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Application of LiDAR visualisations for mapping the tillage direction

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Abstract: Contour tillage is an agricultural practice that significantly contributes to enhancing water retention, reducing the risk of flooding, and mitigating soil erosion. Information about the tillage direction is used for modelling water and tillage erosion. In our study, we used Light Detection and Ranging (LiDAR) visualizations, originally developed for archaeological research, to visualise tillage traces and map tillage direction in the Nitra district (SW Slovakia). The tillage traces were visible in all agricultural parcels, on various agricultural fields, under various agricultural crops. The LiDAR visualisations also revealed pre-collectivization field patterns and even prehistorical field patterns in certain areas. Among the 5 961 investigated points, we recorded the application of contour tillage in 30.63% of the cases. The preference for contour tillage varied among farmers, with the highest reported percentage reaching 49.74%. Our analysis did not reveal a significant correlation between the preference for contour tillage and the slope steepness.

Keywords: contour tillage; Slovakia; soil erosion; tillage orientation

Contour tillage is a soil management practice that increases water retention, reduces surface runoff (Carvalho et al. 2015; Papanicolaou et al. 2018; Zhang et al. 2010) and reduces the risk of flooding and soil erosion. Rainfall simulation experiments with maize fields in the Czech Republic showed that contour farming and shallow tillage reduced runoff by 38% (Stašek et al. 2023) and transported sediments by 70%. In Iowa (USA), the runoff coefficient was reduced from 0.82 for ridge till to 0.03 for contour till, and erosion was reduced by 97% (Wacha et al. 2020). Similar experiments with black oat and vetch in Lages (Brazil) showed a 56% reduction in soil loss by contour tillage (Luciano et al. 2009). The positive effect of contour tillage on the mitigation of phosphorus loss (Stevens et al. 2009) or carbon storage (Dlugoß et al. 2012; Wacha et al. 2020) has also been documented as well. Contour tillage is recommended as management practices limiting the risk of soil degradation and erosion under the Good Agricultural and Environmental Condition (GAEC) of the EU Common Agricultural Policy (European Commission 2023; Pipíšková et al. 2023), as well as an erosion mitigation measure under national legislation of Slovakia (Law 220/2004 on the conservation and use of agricultural land).

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Application of contour tillage is an important input in modelling water and tillage erosion (Wischmeier & Smit 1978; Van Oost et al. 2005), but also in assessing surface roughness in modelling surface runoff. The contour tillage enters the water erosion model as one of the erosion control measures, the factor P (Wischmeier & Smit 1978; Morgan 2005). The data obtained by water erosion modelling are used, for example, in the location of erosion-prone areas where erosion control measures need to be implemented within the framework of the conditionality of the Common Agricultural Policy (MARDSR 2023). Erosion modelling is also used in the design of erosion control measures in landscape plans and other environmental legislation.

Tillage direction (also known as tillage orientation) refers to the angle at which tillage operations are performed relative to the contour lines. According to Drzewiecki et al. (2014), tillage is considered contour tillage when the tillage direction is maintained below 15 degrees. Due to the complexity of tillage direction mapping, its integration into water erosion models is often simplified, leading to a significant increase in model inaccuracy. Tillage direction is frequently neglected, with the assumption that ploughing occurs parallel to the slope gradient. (Vrieling 2006; Cebecauer & Hofierka 2008). In the pan-European erosion model, Panagos et al. (2015) assumed that farmers correctly implement contour ploughing as one of the erosion control measures recommended within the framework of GAEC conditions of the Common Agricultural Policy (CAP). At the local level, tillage direction has been classified from aerial images (Drzewiecki 2008; Lima et al. 2021). This approach is limited to local circumstances because the classifier needs to be calibrated to a specific crop in a specific growth period, or images without vegetation must be available. The spectral response of vegetation cover varies throughout the year, and therefore, it is challenging to develop a robust classifier that works for different agricultural crops at different times of the growing season. Furthermore, disturbing features, such as trees, shrubs, and shadows, add complexity to the automatic classification of aerial imagery. Another approach is to derive the tillage direction from the shape of the parcel, with the assumption that the tillage is performed in the direction of the longest boundary of the parcel (Drzewiecki et al. 2014; Bozek et al. 2016). This approach is not applicable to irregularly shaped parcels, square parcels, parcels containing another landscape feature (e.g. forest, wetland), or sloping parcels where ploughing is more complicated (Li et al. 2009). The need for a more accurate and robust methodology to analyse tillage direction has been highlighted by several authors (Rawat et al. 2016; Panagos et al. 2020; Lima et al. 2021).

Remote sensing capabilities for mapping the tillage practices were reviewed by (Zheng et al. 2014). The review focused on optical and radar system capabilities for mapping the tillage practices, crop residues, surface roughness, and application of tillage indices. The potential of airborne Light Detection and Ranging (LiDAR) data for detecting topographical features has been predominantly explored by geomorphologists and archaeologists (Johnson & Ouimet 2018; Tarolli et al. 2019; Vinci et al. 2024). Examples of LiDAR applications from central Europe include the identification of relics of former ponds (Frajer et al. 2021) or barrows ditches, hillfort and artillery redoubts in the historical Bohemia region (Gojda 2017). The advantage of LiDAR data is the ability to penetrate vegetation and identify macro- and microtopographical features, including tillage furrows. The LiDAR data has been used to examine tillage pattern (Li et al. 2009), assessing the gully erosion and rehabilitation (Khan et al. 2024) and for measurement of the soil surface roughness (Liu et al. 2024), but not for measurement tillage direction. The aim of this paper is to present the potential of airborne LiDAR data to map the tillage direction. Particularly we aimed to: (1) Explore the visibility of tillage traces on LiDAR-based visualisations; (2) Map the tillage direction on regional level in Nitra district; (3) Analyse the preferences for contour tillage in the Nitra district case study to determine whether it is favoured on steeper slopes and by specific farmers.

MATERIAL AND METHODS

Study area. The Nitra district area (87 044 ha) is located in western Slovakia (Figure 1). The selection of this area was influenced by its significant expanse of arable land (58 512 ha), largely located in hilly areas that are at risk of water erosion (NPPC-VÚPOP 2023; Šúri et al. 2002). According to the Land Parcel Identification System (LPIS), agricultural land in the region spans 60 210 hectares, with arable land comprising 97.18% of the total, followed by vineyards (1.60%), grasslands (0.82%), orchards (0.37%) and other permanent crops (0.03%). Domi-

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nant agricultural crops are wheat, rapeseed, and corn. The most common agrotechnical practices include moldboard ploughing, deep soil loosening, chisel or disc tillage, and mulching. Most of the arable land consists of large fields, farmed by large agroholdings. In addition to the prevailing large-scale parcels, there are small-block agricultural mosaics covering a total area of 1 584 hectares (Bugár et al. 2020). The average elevation is 185 m a.s.l., with the lowest point (117 m) located in the southern part, and the highest point (619 m) located in the north-eastern part of the district. The dominant geomorphological unit is the Podunajská pahorkatina (Danubian Hills), which belongs to the geomorphological subsystem of the Pannonian Basin. The area belongs to the warm climatological area; the average annual temperatures range from 8.28 °C to 10.05 °C, with an average annual precipitation of 529–895 mm (Kočický et al. 2019). The prevalent soil types consist mainly of Haplic Chernozems, locally eroded Calcari-Haplic Chernozems and Cutani-Haplic Luvisols and Calcic Luvisols, locally eroded located on thick loess and alluvial deposits. Most of the soils fall into the sandy loam and loam categories based on Novák's classification.

LiDAR visualisations. We used the LiDAR data point cloud, scanned in years 2017–2018, obtained from Geodesy, Cartography, and Cadastre Authority of the Slovak Republic administration. Point density on open arable fields reaches 25–35 points per square metre, with horizontal and vertical accuracy of 5–6 cm (Leitmannová et al. 2020). From the LiDAR point cloud, we generated a TIN-based DEM by employing Delaunay Triangular Irregular Network interpolation, which was then converted to a 25 cm resolution grid through linear interpolation. This process was executed using the LidarTINGridding tool within the Whitebox GAT (Ver.1.4.0) software (Lindsay 2016).

Various LiDAR visualisation techniques have been developed to depict topological variations in terrain surface (Kokalj & Hesse 2017; Štular & Lozić 2022; Vinci et al. 2024). We adopted visualisation techniques developed for the identification of historical anthropogenic landforms in archaeological research (Lieskovský et al. 2022). Visualisation techniques are based on a simple local relief model (Kokalj & Hesse 2017) with added representation of local dominance to relief curvature and added combination of slope steepness and sky view factor to relief contrast visualisation. LiDAR visualisations depict convex features in a blue-green hue, while concave features appear in yellow. The dynamics of relief changes are illustrated through variations in the intensity of the red colour. The contrast in the image reflects the combination of sky view factor and slope steepness. We obtained the sky view factor and local dominance from the digital elevation model by employing the Relief Visualisation Toolbox (Ver. 2.2.1). To integrate and visualise the resulting layers, we utilised QGIS (Ver. 3.18).

Mapping the tillage direction. We have identified arable land fields from the LPIS geodatabase,

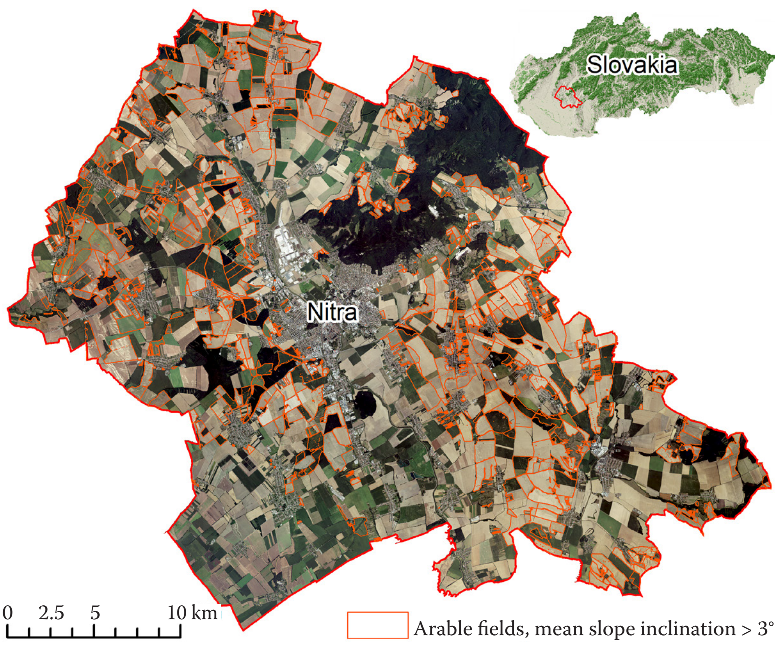

Figure 1. Study area Nitra district Orthophotomosaic source data provided by Geodetic and Cartographic Institute Bratislava and National Forest Centre

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which is specifically designed for the implementation of area-related EU common agricultural policy schemes (Houšková et al. 2015) and is updated in the three-year cycle from detailed orthophoto images. This geodatabase is in the ownership of the Ministry of Agriculture and Rural Development of the Slovak Republic and can be accessed at https://data.gov.sk.

To concentrate on fields susceptible to water erosion, we specifically chose arable land fields with an average slope steepness exceeding three degrees. Within these fields, we created random points at a density of 25 points per square kilometre. Using the measure angle tool in QGIS (Ver. 3.18), we measured the angle in degrees of tillage traces identified from LiDAR visualizations, relative to the nearest contour at each point (Figure S1 in Electronic Supplementary Material). The contours were derived from LiDAR DEM with a resolution of 1 meter using the gdal_contour function for QGIS. The elevation interval between the contours was 1 meter.

Analyse of contour tillage preferences. To test if the contour tillage is preferred on the steeper slopes, we performed a correlation analysis between slope steepness and tillage direction. The slope steepness map was derived from the digital elevation model obtained from the LiDAR points. To remove microtopographical features that elevate average slope steepness, a 5-meter neighbourhood mean filter was applied to smooth the digital elevation model before the slope steepness was derived.

We also tested whether contour tillage is preferred by certain farmers. Data on parcel management was sourced from the Geospatial Aid Application (GSAA). This database houses information about farms and farmers who receive EU agricultural support for agricultural parcels registered in the LPIS database. The GSAA database is owned by the Ministry of Agriculture and Rural Development of the Slovak Republic and is accessible at https://gsaa.mpsr.sk/. We specifically chose farms that had more than 100 measurements of tillage direction and analysed the average tillage direction and the percentage of points, where contour tillage was recorded. According to Drzewiecki et al. (2014), we considered contour tillage as a tillage method, where the angle between the tillage direction and the contours is kept below 15 degrees. We assumed that if the tillage is carried out regardless of contour tillage, then the average tillage direction would be 45 degrees. To examine whether farmers prefer contour tillage (thus if the average tillage direction is significantly lower than 45 degrees), we employed a one-tailed t-test. Statistical tests and data visualizations were performed in R Statistics (Ver. 4.3.1).

RESULTS AND DISCUSSION

Visibility of tillage traces on LiDAR visualizations. Tillage marks can be easily distinguished in LiDAR visualisations for all types of crops cultivated in the Nitra district (Figure 2A). From the point cloud with a density of 25–30 points per square metre, we were able to produce LiDAR visualizations with a 25 cm pixel resolution, where the tillage traces from all agricultural crops were clearly visible. To identify the tillage traces and measure the tillage direction, we employed visual interpretation, which is relatively accurate but is also subjective and time-

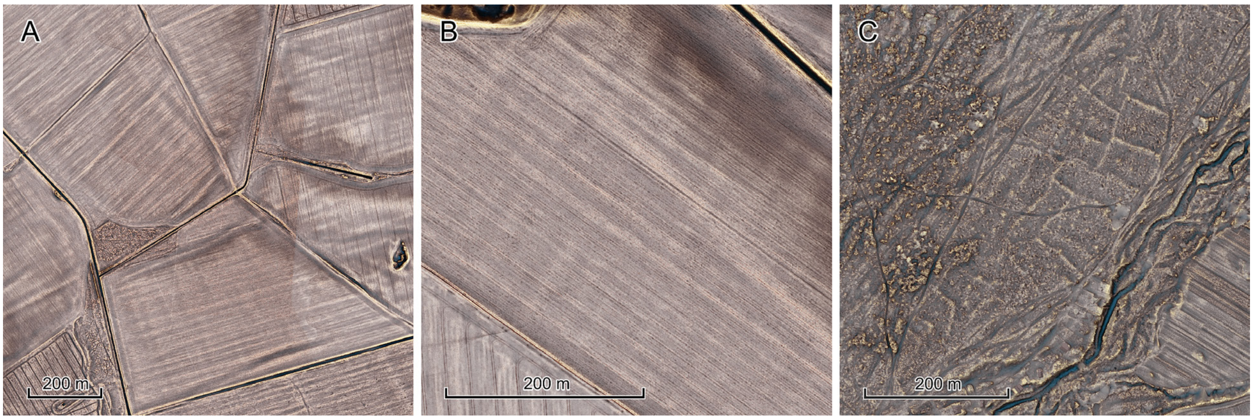

Figure 2. Examples of the visibility of tillage traces on Light Detection and Ranging (LiDAR) visualizations: traces of recent tillage from various agricultural fields in Malé Chyndice cadastral area (A), traces of recent tillage and old field composition in Vráble cadastral area (B), traces of prehistoric field system in Svätý Kríž cadastral area (C)

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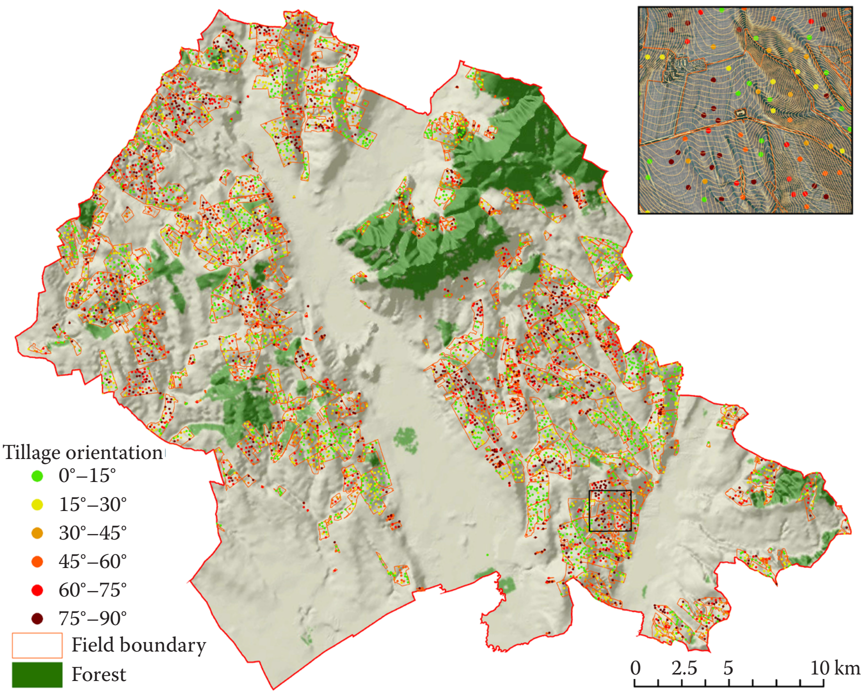

Figure 3. Point measurements of tillage direction in Nitra district

consuming. This process could be automatized with the application of image classification techniques such as object-based image analysis (Blaschke et al. 2014; Lima et al. 2021).

In particular areas the structure of the old field composition is recognisable. In Figure 2B, the recent tillage traces are orientated toward the southwest. Under the current tillage pattern, the underlying structure of an older field layout, orientated from the northwest, is discernible. This field pattern was documented on historical cadastral maps from 1890 and also on historical aerial images from 1949 (Boltižiar et al. 2008; Gerard et al. 2010). The small-scale field pattern was typical for the Slovak agricultural landscape until the second half of the twentieth century when socialist collectivisation of agriculture led to the homogenization of the agricultural landscape (Lieskovský et al. 2014; Jepsen et al. 2015). The remnants of pre-collectivization fields are regarded as traditional agricultural landscapes (Fanta et al. 2022; Dobrovodská et al. 2023; Vasilescu et al. 2023), which are valuable for their high biocultural value (Agnoletti & Emanueli 2016; Dobrovodská et al. 2019; Baránková & Špulerová 2023). The incorporation of LiDAR data into traditional agricultural landscape research provides supplementary perspectives, particularly in relation to historical anthropogenic landforms (Duma et al. 2020; Stereńczak et al. 2020; Hanušin et al. 2021).

The application of LiDAR visualisations enables the visualization of even prehistoric field patterns, leading to new archaeological discoveries. Figure 2C shows a prehistoric field system from Sväty Križ, which was preliminary dated between the middle bronze age and late bronze age, approximately 1750–800 BC (Hajnalova et al. 2023). Another example is the agricultural terraces system from the late bronze age and early iron age (1000 – 600 BC) and various medieval agricultural structures discovered in Veľký Tríbeč mountains (Bisták et al. in press). These findings deepen our understanding of past agricultural landscape utilization, its evolution, and its adaptation to changing conditions.

Tillage direction in the Nitra district case study area. Among 2 241 arable parcels, we measured the tillage direction in 902 parcels that exhibited an average slope steepness exceeding 3 degrees. Totally 5 961 measurements have been conducted (Figure 3). We recorded contour tillage (angle between tillage direction and contours is kept equal or below 15 degrees) in the Nitra district in 30.63% cases (Figure 4A). 18.07% of the cases employ tillage within the tillage direction of 15–30 degrees, and higher tillage angles are recorded in 51.30% of the cases.

Even contour tillage significantly reduces water erosion (Morgan 2005; Da Rocha Jr. et al. 2016) and is not widely applied by farmers because it complicates tillage operations and decreases field efficiency (Li et al. 2009). In the years of data acquisition 2017–2018, contour tillage was not applied in Slovakia as a requirement

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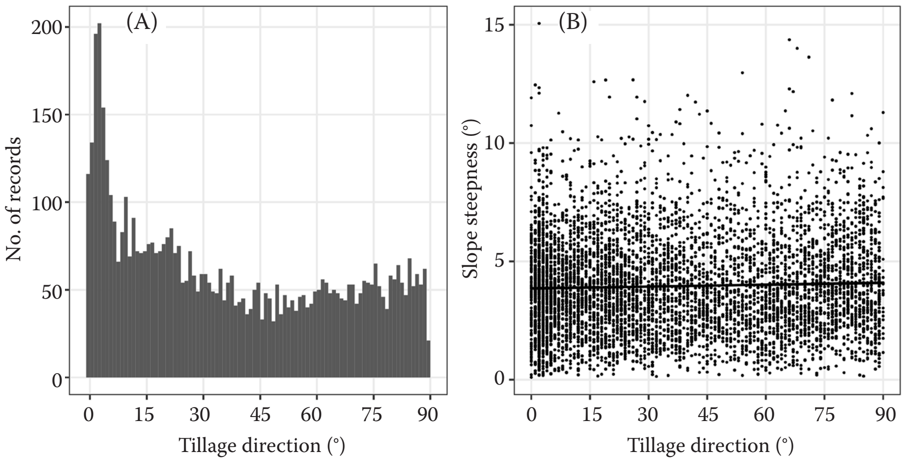

Figure 4. Measured tillage direction (A) and relation between tillage direction and slope steepness (B) in Nitra district

of Good Agricultural and Environmental Condition of the EU CAP, however, it was recommended as one of the erosion-mitigation measures under the national legislation of Slovakia (Law 220/2004 on the conservation and use of agricultural land). The current CAP (2023–2027) recommends contour tillage as one of the soil conservation measures that need to be applied on soils endangered by water erosion. This is included under good agricultural and environmental conditions (GAEC 5) that must be implemented to receive CAP support (Pipíšková et al. 2023). Additionally, the CAP eco schemes in Slovakia include the implementation of grass strips that are required to be positioned to divide arable parcels that exceed 50 hectares in size. It is recommended that these grass strips be positioned parallel to contours or within valleys. Therefore, we anticipate that contour tillage will be more preferred in the upcoming years.

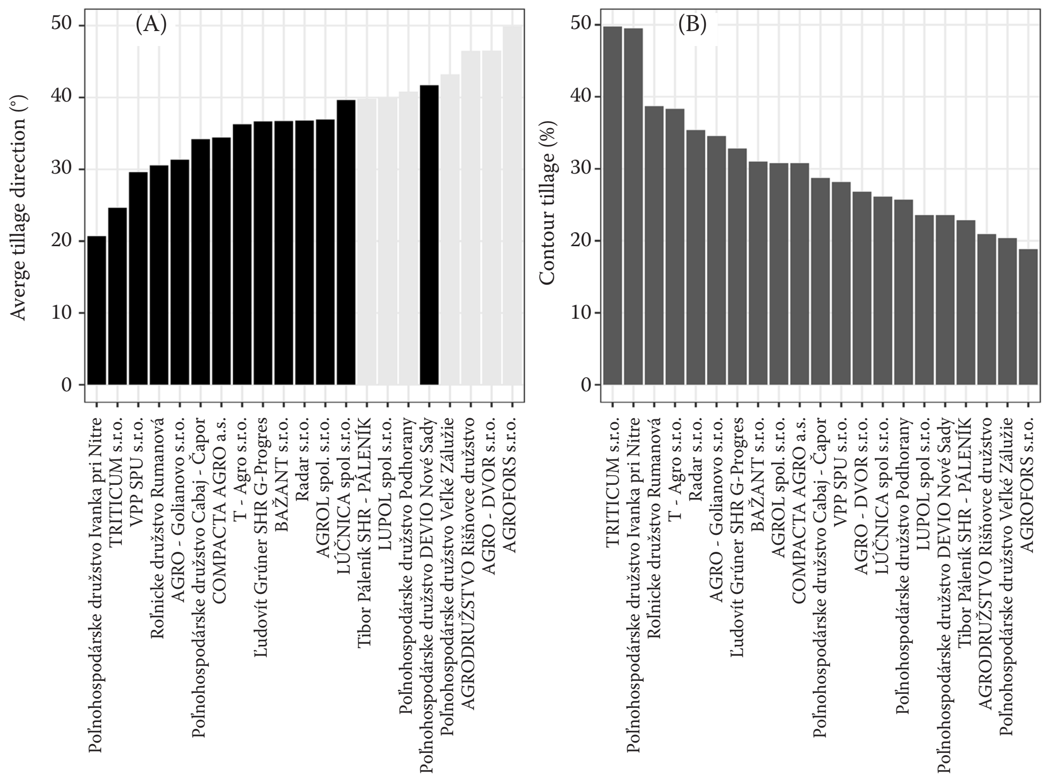

Figure 5. Average tillage direction (left) and preference of contour tillage (right) for selected farms in the Nitra district
The black bars denote cases where there are significant differences ($P < 0.01$) compared to the assumed random tillage direction of 45 degrees

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Preferences for contour tillage in the Nitra district case study area. We did not find any significant correlation between contour tillage preference and slope steepness (Figure 4B). The Person correlation coefficient was equal to 0.036, and the *P* value equal to 0.00528. This indicates that the contour tillage is not preferred with increasing slope steepness. Of the 22 farms we examined, the preference for contour tillage was statistically confirmed in 15 farms (Figure 5A). The preference for contour tillage was statistically significant in all cases where the average tillage direction was lower than 37 degrees. In two cases (LÚČNICA spol. s r.o. and Poľnohospodárske družstvo DEVIO Nové Sady) significance was also confirmed for average tillage directions of 39.67 degrees and 41.73 degrees. This is due to a large number of measured points in both farms, which increases the significance of the average value. While the overall average number of measurements was 183.71, LÚČNICA spol. s r.o. had 310 measurements, and Poľnohospodárske družstvo DEVIO Nové Sady had 632 measurements. For the same reason, the preference for contour farming at Poľnohospodárske družstvo DEVIO Nové Sady is significant, even though three farms had lower average tillage directions but did not show significance for contour farming. However, if the significance level were set up to $P < 0.001$, the preference for contour farming at Poľnohospodárske družstvo DEVIO Nové Sady would be insignificant. Two farms applied contour tillage in almost 50% of their land (Figure 5B). The lowest preference was statistically confirmed on a farm that applied contour tillage to only 23.57% of its area.

CONCLUSION

The capability of LiDAR technology to capture microtopography, even below the vegetation canopy, allows its use as a tool for mapping tillage direction. In the Nitra district, we identified tillage traces and measured the tillage direction in various agricultural fields. We adopted visual interpretation, which is subjective and time-consuming. However, advanced remote sensing and GIS tools, such as object-based image analysis, could automate the identification of tillage traces and the measurement of tillage direction. In addition to the current tillage pattern, the LiDAR visualisations also revealed pre-collectivization field patterns and even prehistorical field patterns in certain areas, which is applicable, for example, in historical landscape ecology or landscape archaeology research.

We recorded the application of contour tillage in Nitra district in 30.63% of cases. The preference for contour tillage varies between farmers and was statistically confirmed in 15 of 22 farms. Two farms applied contour tillage to nearly 50% of their land. The lowest preference was statistically confirmed on a farm that implemented contour tillage in only 23.57% of its area. We did not find any significant correlation between the preference for contour tillage and slope steepness.

Given that contour tillage is recommended as a management practice to mitigate soil degradation and erosion risk under the Good Agricultural and Environmental Condition (GAEC) of the EU CAP, the use of LiDAR data could enhance the ability to monitor the implementation of contour tillage in erosion-prone areas. The upcoming emphasis is on automating the measurement of tillage direction to enable its application across large areas in a timely manner.

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