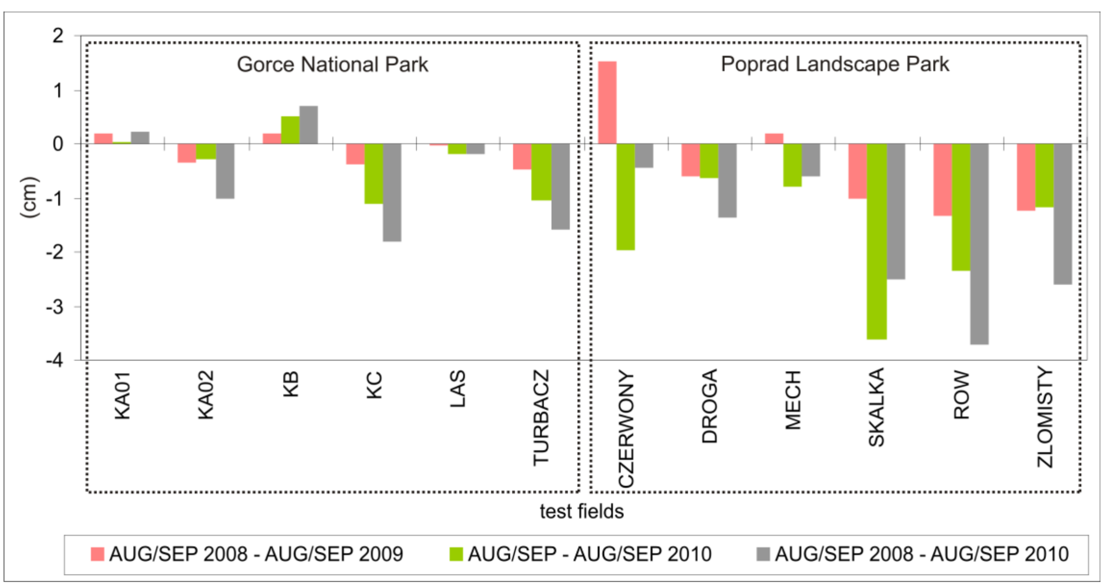

Fig. 8. Mean changes in surface elevation in test fields located in the GNP and PLP

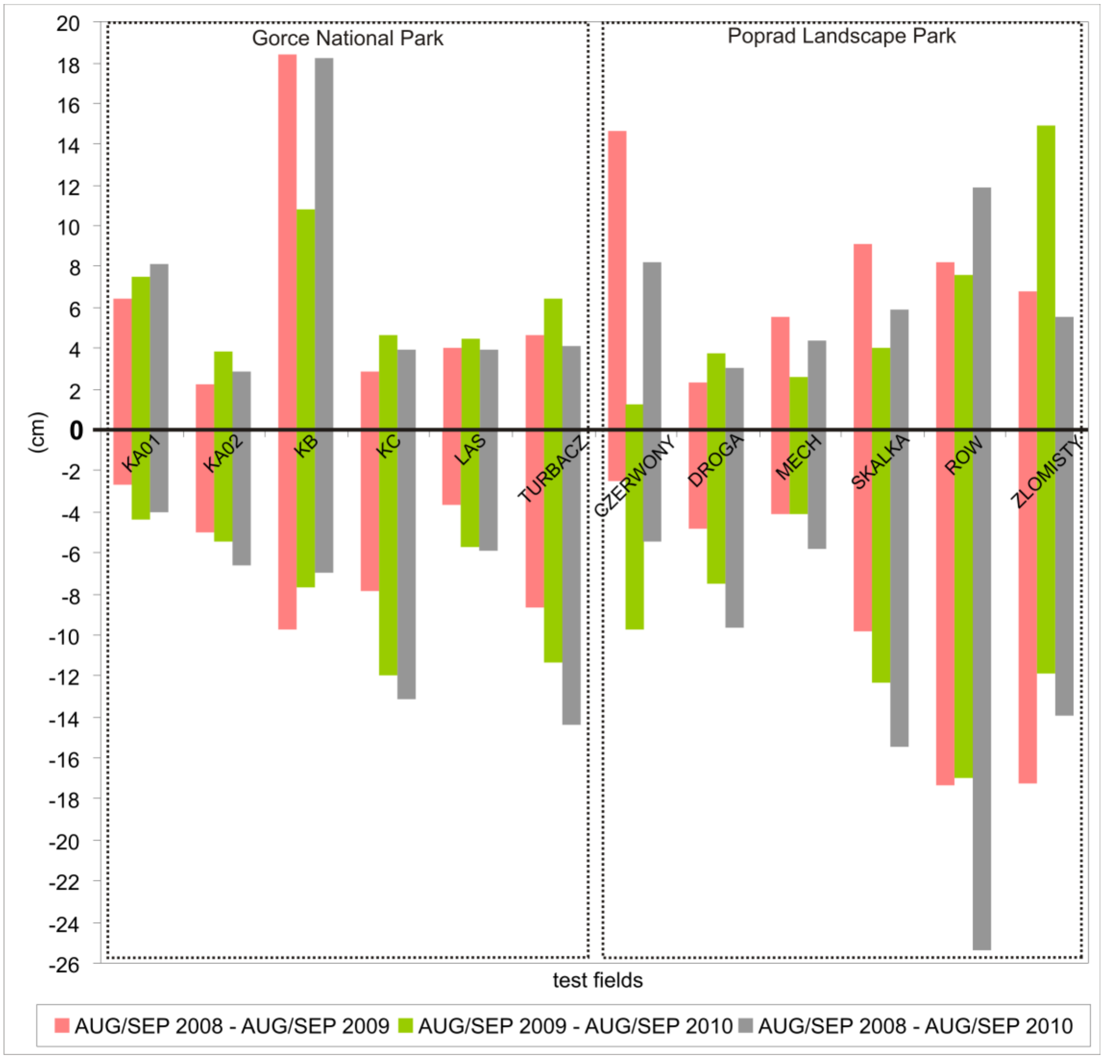

Fig. 9. Local maximum changes (lowering and raising) in the elevation of the recreational trails' surface in test fields located in the GNP and PLP

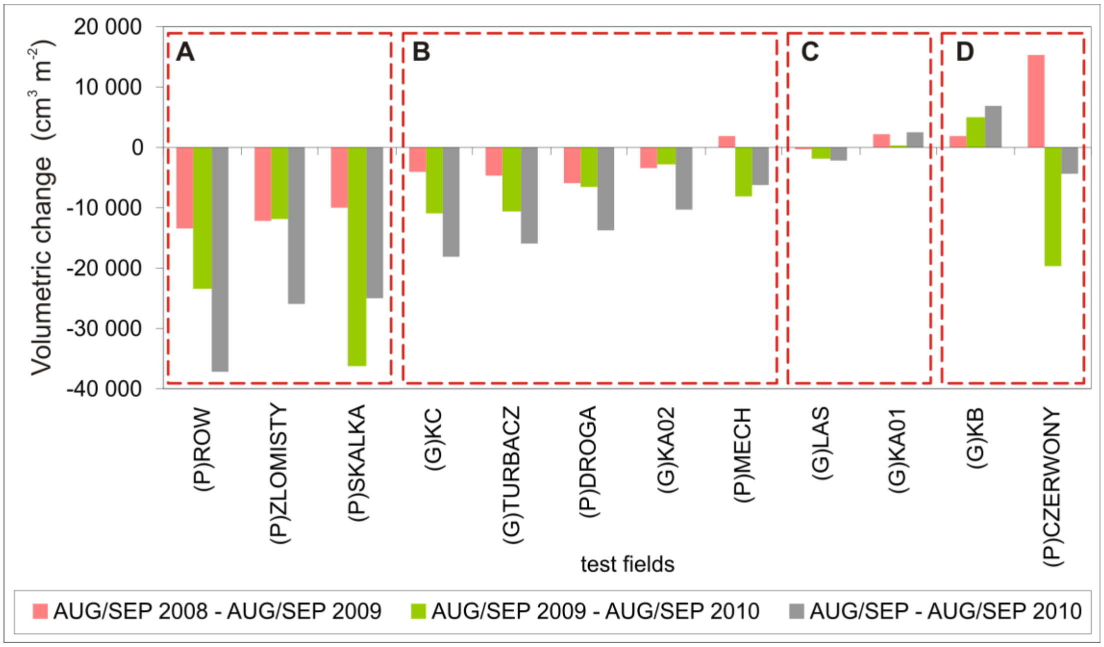

Fig. 10. The average change in the volume of soil per 1 m^2 within the test fields located on recreational trails of the GNP and PLP. Groups of the test fields are marked by capital letters as follow: A - Test fields with a substantial soil loss; B - Test fields with a moderate soil loss; C – Test fields with low relief transformation; D – Test fields on which unusual phenomena occurred.

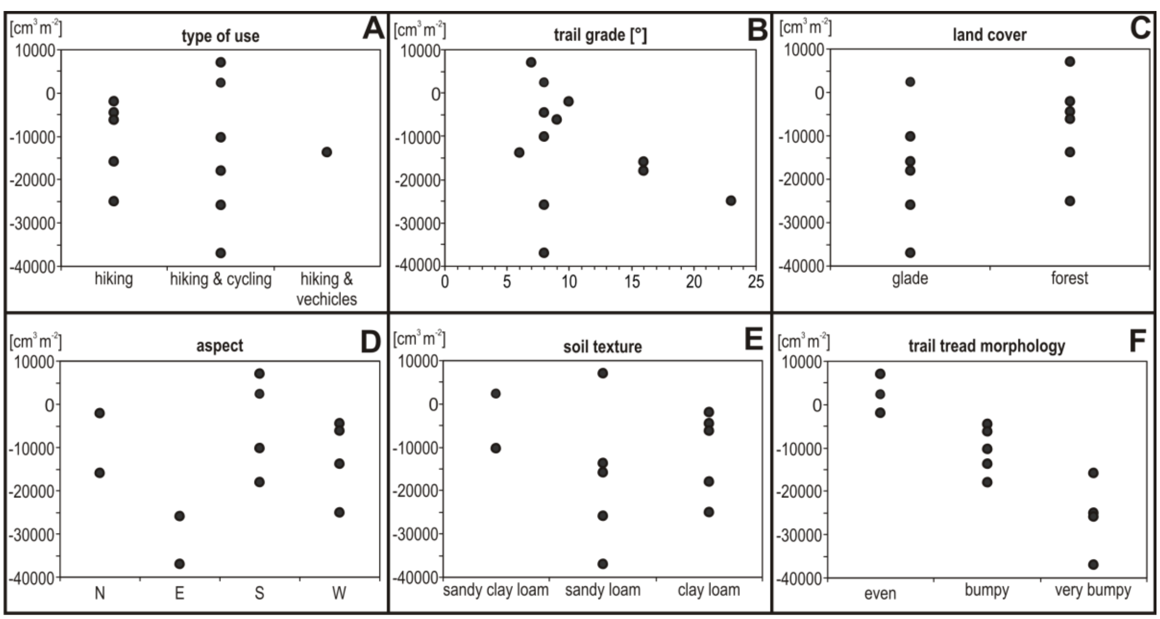

Fig. 11. Relationship between changes in the volume of soil in the period August/September 2008 to August/September 2010 and selected managerial and environmental factors

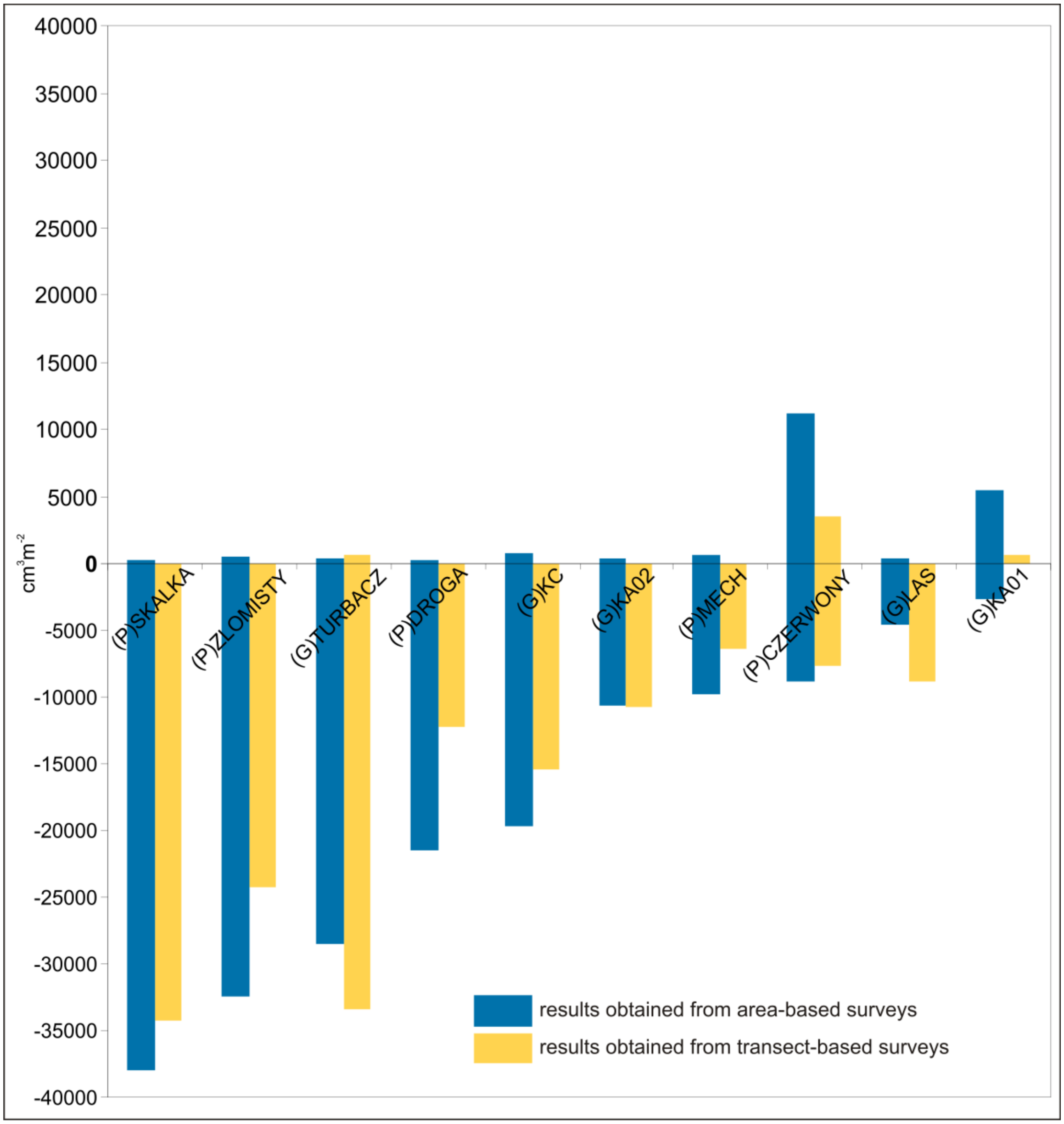

Fig. 12. Comparison of the volumes of soil loss/deposition calculated from transect- and area-based measurements.

List of table

Table. 1. Characteristics of test fields chosen for the elevation surveys

Name of the test field	Trail grade [°]	Aspect	Altitude [m a.s.l.]	Type of use	Land cover	Soil texture[1]	Plant community[2]	No. of visitors per day[3]	Trail tread morphology	Trail/slope relationships
Gorce National Park										
KA01	8	S	1143	Hiking and cycling	Glade	SCL	1	60-140	Even	Ridge / Oblique to slope
KA02	8	S	1150	Hiking and cycling	Glade	SCL	1	60-140	Bumpy	Ridge / parallel to slope
KB	7	S	1219	Hiking and cycling	Forest	SL	4	60-140	Even (deep gully with bedrock)	Ridge / oblique to slope
KC	16	S	1243	Hiking and cycling	Glade	CL	2	60-140	Bumpy	Slope / oblique to slope
LAS	10	N	1071	Hiking	Forest	CL	5	30-80	Even (with stone pavement)	Ridge / parallel to slope
TURBACZ	16	N	1176	Hiking	Glade	SL	2	30-80	Very bumpy	Slope / parallel to slope
Poprad Landscape Park										
CZERWONY	8	W	1145	Hiking	Forest	CL	3	10-50	Bumpy (with tree roots)	Ridge / perpendicular to slope
DROGA	6	W	1129	Hiking and motorized vechicles	Forest	SL	3	10-50	Bumpy	Ridge / oblique to slope
MECH	9	W	1158	Hiking	Forest	CL	3	10-50	Bumpy	Ridge / perpendicular

										to slope
SKALKA	23	W	1153	Hiking	Forest	CL	3	10-50	Very bumpy	Ridge / parallel to slope
ROW	8	E	1168	Hiking and cycling	Glade	SL	2	30-60	Very bumpy	Ridge / parallel to slope
ZLOMISTY	8	E	1163	Hiking and cycling	Glade	SL	2	30-60	Very bumpy	Ridge / parallel to slope

[1]**Soil texture**: SCL: sandy clay loam; SL - sandy loam; CL - clay loam.

[2]**Plant community**: 1 - European Blueberry (vaccinium myrtillus) communities; 2 - European Blueberry (vaccinium myrtillus) communities the addition of spruce - pices abies - secondary communities; 3 - transitional communities Abieti-Piceetum / Plagiotecio-Piceetum; 4 - Norwegian spruce association (Plagiothecio-Piceetum); 5 - “Carpathian beech forest”, Dentario glandulosae-Fagetum typicum.

[3]**Number of visitors:** it is number of visitors per day during weekend and high season. It can varied according to meteorological condition.

Table 2. Changes to the width of recreational trails within the test fields located in the GNP and PLP

Test Field	Width of the trail in AUG/SEP 2008 [m]	Increase of the width of trails in two years [m]
Gorce National Park		
KA01	1.9	0.6
KA02	2.3 - 2.45	0.4 - 0.6
KB	1.9-2.1	no change
KC	2.65	no change
LAS	1.1 - 1.6	no change
TURBACZ	1.7 - 3.3	0.2 - 0.75
Poprad Landscape Park		
CZERWONY	1.3	0.5
DROGA	2.8 - 3.15	0.5
MECH	1.15	0.05 - 0.2
SKALKA	1.8 - 2.3	no change
ROW	1.7 - 2.7	0.10 - 0.25
ZLOMISTY	1.0 - 1.35	0.4 - 0.5

Table 3. Standardized amount of soil loss/deposition for the studied test field

Test field	Area of the test field [m^2]	Volume of soil loss/deposition per m^2 [cm^3 m^{-2}]				
		AUG 2008 – JUN 2009	JUN 2009 – AUG 2009	AUG 2009 – JUN 2010	JUN 2010 – AUG 2010	AUG 2008 – AUG 2010
Gorce National Park						
KA01	26.3	+1,159	-1,058	+2,433	-1,225	+2,371
KA02	13.4	-407	-3,023	-934	-795	-10,193
KB	12.7	+4,178	-3,893	+5,090	+593	+6,919
KC	13.7	-1,875	-1,505	-8,897	-950	-18,095
LAS	13.2	+279	-3,208	-2,722	+346	-2,063
TURBACZ	15.2	-590	-5,019	-5,596	-2,864	-15,900
Poprad Landscape Park						
CZERWONY	10.6	+15,664	-6,049	-7,754	-7,917	-4,499
DROGA	18.0	-1,046	-3,075	-5,393	-1,133	-13,744
MECH	7.9	+1,939	-1,248	-5,294	-439	-6,138
SKALKA	9.7	-6,622	-5,352	-12,155	-11,288	-25,058
ROW	12.9	-6,409	-8,684	-11,410	-11,284	-37,039
ZLOMISTY	10.6	-5,004	-6,114	-6,692	-4,342	-25,995

Table 4. Changes in surface elevation based on cross-section measurements on recreational trails and forest roads for several selected mountain areas in Poland and Slovakia.

Study area	Period	Number of surveyed cross-sections	Mean change [cm]	Max change [cm]	Min change [cm]	Reference
Gorce Mts.	Aug 2008 – Aug 2009	17	-0.7	+2.5	-2.3	This study
Gorce Mts.	Aug 2008 – Aug 2010	17	-0.9	+0.2	-2.3	This study
Radziejowa Range	Aug 2008 – Aug 2009	15	-0.8	+3.1	-3.0	This study
Radziejowa Range	Aug 2008 – Aug 2010	15	-1.6	+0.3	-3.8	This study
Turbacz (Gorce Mts.)	Oct 2004 – Oct 2005	several	-	-1	-20	Wałdykowski 2006a, b
Tatra Mts.	Jun 2007 Apr/Aug 2009	5	-	+14.5	-6.3	Rojan 2009
Beskid Sadecki Mts (Homerka Catchment)	Oct 1976 – Oct 1978	30	-1.7	-	-	Froelich and Słupik 1986
Karkonosze	Apr – Oct 2003	17	-1.1	-0.2	-2.1	Kasprzak 2005
Pilsko	May 1993 – Nov 1993	30	0.5	-	-5	Łajczak 1996

Supplementary Figures

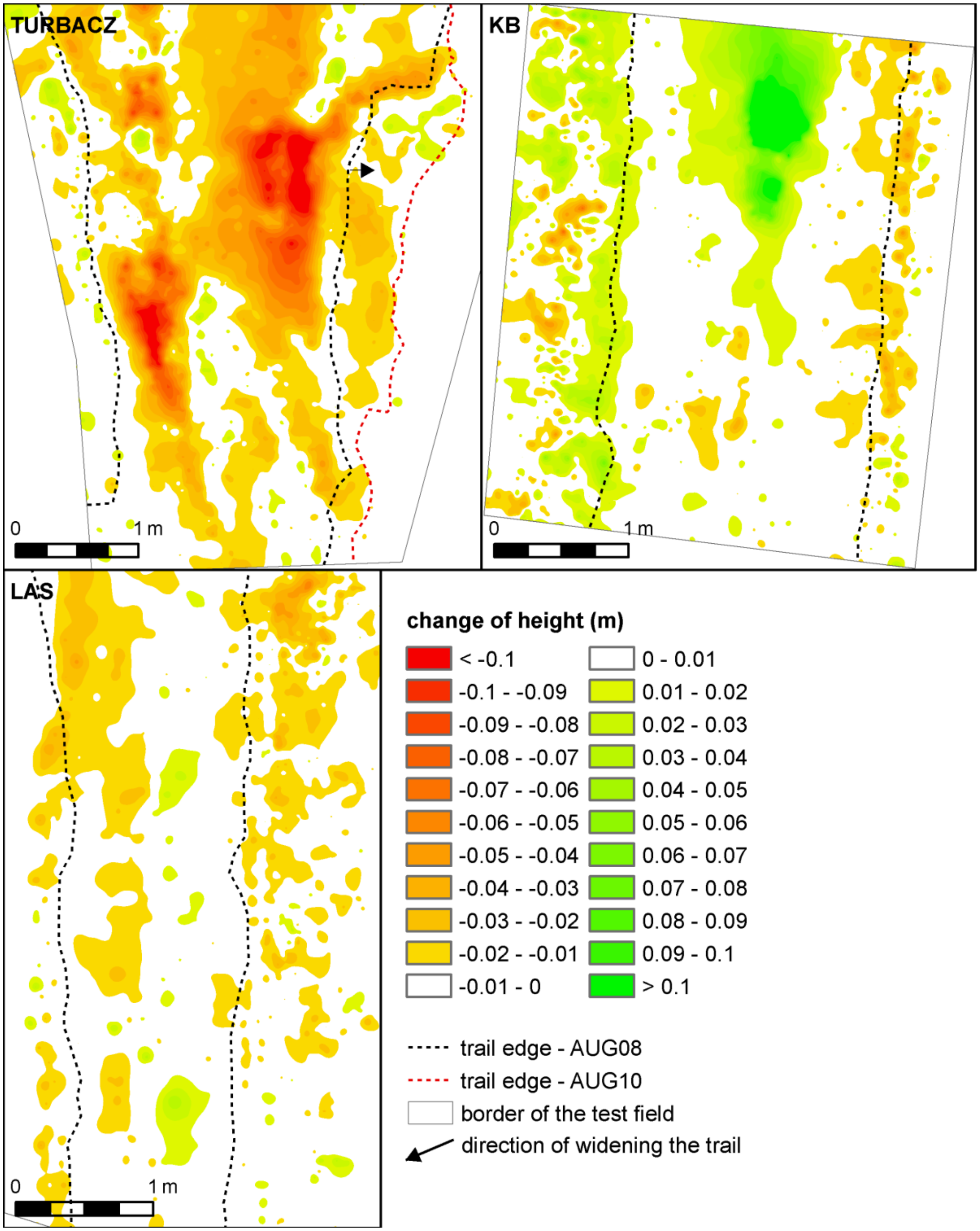

Figure A-1. DEMs of Differences (DODs) showing the spatial distribution of surface transformations between August/September 2008 and August/September 2010 – test fields located in the GNP – Part I.

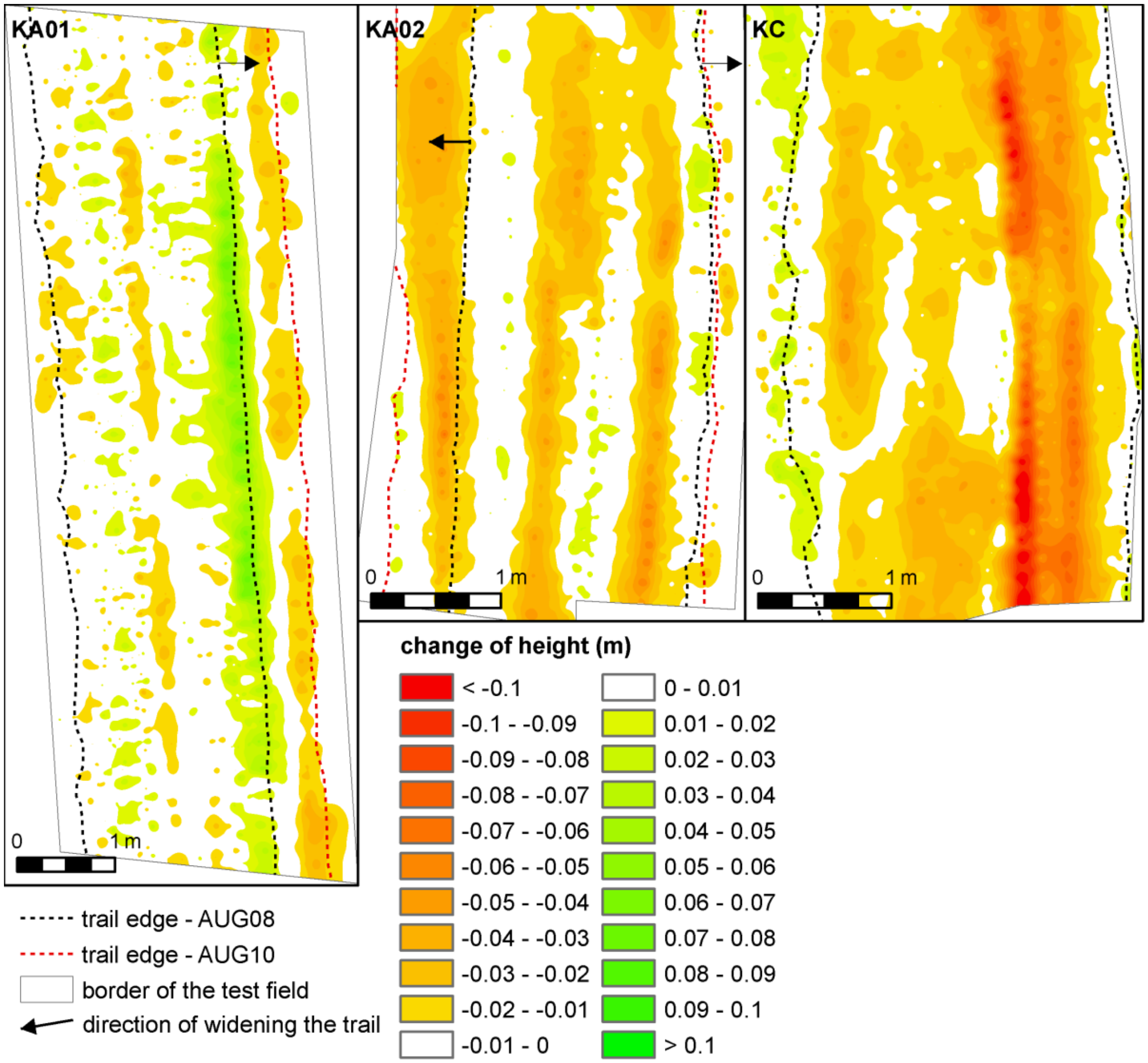

Figure A-2. DEMs of Differences (DODs) showing the spatial distribution of surface transformations between August/September 2008 and August/September 2010 – test fields located in the GNP – Part II.

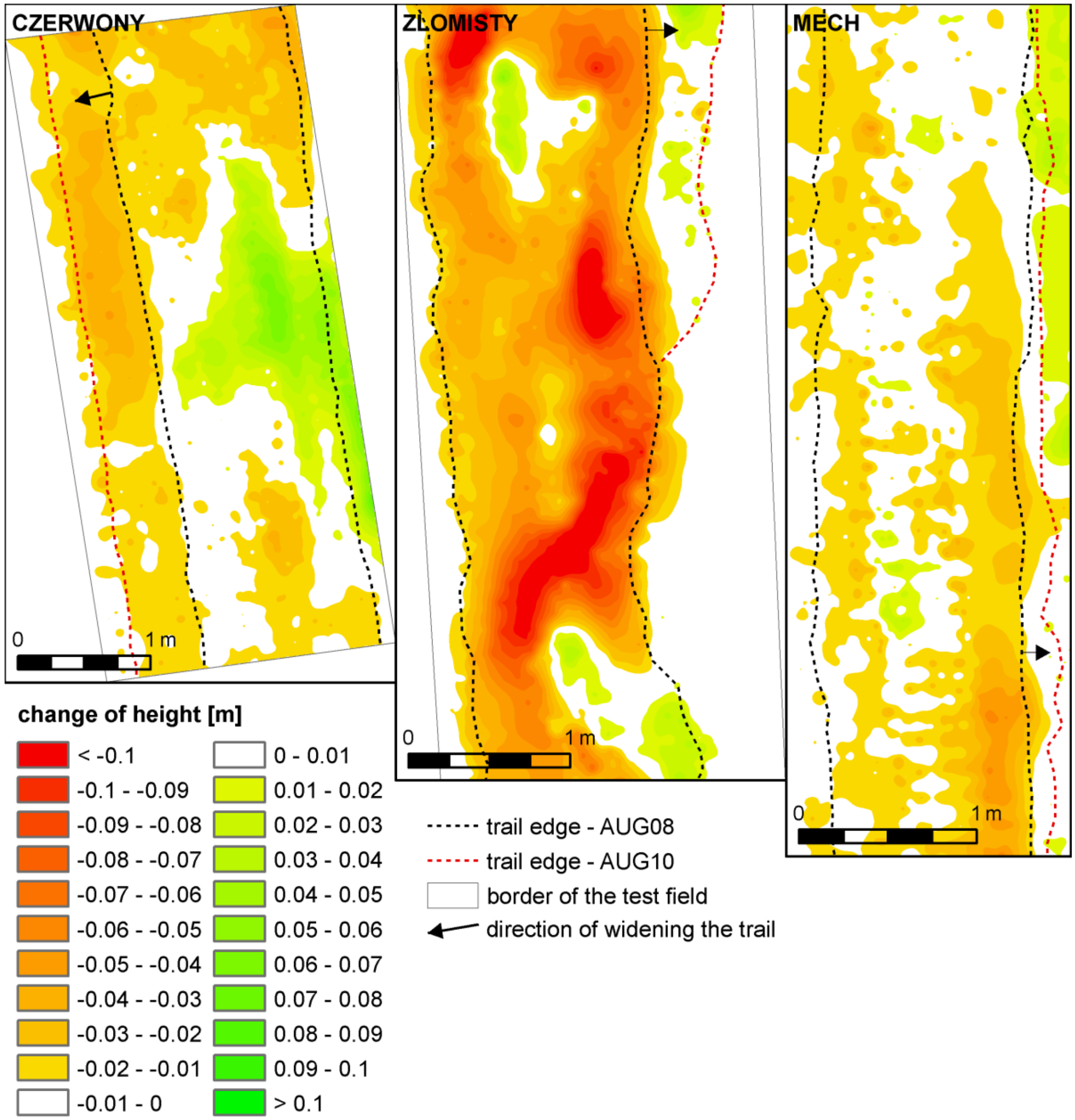

Figure A-3. DEMs of Differences (DODs) showing the spatial distribution of surface transformations between August/September 2008 and August/September 2010 – test fields located in the PLP – Part I.

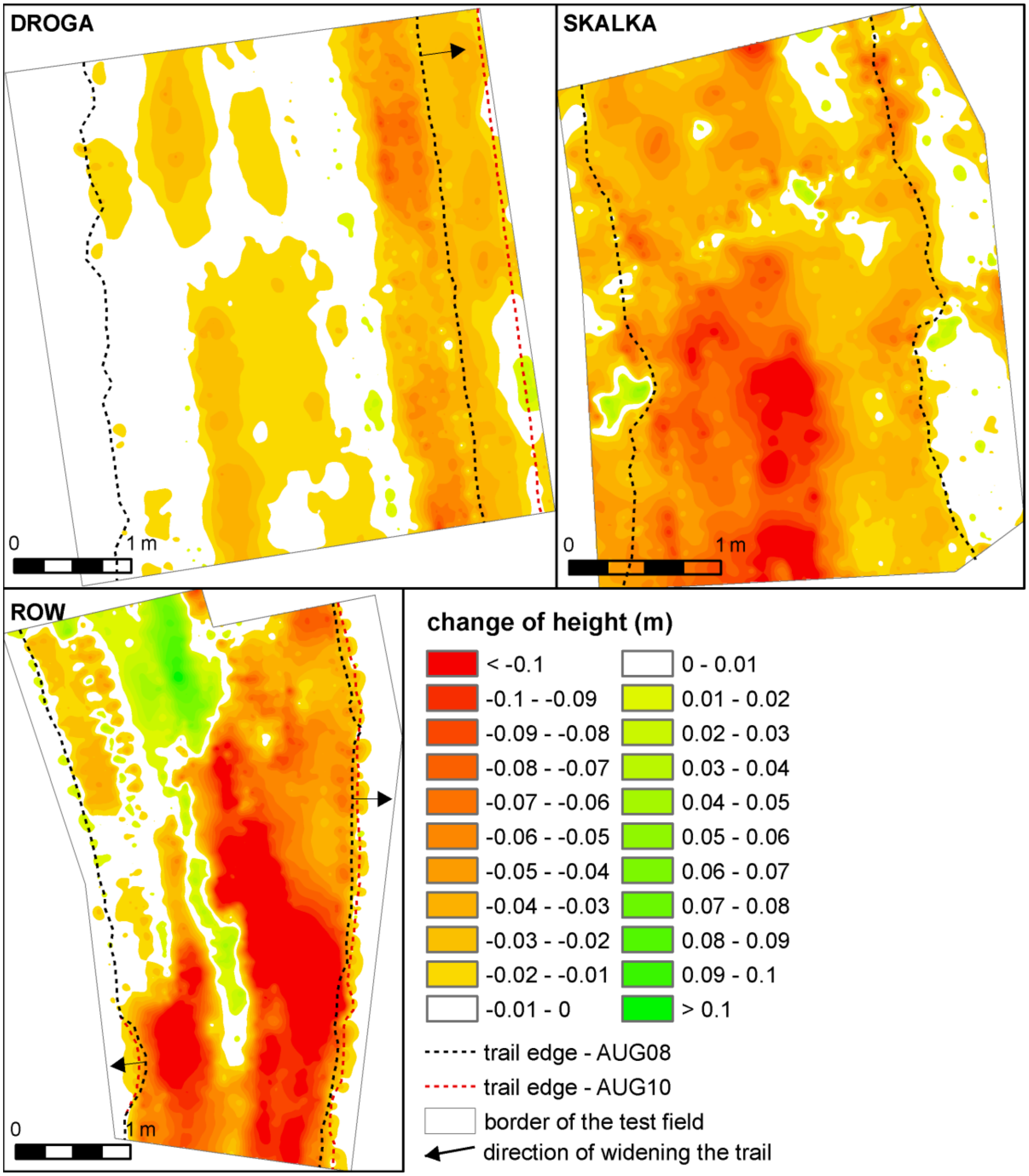

Figure A-4. DEMs of Differences (DODs) showing the spatial distribution of surface transformations between August/September 2008 and August/September 2010 – test fields located in the PLP – Part II.