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Landscape degradation and development as a result of the intensification of tourism activity in a fragile, high-mountain environment: a case study of Vinicunca (Rainbow Mountain), Peru

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Motivation and aim: Mountain areas with beautiful scenery are attractive to visitors and offer such ecosystem services as recreation and spiritual opportunities. However, the mountain environment is fragile and easily degraded when recreation is not appropriately managed. This degradation limits recreation potential and can also be dangerous to visitors and local communities. Our study presents documentation of landscape degradation in response to a rapid increase in visitors number in an extreme environment of high-altitude (> 4000 m a.s.l) tropical mountains. Rainbow Mountain (Vinicunca) in Peru only recently became a world-renowned tourist destination. Rapid visitors' influx caused severe landscape degradation and partly uncontrolled infrastructure development. We characterized and mapped different types of impacts related to visitor pressure and evaluated activities aimed to limit degradation and enhance visitor behaviour.

Method of investigation: Fieldworks in the vicinity of Vinicunca were conducted in 2017, 2018 and 2019. Geomorphological mapping involved a field-based approach combined with the interpretation of orthomosaics generated from UAV imagery and high-resolution satellite data (WorldView-2, 2020). UAV images were processed using the structure-from-motion workflow. The characterization of dominant morphogenetic processes was based on ground-based observations, photographic documentation, and remote sensing data.

Results and conclusions: We identified seven dominant morphogenetic processes responsible for landscape degradation: Based on field geomorphological mapping, five processes were most important in the degradation of landscape: (1) Vegetation trampling by hikers and animals (mostly horses, but also llamas); (2) Soil erosion concentrated on bare soil surfaces and caused the development of rill erosion and surface flow; (3) Soil compaction lead to soil hardening which in turn facilitate accelerated surface flow from the trail surface and enhancing water erosion further downslope; (4) Freeze-thaw cycles which weakened structure of the material making it more prone to erosion; (5) Dry-wet cycles also preparing the soil for further degradation activity. The abovementioned processes formed characteristic morphogenetic elements of the trails, which included: (1) Severely incised trail surface where the bottom of the trail can be as low as 1 m below the original land surface; (2) Braided trail network consisting of several parallel paths, without incision, or moderately incised with vegetation between individual paths; (3) Single, wide, bare soil

trail tread indicating that vegetation was removed, and the surface is prone to soil erosion; (4) Water puddled in flat areas caused the development of muddy section, That in turn lead to increase in trail width, as the visitors tried to bypass muddy segment and trampled vegetation in their vicinity. Based on collected data, trail classification was developed that include a functional model of trails in slope and flat conditions. Our results indicate that in such a fragile environment, a rapid increase in visitors numbers can lead to permanent changes in the environment. Therefore, appropriate managerial actions need to be taken to limit the degradation of the environment. Trails' maintenance is critical for limiting the degradation of trail vicinity, enhancing visitor perception, and limiting hazardous conditions.

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