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The application of unmanned aerial vehicle (UAV) surveys and GIS to the analysis and monitoring of recreational trail conditions

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ABSTRACT

Recreational trails are a vital element of protected natural areas (PNAs) infrastructure, which enables visitors to travel through and engage in various activities such as hiking, biking, horse riding. Degradation of trails adversely affects the natural environment as well as the safety and comfort of visitors. As the role of many PNAs is to protect the natural environment and to provide recreational opportunities, the need to obtain accurate information about the condition of the trails and the direction of their transformation is evident. Spatial characteristics of trails can be very heterogenic even within a single park, and this heterogeneity hinders our understanding of different types of direct human impacts across the landscape. Therefore, there is a need for a tool allowing for mapping large portions of trail networks within a reasonable time to get a full picture of trail conditions in space and their change through time. In this paper, we present a protocol for high-resolution mapping and monitoring of recreational trail conditions using UAV surveys, Structure-from-Motion (SfM) data processing and geographic information systems (GIS) analysis to derive spatially coherent information about indicators of trail degradation and associated trail characteristics, e.g., by detailed mapping of trail width, and incision. We tested the approach in three dramatically different settings: (1) Two trails studied in Orange County (California, USA) were characterized by mean width of 0.6 m and 2.8 m and mean incision of 0.05 m and 0.3 m, respectively – in this case study we demonstrated a strong correlation between ground-based and UAV-based surveys of trail width and incision; (2) Valle de Cocora (Colombia) hiking and horse-riding trails were characterized by mean width of 0.5 m and 1.2 m respectively, and incision which occurred on 28% of hiking and 87% horse-riding trail – this case study indicated good agreement between object-based classification and manual delineation of the trail tread; (3) in Rainbow Mountain (Peru) mean width was 1.8 m for hiking, 15.6 m for horse-riding trail and 23.6 m for the multi-use trail. Presented case studies enabled us to verify the broad applicability of the proposed workflow.

1. Introduction

The role of many protected natural areas (PNAs) is both the conservation of the natural environment and the provision of recreational opportunities (Anon, 1994). Therefore, the management needs to be directed towards minimizing conflicts between recreation use and conservation. Recreational trail networks enable visitors to travel through PNAs and engage in various activities such as hiking, biking, horse riding. However, degradation of trails adversely affects the natural environment (e.g., by accelerated soil erosion) as well as the safety and comfort of visitors (Leung and Marion, 2000; Cole, 2004; Monz et al., 2013; Hammitt et al., 2015). Therefore, effective management of PNAs requires access to accurate information about the current state of the trails and their dynamics (Hawes and Dixon, 2014). This need becomes even more acute when the resources for maintenance and trail repairs are limited, so it is important to spend them productively. Thus, gathering accurate and spatially uniform data about trail network condition is crucial for proper management of PNAs.

Two most important indicators of trail condition are trail width and trail incision (Fig. 1) (e.g., Monz, 2002; Dixon et al., 2004; Olive and

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Fig. 1. Examples of trail impact: A – deposition of material (indicated by arrow) due to improper trail drainage; B – muddy section and water puddle; C – exposed bedrock on the too-narrow section of the trail, which forced visitors to trample trail sides; D – erosional rill (indicated by arrow) along the trail tread; E – deep gully reaching bedrock; F – strong trail incision and development of rills; due to uncomfortable and dangerous walking conditions, visitors created informal paths (marked by arrows) next to the designated trail.

Marion, 2009; Wimpey and Marion, 2010; Tomczyk and Ewertowski, 2011; Ólafsdóttir and Runnström, 2013; Meadema et al., 2020; Salesa and Cerdà, 2020; Tomczyk and Ewertowski, 2023), which characterize all recreational trails regardless their design and environment settings. In addition, five other indicators of trail degradation (Fig. 1) may occur depending on the local conditions (Monz et al., 2010; Tomczyk and Ewertowski, 2011, 2013a, 2013b; Hammitt et al., 2015; Tomczyk and Ewertowski, 2016, 2023): (1) presence of muddy sections (which indicate problems with trail drainage); (2) occurrence of local depositional centers, where soil transported from one part of a trail is deposited to either on or off-trail locations; (3) presence of informal (visitor-created) trails; (4) occurrence of abandoned trail sections; (5) number and density of invasive species along trail corridors.

Previous studies on trail conditions were based on: (a) intensive point sampling strategies, which delivered detailed data, but for specific locations only (e.g., Monz, 2002; Pickering and Growcock, 2009; Tomczyk and Ewertowski, 2013b; Barros and Pickering, 2015; Nir et al., 2022); or (b) more general assessments of longer sections or whole networks of trails, which generated less detailed data but for broader spatial context (e.g., Dixon et al., 2004; Nepal and Nepal, 2004; Hawes et al., 2006; Eagleston and Marion, 2020; Meadema et al., 2020; Spernbauer et al., 2023). Studies on soil erosion and landscape dynamics were particularly very accurate, but at the same time very localized (see Salesa and Cerdà, 2020 for review). However, spatial characteristics of trails can be very heterogenic even within a single park (e.g., Tomczyk and Ewertowski, 2011, 2016), and this heterogeneity in many PNAs hinders our understanding of the impacts of different types of direct human activities within the landscape. Therefore, an approach for mapping large portions of trail network more efficiently is needed to get a full picture of the trail condition in space and its change through time. Satellite images provide broader-scale data on human disturbances in the landscape but with relatively low (m-scale) spatial resolution (Nagendra et al., 2015; Naegeli de Torres et al., 2019). To get information in the spatial scale relevant to trail management (cm-scale), unmanned aerial vehicles (UAVs or drones) offer the best capabilities to determine the dynamics of trails and assess their spatial and temporal aspects (Ancin-Murguzur et al., 2020; Grubesic and Nelson, 2020; Salesa et al., 2020; Wang and Watanabe, 2022). However, this approach is very recent, and so far, no standardized way of collecting and analyzing UAV-gathered data has been proposed.

In this paper, to fulfil this gap, we present and test a protocol for high-resolution mapping and monitoring of recreational impacts in PNAs using UAV surveys, Structure-from-Motion (SfM) data processing and geographic information systems (GIS) analysis to derive spatially coherent information about trail conditions. This new, comprehensive framework will ensure meaningful compatibility of outputs of future works in PNAs and will be useful for both practitioners (e.g., park managers and rangers) as well as researchers working within the field of recreation ecology. Our approach provides quantitative, detailed measurements of trail width and incision in a semi-automated way in a GIS environment, thus enabling standardized surveys of indicators of trail conditions over long sections of trail—something that has not been proposed previously—which can be then compared between trails and also between different areas and statistically test against various environmental and social factors (e.g., soil type, vegetation cover, use type).

The aims of this study are:

1) To develop a new operational framework for the use of low-cost UAVs and GIS for assessment and monitoring of recreational trail condition.
2) To test the proposed framework in three different case studies as proof of concept.
3) To indicate and discuss more complex applications of the proposed framework.

Results of our study contain step-by-step guidelines, which can easily be adapted for different environmental conditions, and thus, implemented by managers of various PNAs. The designed framework is particularly important for environment conservation in PNAs where the number of visitors is fast-growing, and use is trail-related (e.g., hiking, horse-riding, biking). As the main disadvantage of optical remote sensing data is lack of ability to penetrate tree canopies, the proposed protocol is most relevant to open-range areas. However, as the development of autonomous vehicles progresses, we may expect the increasing ability of drones to perform surveys under tree canopy (cf. Hyyppä et al., 2020; Wang et al., 2021), which will enable to use the proposed workflow to obtain data on trail conditions also in forested areas.

2. Materials and methods

2.1. *An operational framework for mapping and monitoring recreational trail conditions using UAV surveys and GIS*

In this work, we employ relatively inexpensive UAV equipment widely available for park managers, and therefore, we concentrate on trail characteristics that can be readily derived from common RGB-only optical imagery (Table 1). We propose a protocol consisting of six stages (Figs. 2-5):

2.1.1. *UAV surveys*

Preparation stage includes specification of the study character (one-time mapping or multi-year monitoring) and the desired final products (e.g., orthomosaic, digital elevation model [DEM]). The increasing use of UAVs resulted in changes in UAV-related regulations in many countries (see Merkert and Bushell, 2020; Lee et al., 2022) – local and national regulations tend to change dynamically, so before the survey, it is necessary to check the current regulations with legal authorities. In addition, in many conservation areas, using UAVs requires obtaining a permit from park managers. The size and character of the studied area guides the selection of the UAV platform. Fixed-wing or hybrid UAVs offer excellent efficiency and can cover more extensive grounds comparing to multi-rotors; therefore, their use is beneficial for studying large trail networks in open, flat areas. Multirotor UAVs are better suited to study moderately long and short trails in mountains, as they offer better maneuverability, and the ability to hover to take sharp pictures in low-light conditions. In the case of monitoring, it is beneficial to set-up fixed hours during the day and approximately the same dates every year to obtain similar lighting and vegetation conditions.

Pre-flight activities and mission designing include communication with local airport control and land managers. Surveying ground control points (GCPs) is beneficial; however, if local stable points are available, they can be used to provide ground controls in the later stages of the data

Table 1
Indicators of trail degradation and trail characteristics which can be derived from optical RGB UAV-generated products.

Indicators of trail degradation	Trail characteristics	Characteristics of trail vicinity
The total area of exposed soil/ trampled vegetation	Type of trail tread (e.g., bare soil, trampled vegetation, artificial surface)	The type of vegetation cover
Trail width	Trail slope	Landform slope
Trail incision	Trail aspect	Landform aspect
Presence of muddy sections	Trail alignment	Elevation
Presence of informal (visitor-created) trails	Rugosity (surface roughness)	Landform type
Presence of abandoned trail sections		
Small-footprint features (e.g., firepits, garbage)		

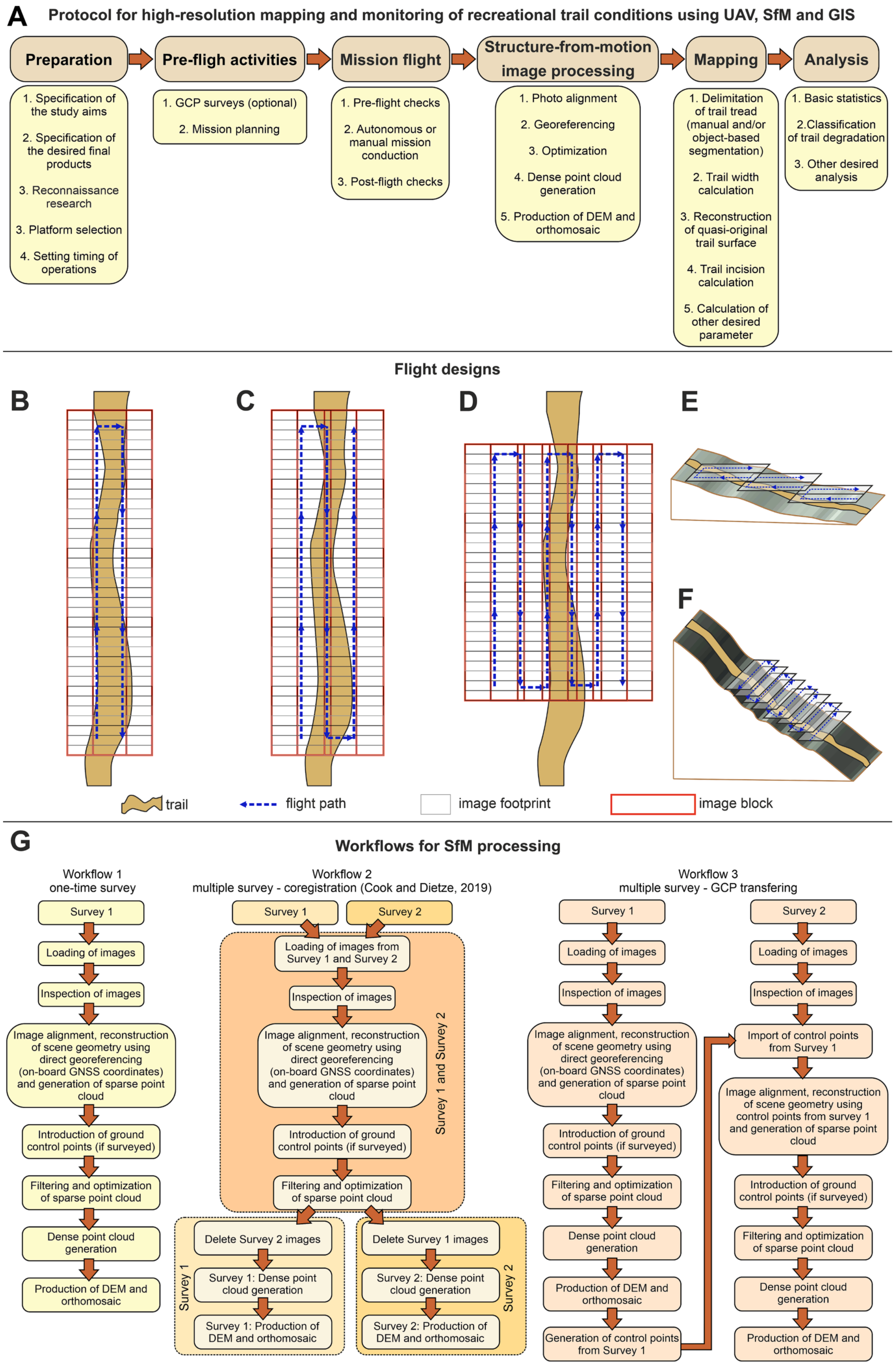

Fig. 2. A - Protocol for high-resolution mapping and monitoring of recreational trail conditions using UAV, SfM and GIS; Proposed flight designs: B – two parallel lines along the trail; C – four parallel lines along the trail (3 lines with vertical images, one line with oblique images); D – grid; E – moderately steep trail divided into sections; F – steep trail with lines perpendicular to the slope. G - Workflows for SfM processing.

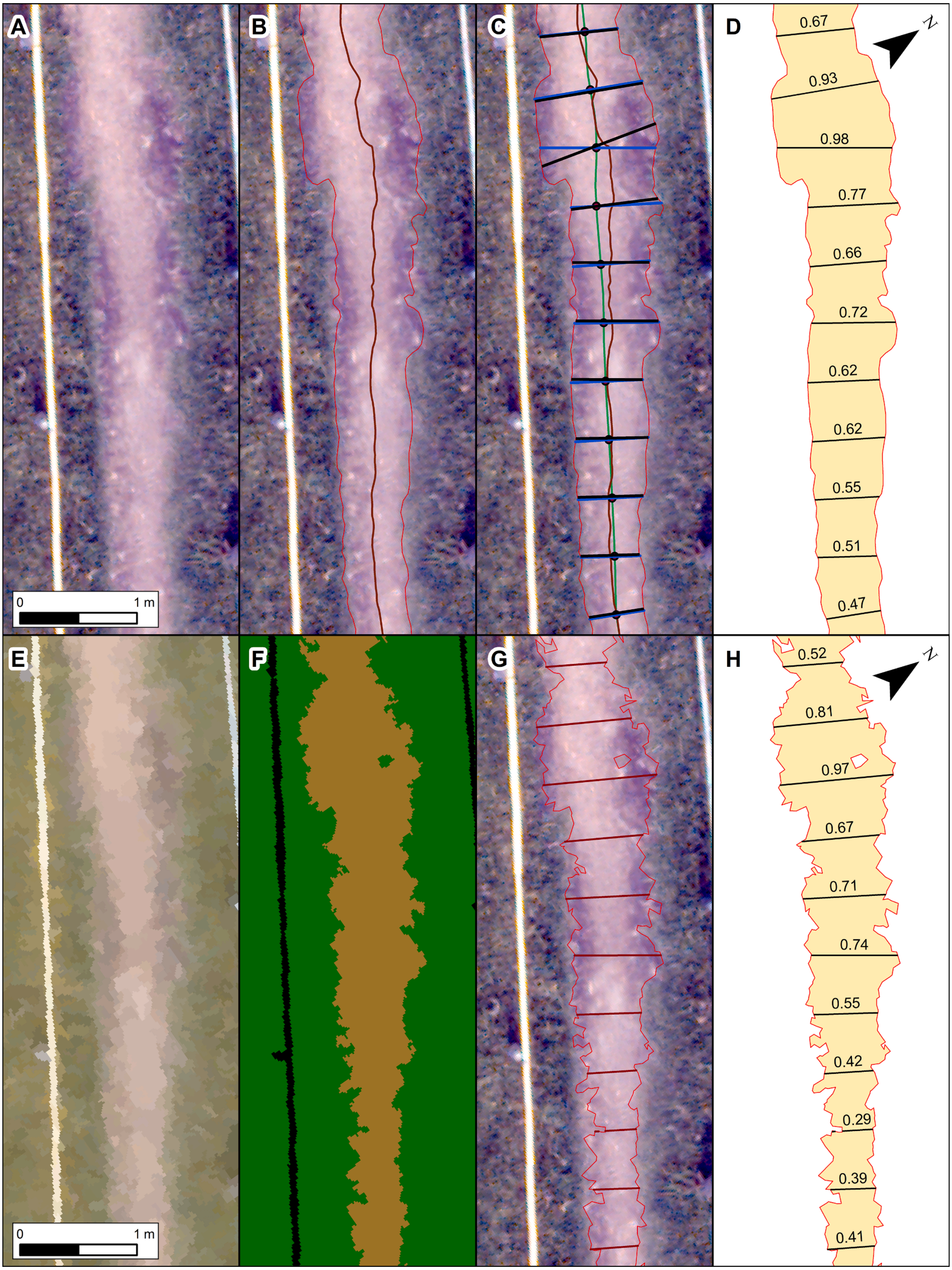

Fig. 3. Illustration of protocols for deriving information about trail tread area and trail width: A – orthomosaic 1.5 cm GSD; B – manually delineated trail tread; C – centerline automatically generated from the smoothed polygon and profiles in 0.5 m interval; D – trail width. E – output of segmentation of orthomosaic from panel A; F – classification of the segmented image into trail tread and trail vicinity; G – trail tread generated from the result of segmentation; H – polygon of automatically generated trail tread with width measured at 0.5 m intervals.

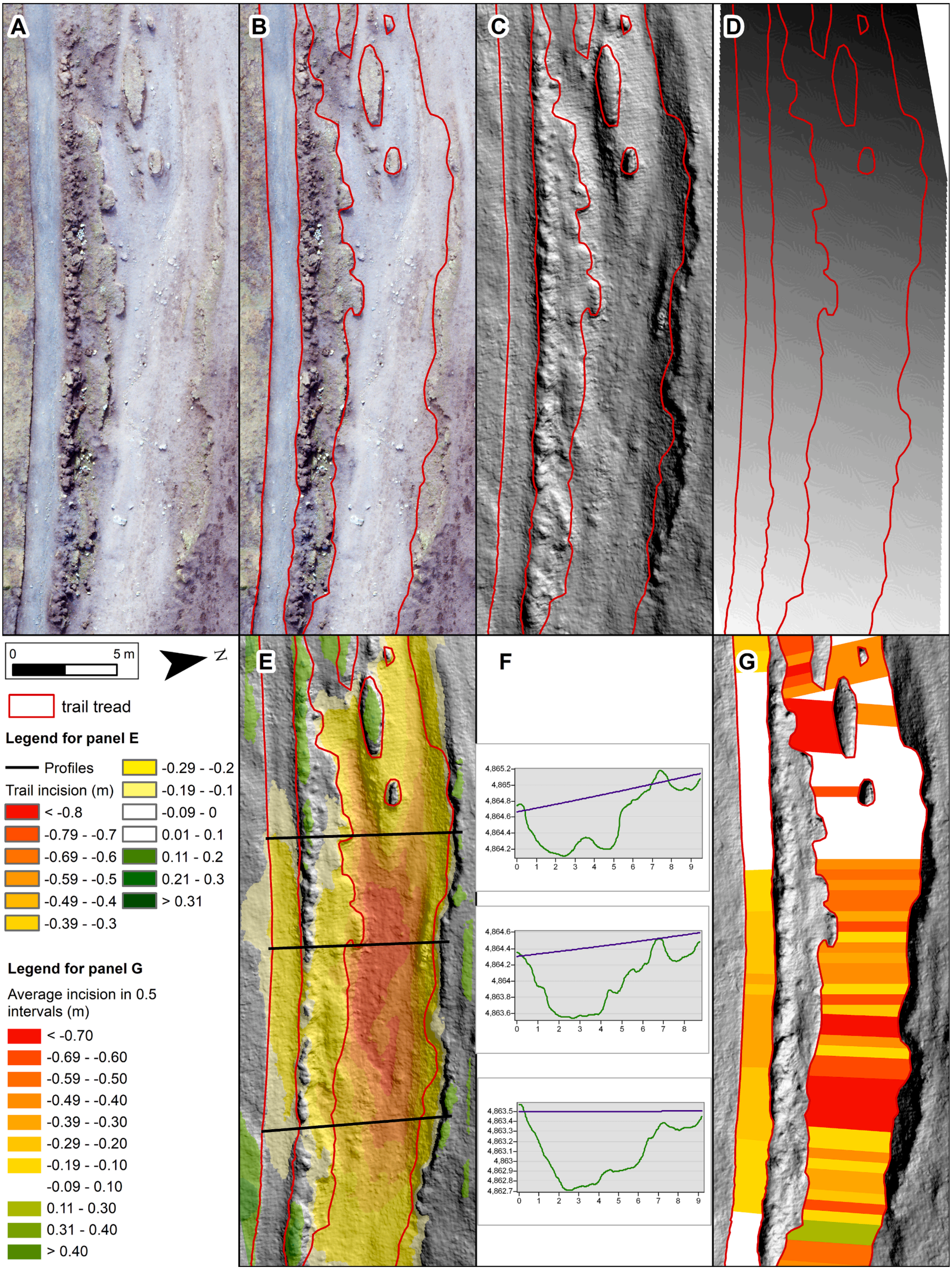

Fig. 4. Illustration of protocols for deriving information about trail incision: A – orthomosaic 1.3 cm GSD; B – trail tread derived from the interpretation of orthomosaic; C – hillshade model; D – surface interpolated from the vicinity of the trail (an approximation of original terrain surface); E – trail incision measured from the original terrain surface; F – examples of interpolated and incised surface profiles; G – average incisions in 0.5-m-long sections.

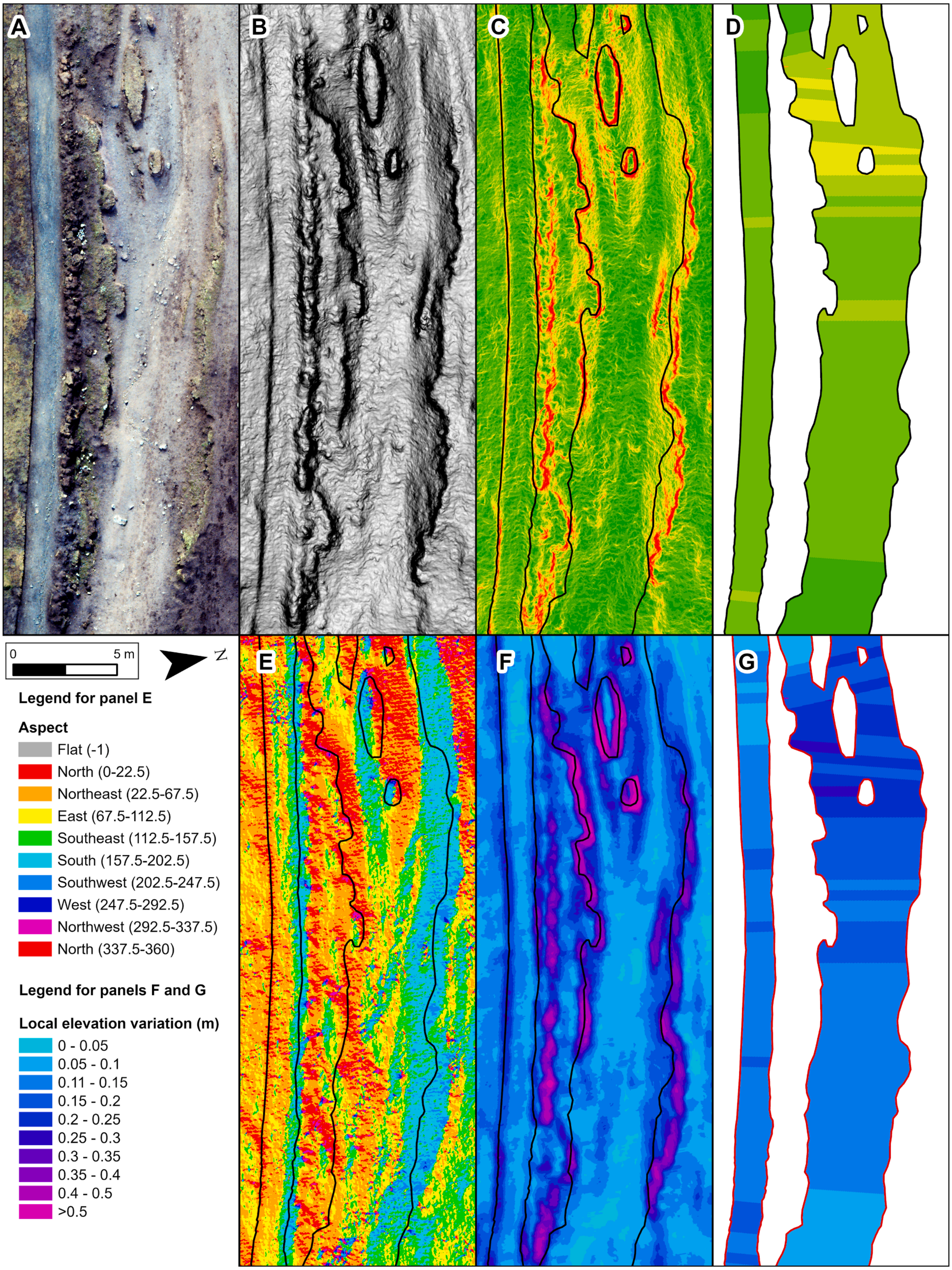

Fig. 5. Illustration of protocols for deriving information about trail roughness (microtopography of trail): A – orthomosaic 1.3 cm GSD; B – slopeshade (i.e., slope displayed in greyscale); C – slope map and trail tread; D – average slope in 0.5-m-long sections; E – aspect; F – local variation in elevation as an approximation of trail roughness; G – average elevation variance for 0.5-m-long trail sections.

processing. In most cases, recreational trails tend to be narrow (<2 m, but even as narrow as 0.2 m), therefore, to investigate their characteristic features (including microtopography and trail tread rugosity) the level of detail needs to be high. Ground sampling distance (GSD) between 1 and 2 cm and high images overlap (>80%) offer a good compromise between the desired level of details and necessary flight altitude and duration of surveys – these two parameters will guide the above-ground level (AGL) altitude depending on the sensor and lens specification. For the most typical application, simple mission planning is sufficient (Fig. 2B-F).

Mission flight: The prepared flight plan can be conducted manually or implemented in any existing mission planning software. However, some of the software does not allow capturing images in RAW format, resulting in a reduced ability to process individual images (e.g., brightness or color adjustments) prior to the orthomosaic creation.

2.1.2. *Structure-from-motion image processing*

A broad spectrum of structure-from-motion software ranges from fully-automated online-processing solutions to desktop packages. We suggest using software which allows for at least some modification and optimization of processing parameters, as this approach enables better precision and accuracy, or at least improved knowledge about errors present in the final products (cf., James et al., 2019). The processing of the one-time mapping scenario is usually straightforward (Fig. 2G – Workflow 1). In the case of multi-temporal observations, when GCPs are present for all surveys, the processing is the same as for a one-time survey. When no GCPs were surveyed, multi-temporal surveys can be co-aligned (co-registered) together, following the approach proposed by Cook and Dietze (2019) (Fig. 2G – Workflow 2); or one of the models can be selected as a primary model, and CPs can be transferred from this primary model to the remaining surveys (secondary models) (Fig. 2G – Workflow 3).

2.1.3. *Mapping of the trail characteristics and conditions*

We propose mapping approach for six attributes of trail characteristics and conditions:

1) **Exposed area (total area of exposed soil/trampled vegetation)** provides information about the overall size of impacts and the area prone to water erosion. It is obtained through delineation of the **trail tread shape** (which also constitutes a baseline for most further analysis). Lateral margins of the trail tread are defined as a visual disturbance to the surface vegetation cover in the vicinity of the trail (Fig. 3A). The trail tread is delineated and stored in a geodatabase as a polygon, allowing for the calculation of the total area affected by trail impacts. Trail tread can be delineated through manual vectorization (Fig. 3B) or object-oriented classification. In the latter case, the first step includes segmentation of orthomosaics based on different values of spectral details (1, 5, 10, 15–20), spatial details (1, 5, 10, 15, 20) and minimum segment size (20). In most cases, the best differentiation between non-vegetated trail tread and vegetated trail sides can be obtained using the following values of spectral details: 15, and spatial details: 1 (Fig. 3E). However, the values might be adjusted depending on the type of vegetation in the trail surroundings. Subsequent filtering combines the output into three main classes: trail tread, vegetation, artificial objects (e.g., fence) (Fig. 3F). Next, raster to vector conversion (Fig. 3G) produces a polygon with the trail tread.
2) **Trail length** provides information about the extent of the trail network. As trail treads are usually very irregular (Fig. 3B), smoothed polygons representing generalized trail tread shapes are produced. Based on this smoothed output, the centerlines are generated automatically (Fig. 3C) and stored as a polyline, enabling straightforward calculation of trails' length.
3) **Trail width** indicates how wide is the corridor directly affected by human impact and is measured automatically. First, points along the centerline are generated in desired intervals (e.g., 0.5 m). Subsequently, a direction along the centerline is established, and lines perpendicular to it are generated for each point (Fig. 3C, G). These lines are clipped by the trail tread polygon to obtain trail width (Fig. 3D, H).
4) **Trail incision** illustrates soil loss from soil erosion and compaction, and is calculated in a semi-automated way. First, the elements of the original terrain surface (e.g., unmodified fragments of the landforms along the trail) are identified and delineated through the careful interpretation of orthomosaic (Fig. 4A) and hillshade model (Fig. 4C). Then, the points are generated within the polygons representing elements of the original terrain and elevation values are attributed to them from DEM. Subsequently, the quasi-original terrain surface is interpolated using points representing the original terrain level and TIN interpolation method (Fig. 4D). Subtracting the actual trail surface from the quasi-original terrain surface results in a raster where each cell indicates the difference between the original surface level and the current trail surface (Fig. 4E). Trail incision can also be presented as profiles (Fig. 4F) or attributed to 0.5 m-long sections of trail (Fig. 4G). It has to be noted that in case of trails routed along the pre-existing incisions, e.g., along former gullies, the obtained incision values might be overestimated.
5) **Trail roughness (rugosity)** illustrates potential obstacles on the trail, which can impact how users move over the surface. It can be quantified using slope and aspect of microrelief - the UAV data is very detailed, and therefore slope and aspect calculated directly from very high-resolution (cm-scale) DEMs (Fig. 5B, C, E) illustrate rather a microtopography (e.g., high values of slopes related to trail edges, individual rocks or vegetation patterns) than trail grade measured linearly along the path. However, the spatial distribution of micro-slope and aspect can be beneficial as proxies for trail rugosity. Another approach to quantify trail roughness is to calculate the surface elevation variability in the moving window 0.5 × 0.5 m (Fig. 5F) and attribute it to 0.5-m-long trail sections (Fig. 5D, G). As the trail roughness is an important factor enhancing soil erosion (see Tomczyk and Ewertowski, 2013b, 2023), quantification of slope, aspect and elevation differences in cm-scale is an valuable predictor of trail fragments prone to further degradation.
6) **Trail slope (grade)** – in previous studies, trail slope (grade) was either measured directly in the field with clinometer as a slope angle in the centre of the trail in a sampling site (e.g., Salesa et al., 2019; Salesa et al., 2020) or from the sampling site to a point on the trail 3 m distant in an uphill direction (e.g., Eagleston and Marion, 2020; Meadema et al., 2020) or averaged using GIS data for trail sections of different length, e.g., 1 m (Wimpey and Marion, 2011; Spernbauer et al., 2023), 5 m (Eagleston and Marion, 2020) or variable (mean length = 11 m) (Tomczyk et al., 2017), depending on the available data source and purpose of the study. As mentioned above, UAV data can generate very detailed DEM; therefore, to make it meaningful from the visitors' and managers' points of view and compatible with previous studies, we suggest to express trail slope (grade) as per cent grade (rise/run) (see Wimpey and Marion, 2011; Spernbauer et al., 2023) measured for 1-m-long sections along the trail centreline. High-resolution DEMs of the trail vicinity can also be generalised using drainage-constrained methods (Zhou and Chen, 2011; Chen et al., 2012b) to ensure that terrain drainage patterns are retained.

2.1.4. *Classification of trail degradation levels*

For rapid assessment of trail conditions, three variables: mean width, mean incision, and occurrence of muddy sections are attributed to each of the 0.5-m-long trail segments. The resulting database is then divided into five classes of trail condition following the classification scheme presented in Table 2.

Table 2
Ruleset of assignment of condition class to specific trail segments.

Level of degradation	Trail width	Trail incision	Muddiness
No degradation	<0.5 m	<0.1 m	No
Acceptable level of degradation	<1.0 m	<0.1 m	No
Minor damage	<2.0 m	<0.3 m	Yes/no
Damaged trails	<4.0 m	<0.5 m	Yes/no
Heavily damaged trails	>4.0 m	>0.5 m	Yes/no

Note: all conditions must be fulfilled to qualify a trail segment into a specific level of degradation.

2.2. *Case studies – Testing of the proposed protocol*

We tested the proposed framework in three different settings to verify its applicability in various scenarios. Data related to this study is available from 10.5281/zenodo.8303440 (Tomczyk et al., 2023). The UAV surveys were conducted using a small, lightweight, consumer-grade quadcopter (DJI MavicPro), equipped with 12-megapixel, 2/3-inch, RGB sensor. The focal length was 4.7 mm (26 mm for 35 mm format equivalent). This quadcopter was chosen, as it is light and compact, and can be easily transported in a backpack to reach even remote locations on foot.

2.2.1. *Case Study 1 – Comparison between ground-based surveys and on-screen measurements: Orange County, USA*

In Case Study 1, we compared ground-based surveys and on-screen measurements. Surveys were performed for a set of pre-established grids in Orange County, California, USA (Fig. 6A, D), as a part of a project addressing the impacts of recreational use on highly visited urban parks collectively known as the Nature Reserve of Orange County (Natural Communities Coalition, 2018). Recent estimates suggest that the Nature Reserve lands host over 3.3 million visits annually with the primary trail-based recreation activities, including hiking, running, mountain bicycling and horse riding (Monz et al., 2019; Creany et al., 2021).

UAV surveys followed an intensive purposive sample of a range of trail designations, alignments, use-levels, and ecological conditions in 200 × 200 m grids (Fig. 2D). SfM processing in OpenDroneMap (https://www.opendronemap.org) generated orthomosaics and DEMs. Ground-based data were collected following an intensive sampling protocol of trail width, incision, rugosity, and vegetation cover and soil exposure providing 30 trail profiles using standard assessment methodologies (i.e., Marion and Leung, 2001). Ground-based measurements and spatial position of the trail profiles were collected using a Trimble GeoX7 decimeter precision GPS unit. Two trails were selected to compare the results with on-screen measurements conducted on orthomosaics and DEMs, enabling us to assess the overall accuracy and reproducibility of UAV-generated data. The "Meadows" trail, which has a low slope and minor visible disturbance from recreation use and erosion, was surveyed at three AGLs: 10 m (GSD 0.3 cm), 30 m (GSD 1 cm), and 50 m (GSD 1.7 cm). In total, 474 images were collected. A one-way ANOVA was conducted to determine if measurements of trail width and incision differed between the ground-based and UAV-based surveys from different levels. The "Ibis" trail, an informal (i.e., visitor-created) trail characterized by wide, highly eroded tread with visible recreation disturbance, was surveyed at 10 m AGL (GSD 0.3 cm), and 1885 images were captured. A *t*-test was conducted to determine if measurements of trail width and incision differed between the ground-based and UAV-based surveys.

2.2.2. *Case Study 2 – One-time mapping of trail characteristics: Valle de Cocora, Colombia*

Assessment of trail conditions and characteristics was performed for 600-m-long section of trail in Valle de Cocora, central Colombia (Fig. 6B). This area is characterized by moderate precipitation and dense vegetation cover. The studied section of the trail is routed through the pasture. Pedestrian and horse-riders traffic was split several years ago, and in 2019 these two types of trail use were separated by a fence/barrier (Fig. 6E). The exact number of visitors is unknown, but during the field visit, both types of uses were on a similar level.

UAV surveys followed the most straightforward mission design (Fig. 2B). In total, 184 images were collected at 54 m AGL. Agisoft Metashape was used for SfM processing following Workflow 1 (Fig. 2G) to generate orthomosaic (1.7 cm GSD) and DEM (3.4 cm GSD).

2.2.3. *Case Study 3 – Monitoring of recreational trail changes: Rainbow Mountain, Peru*

Case study 3 represents high mountain (altitude >4200 m a.s.l), sparsely vegetated settings. Assessment of trail condition and monitoring of their annual change was performed for the 1000-m-long section (150 m of multiuse section and 850 m of parallel hiking and horse-riding paths) of recreational trail in Cordillera Vilcanota, Peru (Fig. 6C). The trail is used by hikers and horse riders and is one of two main routes for visiting popular Rainbow Mountain (aka Vinicunca or Montana de Siete Colores) (Fig. 6F) (Tomczyk and Ewertowski, 2023). In contrast to Case Study 2, there was no physical barrier between these two types of trails. The tread of hiking trail was delineated using stone markers; however, horse-riding part was not restricted laterally. Between 2018 and 2019 substantial changes in the organization of visitor traffic happened – new car park and road were built, which caused the abandonment of the studied fragment of the trail - most of the visitors started using a new trail routed from the new car park. Therefore, In Case Study 3, we demonstrated a comparison of multitemporal surveys to verify if this abandonment resulted in any detectable changes in the trail characteristics.

UAV surveys acquired vertical and oblique low-altitude images – part of the survey followed simple flight design (Fig. 2C), while sections with more complicated relief followed flight design E (Fig. 2E). In total, 2884 images from 42 m AGL were taken in 2018, and 1022 images from 64 m AGL in 2019. The SfM processing in Agisoft Metashape followed workflow 2 (i.e., co-alignment of both surveys) (Fig. 2G). Surveys from 2018 and 2019 were co-aligned, following the approach proposed Cook and Dietze (2019), i.e., alignment and optimization of the sparse point cloud was performed for all images from both surveys together. In the next step, surveys were separated into two groups, and dense point cloud was generated independently for 2018 and 2019. The resultant orthomosaics and DEMs for 2018 were characterized by GSD of 1.3 cm and 2.3 cm respectively, and for 2019: 1.9 cm and 3.8 cm, respectively.

3. Results

3.1. *Ground-based verification of measurements of trail characteristics: Case Study 1*

"Meadows" Trail (Fig. 7A) mean trail measurements were compared between ground-based measurement and UAV-based measurements at 10 m, 30 m, and 50 m AGL to understand their relationship as a function of UAV height above the trail (Table 3). We found homogeneity of variances for both trail width ($p = .780$) and incision ($p = .367$) and the results of the ANOVA indicated that manual and UAV-based measurements were not significantly different for trail width $F(3,31) = 0.746$, $p = .533$, or trail incision measurements $F(3,31) = 1.183$, $p = .332$.

Similarly, manual and UAV-based measurements at 10 m AGL were compared from the "Ibis" trail (Table 4). The results of the independent samples *t*-test indicated there were no significant differences in mean trail width ($t(10) = 0.125$, $p = .903$), or incision ($t(10) = 0.707$, $p = .496$). Taken together these results indicate no statistically significant differences between methods and the limited amount of error we observed between the manual and UAV-based measurements is not functionally significant for management of trail conditions.

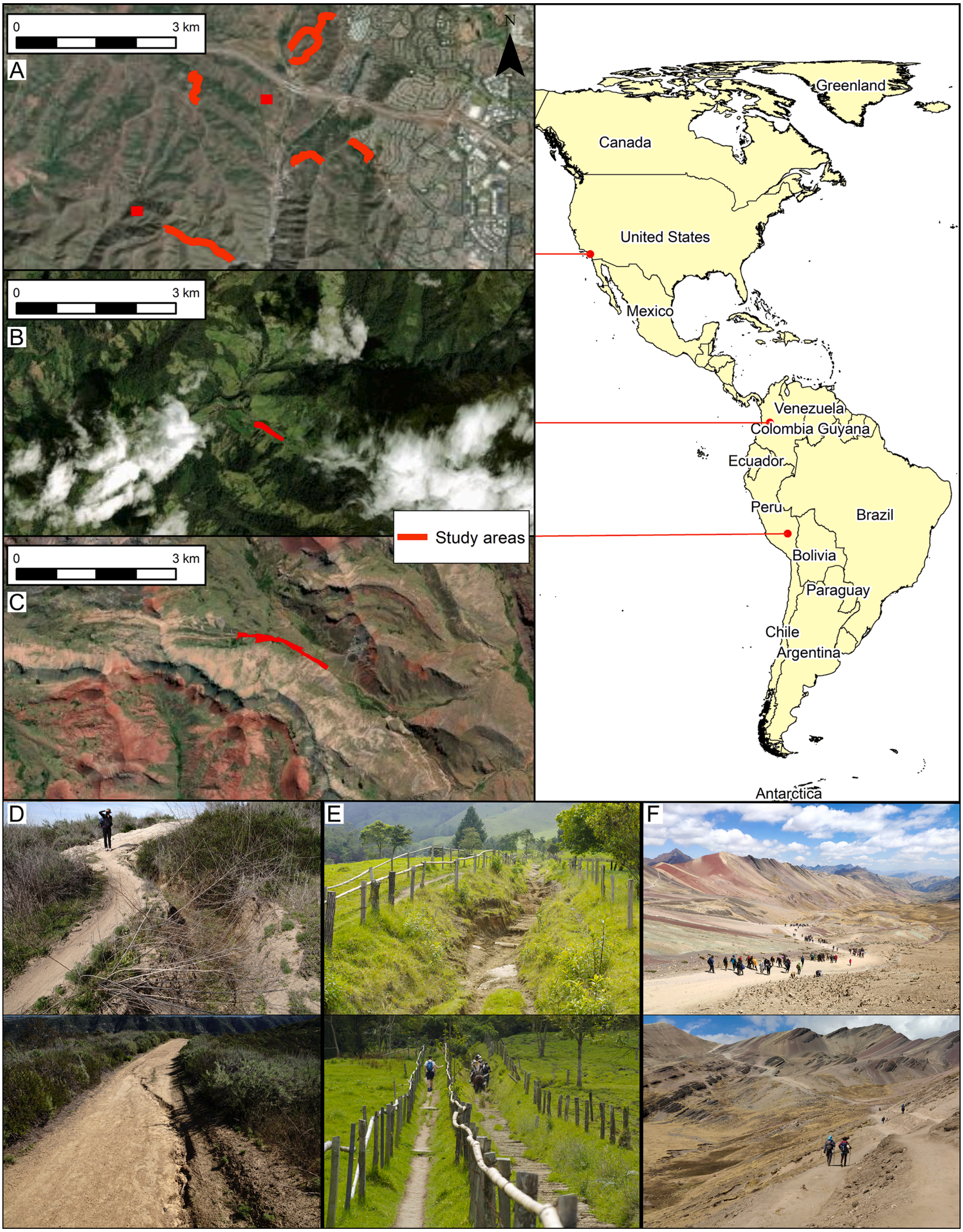

Fig. 6. Locations (A-C) and character of trails (D-F) in studied areas: A, D – Case Study 1 Orange County, California, USA; B, E – Case Study 2 Valley de Cocora, Colombia; C, F – Case Study 3 Vinicunca (Rainbow Mountain), Peru.

3.2. Mapping of trail characteristics and conditions: Case Study 2

Trail width – comparison of manual and object-oriented classification for trail tread delineation (Fig. 8; Table 5). Three types of trail surface: exposed soil, partly trampled vegetation cover, and artificial tread (wooden logs) were delineated. Combining these three classes provided us with the total width and area exposed to hiking and horse-riding impacts. Most of the differences between manual and semi-automatic approaches were associated with areas of partly trampled vegetation cover, which during object-oriented classification, were sometimes included in bare soil class, and sometimes not. However, these differences were not substantial (Table 5) and indicated that both approaches

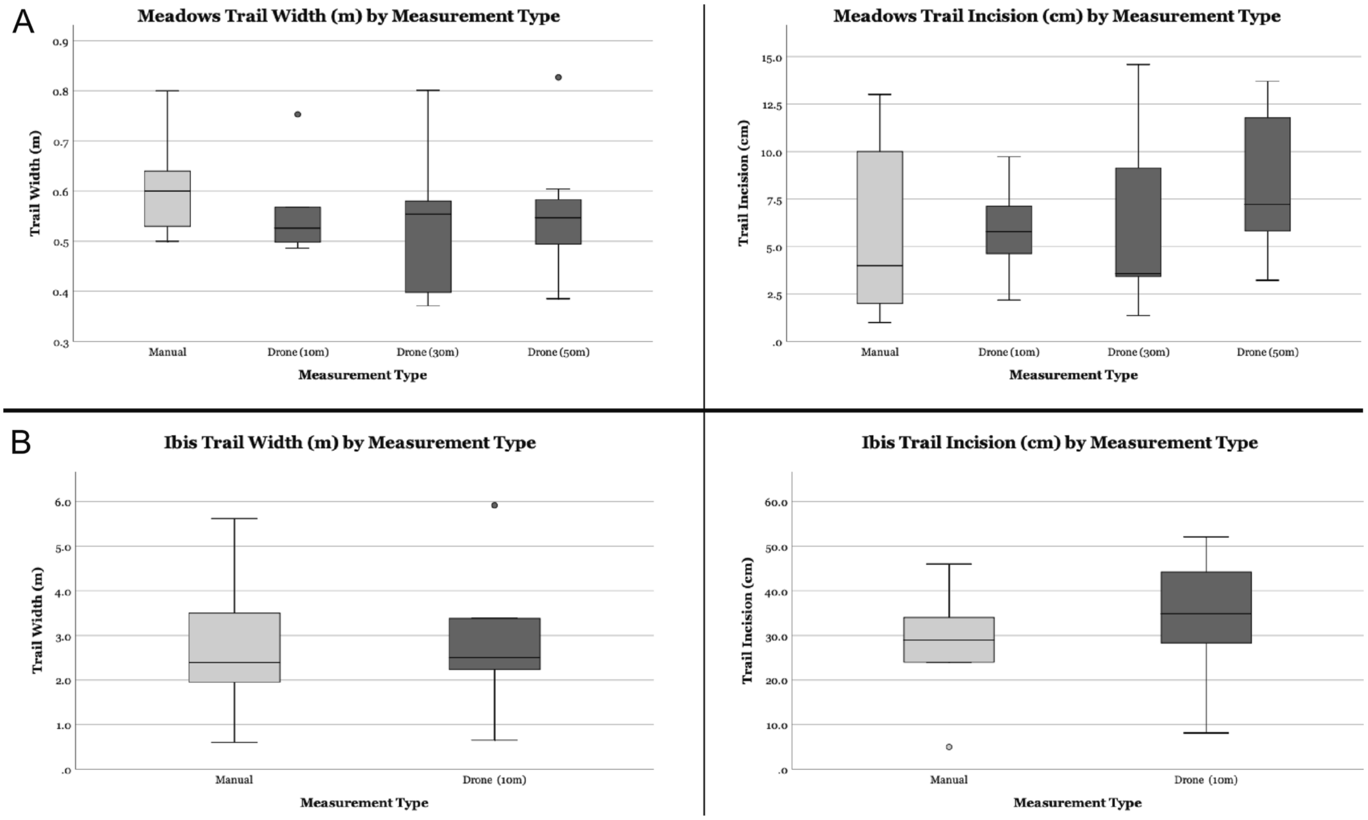

Fig. 7. Comparisons of UAV-based and ground-based manual intensive trail measurements of width and incision for selected trails in Orange County, California, USA: A – Meadows trail B – Ibis Trail.

Table 3
Meadows trail descriptive statistics of trail width and incision: comparisons of manual and UAV-based measurements at three AGL levels.

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
						Lower Bound	Upper Bound
Trail Width (m)	Manual	10	0.61	0.09	0.028	0.544	0.670
	UAV (10 m)	6	0.56	0.10	0.041	0.455	0.664
	UAV (30 m)	9	0.53	0.13	0.045	0.430	0.637
	UAV (50 m)	10	0.55	0.12	0.038	0.465	0.638
	Total	35	0.56	0.11	0.019	0.526	0.603
Trail Incision (cm)	Manual	10	5.40	4.33	1.368	2.306	8.494
	UAV (10 m)	6	5.87	2.55	1.039	3.201	8.545
	UAV (30 m)	9	5.97	4.32	1.439	2.653	9.290
	UAV (50 m)	10	8.39	3.49	1.104	5.891	10.885
	Total	35	6.48	3.88	0.656	5.148	7.815

Table 4
Ibis Trail descriptive statistics: comparisons of manual and UAV-based measurements of trail width and incision.

	Measurement Type	N	Mean	Std. Deviation	Std. Error Mean
Trail Width (m)	Manual	6	2.87	1.74	0.710
	UAV	6	2.74	1.69	0.692
Trail Incision (cm)	Manual	6	33.73	15.28	6.237
	UAV	6	27.83	13.60	5.552

(i.e., manual delineation and object-based classification) provide very similar results.

Comparison between hiking and horse-riding paths. Due to physical restrictions (ropes and fences) which limited visitors' dispersion, most impacts were related to the trampling of vegetation covers along the established corridors, soil erosion and compaction, and developments of muddy sections. Visitors did not fully use designed maximum trail width, i.e., the space between ropes and fences (hiking trail: 1.0–2.1 m; horse-riding trail: 2.8–4.2 m), and actual trail width (i.e., the width of trail tread consisted of exposed soil) was smaller (Table 5). Hikers used 54% of the total available area, whereas horse riders used 35% of the total available area. More significant differences were visible for trail incision. The hiking path was incised up to 0.4 m, and approximately 28% (137 m^2) of the trail surface area was incised >0.1 m (Fig. 9). In contrast, the horse-riding trail was incised along 87% of its whole area (704 m^2), and maximum incision reached up to 2.5 m. Horse-riding trail was also much more prone to the development of muddy sections which occupied 147 m^2 (21% of the equestrian trail area), compared to only 9 m^2 (3% of the hiking trail area) for hiking path.

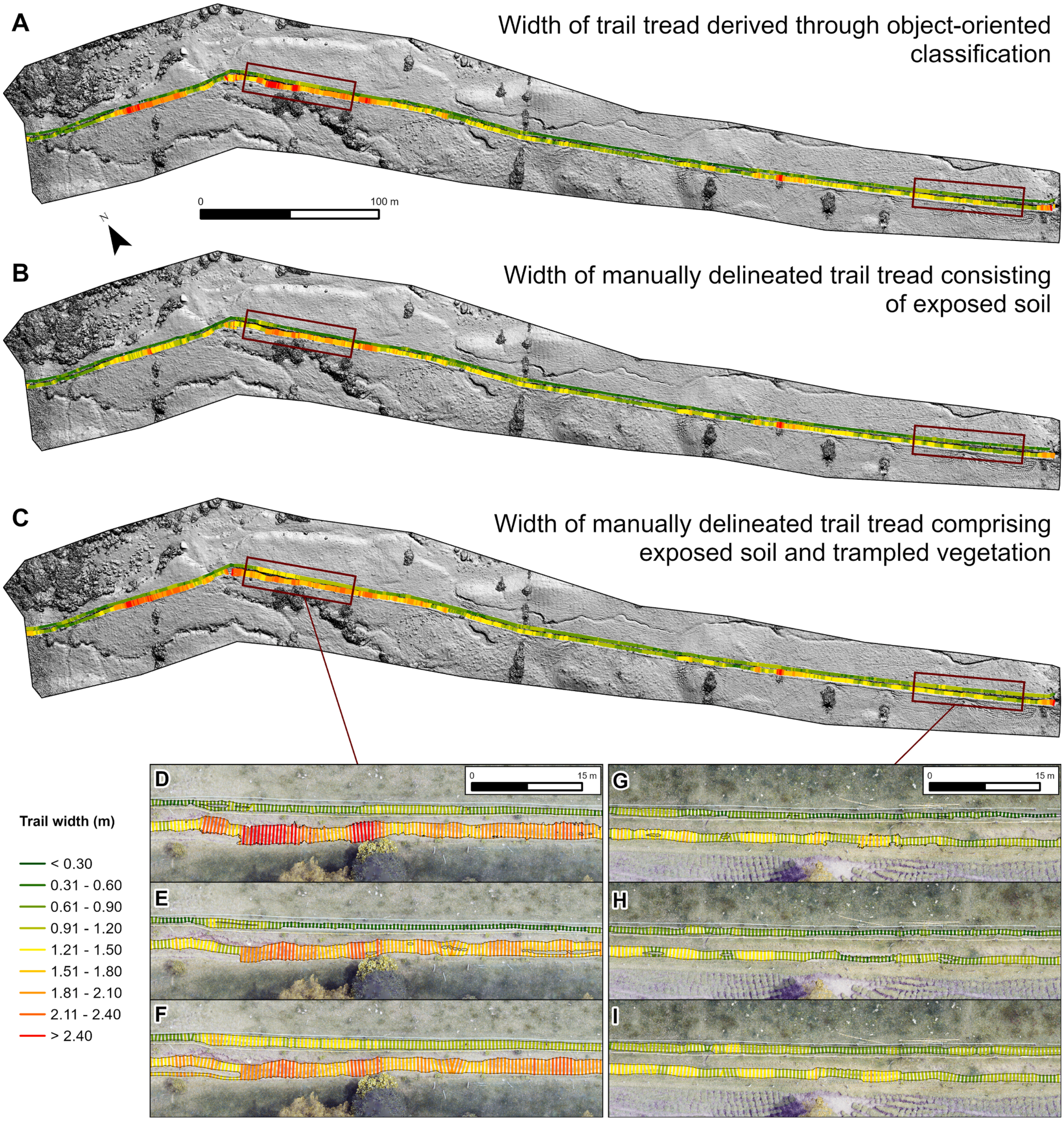

Fig. 8. Cartographic representations of trail width in Valle de Cocora, Colombia: A, D G - Trail tread derived through object-oriented classification; B, E, H - Manually delineated trail tread consisting of exposed soil; C, F, I - Manually delineated trail tread comprising exposed soil and trampled vegetation.

Classification of trail conditions - Based on the classification scheme (Table 2) most of the hiking trail belongs to the class: no degradation (3% of trail length), an acceptable level of damage (17%), and minor damage (81%). In contrast, most of the horse-riding trail belongs to damaged (22%) and heavily damaged class (74%). Cartographic visualization of trail degradation levels allows for rapid and easy-to-understand illustration of trail conditions (Fig. 10). At the same time, detailed spatial information about trail characteristic and condition stored in a geodatabase allows for more in-depth analysis and can inform managerial activities, such as trail restoration and conservation.

3.3. *One-year change in trail characteristics: Case Study 3*

Trail characteristics - The hiking trail in 2018 was relatively narrow (mean width of exposed soil <2 m), and not severely incised (90% of the trail was incised by <0.1 m). In contrast, horse-riding path, developed into the braided trail characterized by generally large width (up to 16 m of exposed soil width) (Table 6, Fig. 11). The incision of the equestrian trail was small (only 30% was incised >0.1 m). The characteristics of both trails in 2019 remained similar to 2018 (Table 6, Fig. 11).

Table 5
Trail characteristics in Valle de Cocora, Colombia.

Type of delineations	Trail	Width (m)				Area (m^2)
		Min	Max	Mean	SD	
Manual	hiking – exposed soil	0.2	1.3	0.5	0.2	305
	horse-riding – exposed soil	0.3	2.6	1.2	0.4	717
Semi-automatic (object-oriented classification)	hiking – exposed soil	0.2	1.2	0.6	0.2	331
	horse-riding – exposed soil	0.3	2.8	1.3	0.5	755

4. Discussion

4.1. Implementation of the proposed framework

As demonstrated in Case Study 1, no practical or statistically significant differences were observed between the trail survey methods or at varying flight altitudes which provides flexibility to configure the flight parameters to match budgets of time without significant trade-offs of accuracy and precision of measurements on the ground. In the case of most-commonly used consumer-grade drones, the desired level of accuracy can be achieved with AGL between 30 m and 40 m. Case Study 2 indicates that object-based classification and manual delineation of the trail tread provide similar results in situations where there are apparent differences in vegetation and exposed soil. Therefore, automatic delineation of the trail can be used for faster data processing when the algorithm can easily differentiate trail tread from trail sides.

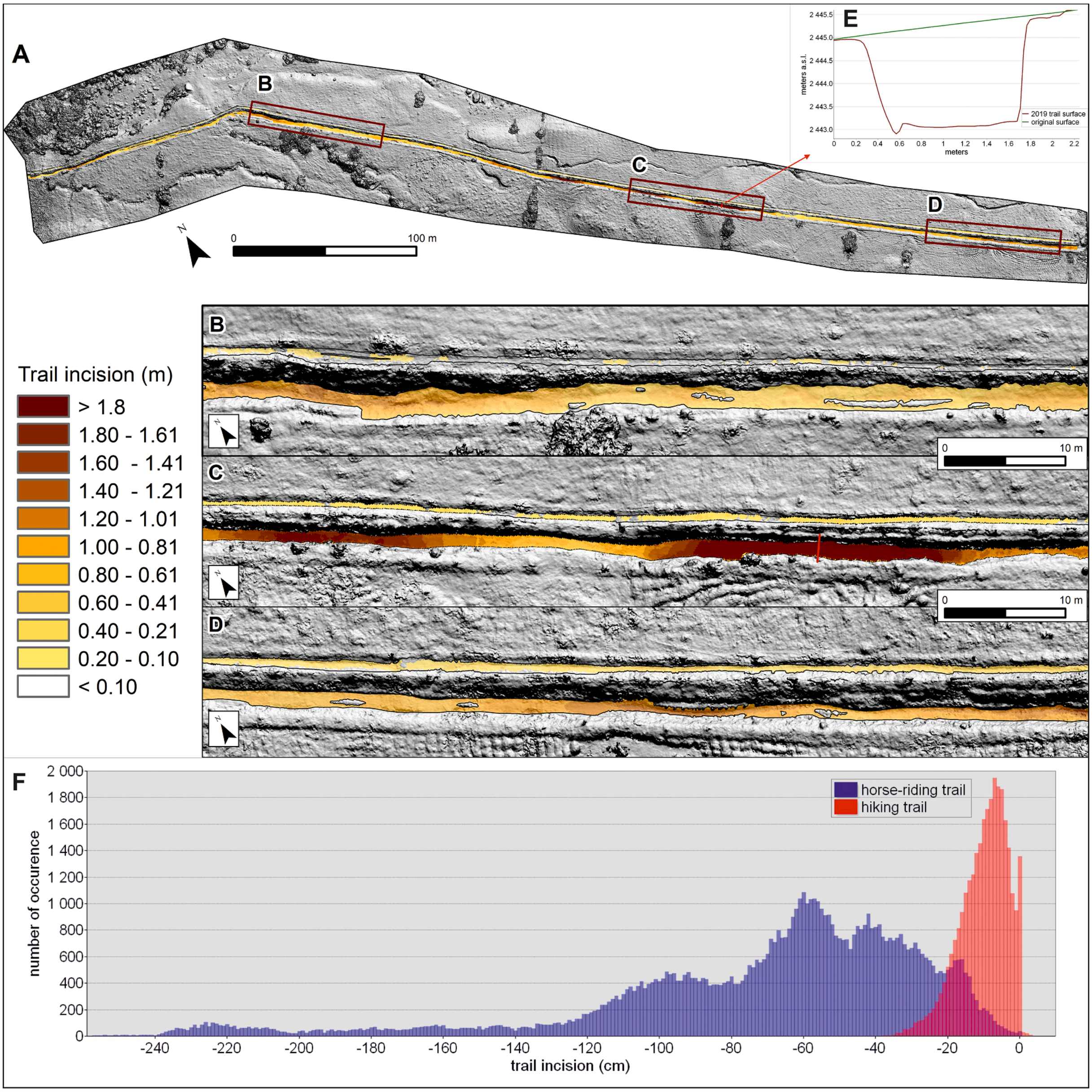

Fig. 9. Trail incision for Valle de Cocora: A, B, C, D – illustration of the spatial distribution of trail incision; E – example of elevation profiles for reconstructed original terrain surface and 2019 trail surface; F – frequency distribution of trail incision for hiking and horse-riding trail.

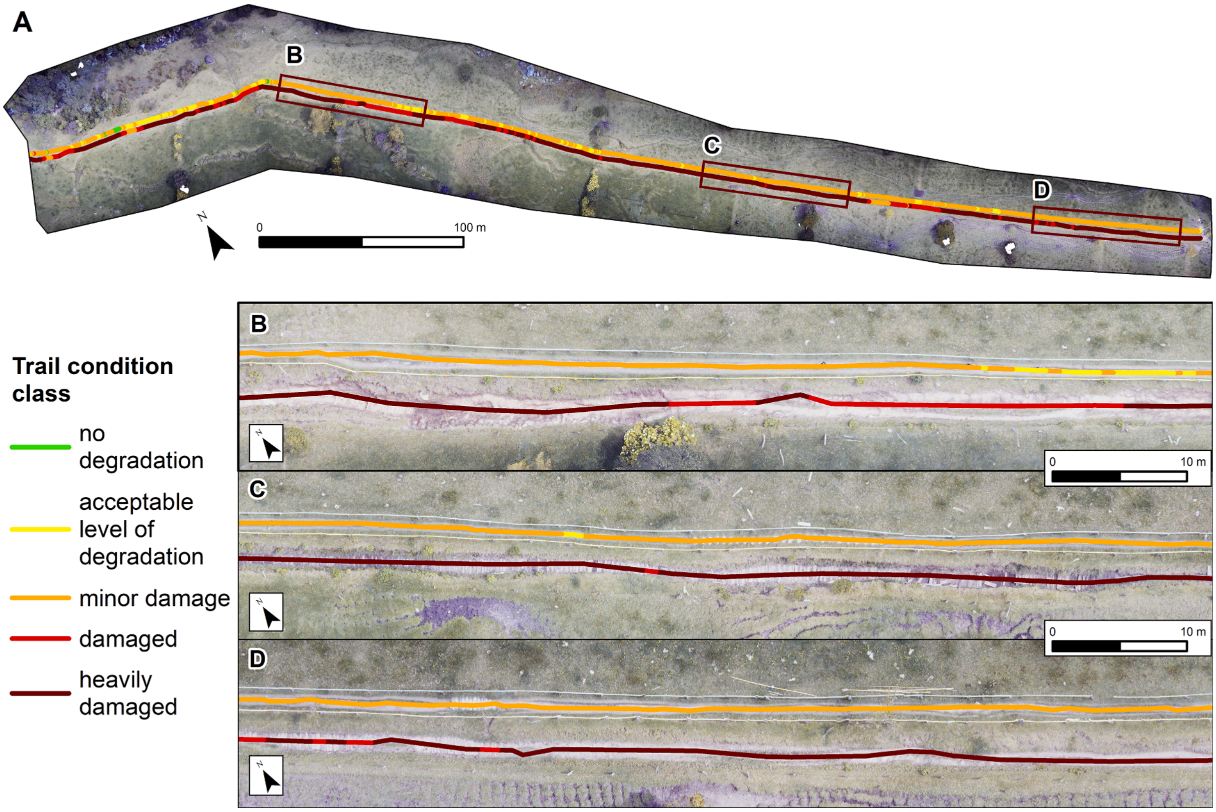

Fig. 10. Visualization of trail degradation levels, Valle de Cocora, Colombia. Trail condition class is based on ruleset presented in Table 2.

Table 6
Trail characteristics in Vinicunca, Peru.

Year	Trail	Width (m)				Area (m^2)
		Min	Max	Mean	SD	
2018	hiking – exposed soil	1.3	3.7	1.8	0.2	1530
	hiking – total	1.3	6.8	2.3	0.9	1930
	horse-riding – exposed soil	3.1	15.4	8.5	2.7	7171
	horse-riding – total	4.3	27.5	11.5	3.0	9758
	multiuse – exposed soil	6.0	23.6	16.5	3.6	2562
	multiuse – total	6.5	23.6	16.5	3.5	2565
2019	hiking – exposed soil	1.2	3.6	1.8	0.3	1520
	hiking – total	1.2	7.2	2.3	1.1	1918
	horse-riding – exposed soil	3.4	15.7	9	3.0	7688
	horse-riding – total	4.2	29.7	11.7	3.3	9998
	multiuse – exposed soil	6.0	24.0	15.9	3.9	2467
	multiuse – total	6.5	24.0	16.3	3.5	2528

Note: Total width = exposed soil + trampled vegetation cover.

4.2. Character of trail impacts

The presented Case Studies differ in the character of trails. For example, in Case Study 2, the visitors' movement was restricted by a physical barrier. Therefore, most of the observed impact was associated with trail incision (up to 2.5 m) and development of muddy sections. In contrast, in Case Study 3, visitors could disperse over a vast area due to the lack of significant physical restrictions. Consequently, the most visible impacts were trail widening (some sections were >20 m wide) and development of braided trails. However, this dispersion was probably a factor contributing to the generally low incision of the equestrian trail (only 30% was incised >0.1 m).

In Case Study 3, we performed multi-temporal surveys. In 2019, the studied trail section was abandoned and experienced much lower use than in 2018. Despite this fact, the trail characteristic in 2019 remained similar to 2018 (Table 6, Fig. 11). It can be related to a relatively short period passed since the opening of the new car park, and harsh, high-mountain setting (>4200 m a.s.l.) that did not allow for rapid vegetation recovery.

4.3. Management implications

Experiences from the implementation of the proposed framework combined with the established knowledge of recreation impacts and trail sustainability (see Monz et al., 2010; Hammitt et al., 2015; Tomczyk et al., 2017; Monz et al., 2021; Marion, 2023) helped to suggest four main applications of our approach in the context of trail management:

1) Assessment of trail characteristics for long sections of trails in open areas – a comprehensive survey of the trail network is required as a baseline for sustainable trail management, especially in the context of extensive trail networks (Hawes et al., 2006; Hawes and Dixon, 2014; Tomczyk et al., 2017; Marion, 2023). The most significant advantage of the proposed protocol is the ability to deliver uniform quality data for long trail sections in open areas thanks to the semi-automatization of the generation of basic trail attributes (e.g., trail width and incision) (see Sections 2.1.3 and 3.2).
2) Rapid inventory of trail impacts – Trails designed and used sustainably are usually stable and not seriously degraded (Cole, 2004; Monz et al., 2010; Marion, 2023). However, extreme natural events (e.g., intensive rainfall, wildfire, landslide) can trigger fast and intensive degradation (Tomczyk et al., 2016; Salesa et al., 2020). In such a situation, a rapid survey is required to assess the extent of the damage. Our framework can deliver detailed, quantitative data on the extent of trail surface damage, facilitating decisions on potential trail closure and quantification of costs related to trail repair.
3) Change-oriented monitoring – Crossing the tipping point concerning the type or level of use makes a trail unsustainable leading to its degradation (Cole, 1993; Hammitt et al., 2015; Salesa et al., 2019; Tomczyk and Ewertowski, 2023). Therefore, changes in trail usage

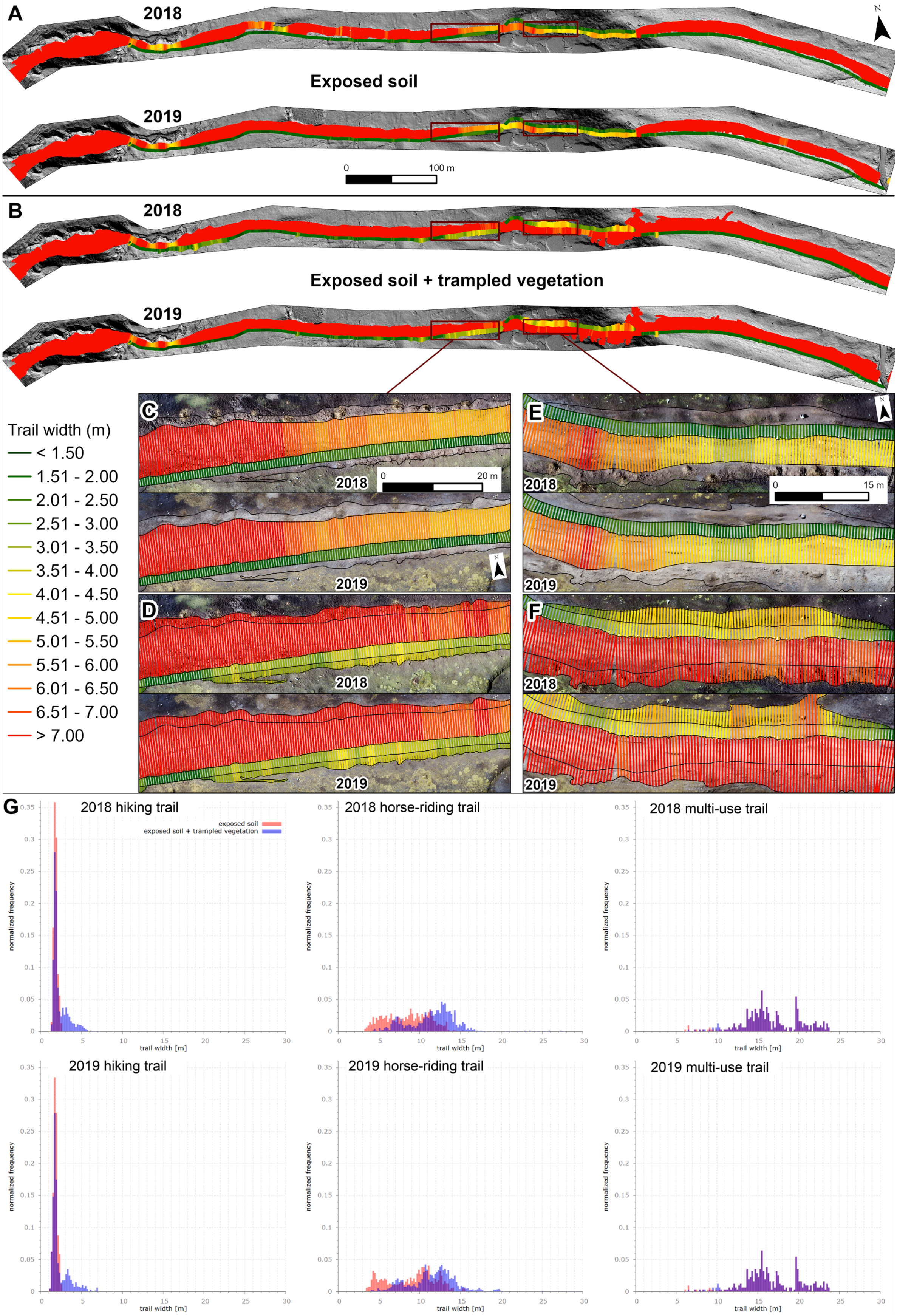

Fig. 11. Comparison of trail width in Vinicunca Case Study, Peru in 2018 and 2019: A, C, E - exposed soil only; B, D, F - total trail width (exposed soil + trampled vegetation cover); G - Histograms of normalized frequencies of trail width.

by introducing new types of use (e.g., biking) or increase in the level of use should be monitored systematically, and a multi-temporal survey using the proposed protocol can deliver regular data helping to assess the direction of changes (see Section 3.3). Monitoring of trail conditions is critical in the context of soil erosion, which is one of the irreversible trail impacts (Olive and Marion, 2009), and therefore should be avoided or limited. The amount of soil loss can be quantified through the repeat surveys of trail surfaces using the proposed workflow.

4) Accessible tools for trail monitoring – A UAV can be ready at any time under favorable weather conditions and can be operated with basic training. Several software solutions make it simple and straightforward to process the images into georeferenced objects, thus allowing park managers to decide on the optimal moment to survey an area without depending on external contractors that might operate within constrained time budgets.

4.4. Future research direction – More advanced application of UAV surveys in trail research

This study proposed a standardized protocol to use drones in trail research. We demonstrated that UAV-generated data can deliver valuable and spatially coherent information on trail conditions, including their spatial dimension and distribution. Such data can inform managers and deliver visualisations for visitors' education. However, UAV-generated data can also be utilized for more advanced analysis, briefly discussed below:

Classification of trail degradation - Park managers need to know about the condition of the trail system to undertake appropriate managerial actions (Hawes and Dixon, 2014; Tomczyk et al., 2017). It is especially problematic for extensive trail networks (see Dixon et al., 2004; Hawes et al., 2006). UAVs are a possible solution, as they deliver data of uniform quality over large areas. This information can be subsequently used to produce a classification of trail degradation using several approaches. One of them is the top–bottom approach, where at first, class ratings are established, and then trails or their segments are assigned to the appropriate class (e.g., Farrell and Marion, 2001; Nepal and Nepal, 2004; Manning et al., 2006; Monz et al., 2010). An example of such approach is presented in Section 3.2, where we used three indicators of trail conditions to assign trail sections to an *a priori* generated classification (Table 2, Fig. 10). The advantage of the top–bottom approach is development of a universal classification, which can be implemented in several different areas. However, the main limitation is that a single condition class usually contains several forms of impact (in our example three indicators), and as a result interpretation of classes can be challenging (Marion et al., 2006). An alternative bottom-top approach utilizes detailed information on trail conditions to perform classification of the trail sections using, e.g., classification and regression trees (Tomczyk et al., 2017). A conceptually similar strategy, which can be used for both site impacts and trail assessment, was proposed by Monz and Twardock (2010), which implemented multivariate data reduction and classification procedures for campsites in Prince William Sound, Alaska, USA. UAV-generated data are predestined to bottom-top approach, as they provide consistent quality data over large trail networks.

Investigations of factors influencing trail degradation - UAV-generated data allow for systematic investigations between various indicators of trail condition (e.g., trail width, trail incision) and environmental factors (e.g., slope, aspect, trail alignment) thanks to uniform quality over extensive areas. The most straightforward approach is a linear regression. More advanced methods may include principal component or cluster analysis to investigate multiple factors and interrelations. After performing object-oriented land cover classification (Juel et al., 2015; Melville et al., 2019), it is possible to extend tested factors to vegetation types.

Modelling of water flow and soil erosion - Modelling of water flow through the landscape is one of the potentially critical applications of UAV-generated data, beneficial for planning and designing of trail networks. It is possible to indicate which slope sections are more prone to the concentrated water flow and, in consequence, accelerated soil erosion, using hydrological models over the detailed representation of the relief (see Méndez-Barroso et al., 2018). With topographic surveys, such analyses were feasible for very short sections of trails (e.g., Tomczyk and Ewertowski, 2013b); however, UAV-generated data offers opportunity to analyze whole trails or even whole trail networks. Identification of sections characterized by accelerated water flow (i.e., prone to erosion) or diminishing in transport capacity (i.e., depositional centers) can be used to (re)route trail to avoid such segments, or indicate the most suitable location for drainage infrastructure.

Investigation of invasive species and their spread along the recreational trail corridors have been traditionally done using time-consuming field-based surveys (Liang et al., 2014). Given the ability to obtain detailed RGB images (and possibly also infrared), multi-seasonal UAV data can be used to investigate invasive species (Wu et al., 2019; Grubesic and Nelson, 2020; Valente et al., 2022). Our study used object-oriented classification of RGB images to delineate trail tread (Section 3.2); however, the RGB data has limited ability to classify some non-green vegetation. This issue can be overcome by including the use of geomorphometric attributes generated from DEM and multispectral imagery to enhance the classification results (see Juel et al., 2015; Prošek and Šímová, 2019).

Quantification of plant disturbance - Optical and multispectral data, combined with DEMs, can be used for biomass estimation (plant height), enhanced by the potential use of multispectral sensors and/or combination with LiDAR (see Chen et al., 2012a; Bendig et al., 2015). In this way, disturbance of plant communities can be assessed by comparison of vegetation along the trail, with analogue plant communities in undisturbed settings.

(Re)designing of trail routes using multi-criteria analysis – The most straightforward approach includes designing an optimal path using only one factor (e.g., excluding slopes >10°). A more sophisticated application involves multi-criteria analysis and least-cost path analysis, e.g. using results of trail conditions classification of existing trail network to develop a model of relationship between factors, and then use this model and least-cost path analysis to design trail routes characterized by minimum potential degradation (see Tomczyk and Ewertowski, 2013a).

5. Conclusions

We proposed a 6-stage operational framework for the application of small, budget UAVs for the mapping and monitoring of the recreational trail conditions. We have demonstrated that through the application of the proposed framework, it is possible to map, in fine-resolution, in a spatially-coherent manner, information about the condition of recreational trails, such as trail width, trial incision, the occurrence of muddy sections, and others. The proposed approach opens new perspectives on detailed mapping and monitoring of trail conditions, and we suggested and discussed possible further directions of research and application development.

CRediT authorship contribution statement

Aleksandra M. Tomczyk: Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Marek W. Ewertowski:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Noah Creany:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Francisco Javier Ancin-Murguzur:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Christopher Monz:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data related to this article is available from 10.5281/zenodo.8303440 (Tomczyk et al., 2023).

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