Geomorphological effects of tourism and recreation: quantification and monitoring of trail impacts in mountain areas

Motivation: Mountain protected natural areas (PNAs) such as national parks often constitute regions rich in bio- and geodiversity with beautiful scenery. They are currently under increasing pressure to supply both conservation and recreation, which frequently leads to conflicts of interest. Recreation often brings substantial revenues for conservation and human health, so excluding visitors from PNAs is not a solution that is possible everywhere. However, recreation unavoidably leads to negative impacts (Fig 1). Therefore, management needs to have detailed data about these impacts to minimise conflicts between recreation and conservation. Yet, methodologies to collect comprehensive data about recreational impacts to inform management activities' prioritisation have received little attention in the previous studies, and this gap in the knowledge is addressed in our project.

Fig. 1. Examples of trail impacts: (A) deposition of material due to improper trail drainage; (B) muddy section and water puddle; (C) exposed roots and rocks on the too-narrow section of the trail, forcing visitors to trample trail sides; (D) erosional rill along the trail tread; (E) deep erosional gully reaching bedrock; (F) erosional gully with exposed rocks: Due to uncomfortable walking condition, visitors created an informal path next to the designated trail.

Objectives*:* Recreational trails are a key element of infrastructure, which enable visitors to travel through recreation areas and engage in various activities such as hiking, biking, horse riding. In this project, we will develop and test a novel framework for high-resolution mapping and monitoring of recreational impacts in mountain areas to derive spatially coherent information about indicators of recreational trail conditions. Implementing this framework in a wide range of benchmark settings will enable us to understand and quantify the dynamics of landscape response to direct human impacts. The main objectives of the project are **(1)** To quantify land surface dynamics in cm-scale: That will be achieved by development and operationalisation of integrated framework (close-range terrestrial and aerial remote sensing + ground surveys + geographic information systems [GIS]) for systematic quantification and monitoring of trail impacts in mountain recreation areas. The framework will enable us to quantify patterns and volume of landscape changes resulting from different types of direct human activities (hiking, biking, horse riding, ATVs) and hydro-meteorological events (e.g. intense rainfalls). **(2)** To determine the role of environmental factors (topography, geology, local climate, type of vegetation), managerial factors (trail design, trail location) and use-related factors (level of use, type of use) in the degradation of trails in recreation areas using data mining approach (classification and regression trees, random forest, neural networks) and statistical correlation and regression models. **(3)** To investigate how spatial patterns of visitors' behaviour influence trail condition by developing an agent-based approach for classifying recreational trail degradation and modelling soil erosion. Such a bottom-top model will include feedback between different types of human activities and geomorphic processes and a capacity to simulate future human impact over a mountain landscape that is undergoing increasing pressure due to the intensification of recreation use.

Methods: In this project, we will develop a new methodological approach leading to understanding not only point-specific 2D changes but also to study volumetric transformation and collect time-series of spatially dependent data. Our approach includes 3D reconstruction of trail surface and its vicinity based on low-altitude aerial images from unmanned aerial vehicles (UAV, i.e. drones) combined with terrestrial images (for forested sections of trails), which can be subsequently processed through the structure-from-motion (SfM) process to generate detailed digital elevation models (DEMs) and linked with qualitative data about visitors' behaviour collected using: (1) map-based interviews; (2) GPS trackers; (3) time-lapse cameras

Expected results: The most important contributions to recreation ecology will be (1) Comparison of impacts generated by different types of use (hikers, bikers, horse riders, ATVs); (2) Quantification of effects of different levels of use; (3) Quantification of relief changes related to intensive rainfalls; (4) Investigation of visitor patterns and their influence on environmental degradation; (5) Simulation of future impacts. From a scientific perspective, the most significant impact will be an increased understanding of the trade-offs between natural environment protection and other external drivers, including recreation. On a broader scale, the project results and their impact on more consistent mapping and monitoring of recreational trail conditions will enhance our understanding of relationships between direct human impact and landscape dynamics, which are among the most critical issues of modern times, not only for scientists and politicians but also for society.