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How Networks of Informal Trails Cause Landscape Level Damage to Vegetation

Agustina Barros[1,2] · **Catherine Marina Pickering**[2]

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Abstract When visitors are not constrained to remain on formal trails, informal trail networks can develop and damage plant communities in protected areas. These networks can form in areas with low growing vegetation, where formal trails are limited, where there is limited regulation and where vegetation is slow to recover once disturbed. To demonstrate the extent of impacts from unregulated recreational use, we assessed damage to alpine vegetation by hikers and pack animals in the highest protected area in the southern Hemisphere: Aconcagua Park, in the Andes. Within the 237 ha area surveyed in the Horcones Valley, over 19 km of trails were found, nearly all of which (94%) were informal. This network of trails resulted in the direct loss of 11.5 ha of vegetation and extensive fragmentation of alpine meadows (21 fragments) and steppe vegetation (68 fragments). When levels of disturbance off these trails were quantified using rapid visual assessments, 81% of 102 randomly located plots showed evidence of disturbance, with the severity of disturbance greatest close to trails. As a result, vegetation in 90% of the Valley has been damaged by visitor use, nearly all of it from unregulated use. These results highlight the extent to which informal trails and trampling off-trail can cause landscape damage to areas of high conservation value, and hence the importance of better regulation of visitor use. The methodology used for off-trail impact assessment can be easily applied or adapted for other popular protected areas where trampling off-trail is also an issue.

Keywords Recreation · Protected areas · Disturbance · Landscape impacts · Mountains

Introduction

Protected areas play a key role in supporting the conservation of biodiversity and the provision of ecosystem services (Chape et al. 2005; Lockwood et al. 2006). They are also popular destinations for nature-based tourism and recreation, with over eight billion visits to terrestrial protected areas globally (Balmford et al. 2015) and a predicted annual growth of 3.3 % through to 2030 (Leung et al. 2015). Reflecting this popularity, there are thousands of kilometers of recreational trails traversing protected areas, which can provide important social and human health benefits, as well as generate revenue to finance conservation activities (Bedimo-Rung et al. 2005; Leung et al. 2015; Morrison et al. 2012). However, recreational trails can also produce negative environmental impacts and reduce the conservation value of the protected areas (Ballantyne and Pickering 2015; Hill and Pickering 2006; Monz et al. 2010a). These impacts pose a challenge to park managers that often have the dual mandate of conserving biodiversity while also providing compatible recreational opportunities (Lockwood et al. 2006; Monz et al. 2010a; Walden–Schreiner et al. 2017).

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✉ Agustina Barros
anaagustinabarros@gmail.com
abarros@conicet-mendoza.gov.ar

[1] Instituto Argentino de Nivología y Glaciología y Ciencias Ambientales (IANIGLA), Centro Científico Tecnológico (CCT) CONICET Mendoza, Av. Ruiz Leal s/n, C.C 330, Mendoza, Argentina

[2] Environmental Futures Research Institute, School of Environment, Griffith University, Gold Coast, QLD 4222, Australia

Recreational trails have a range of negative environmental impacts including on soils, water ways, animals, and plants (Ballantyne and Pickering 2015; Monz et al. 2010a; Newsome et al. 2012). This includes damage to plant communities of high conservation value from the formation and use of trails (Ballantyne and Pickering 2015; Dixon et al. 2004; Pickering and Barros 2015; Pickering and Norman 2017). Impacts include declines in plant cover, height and changes in plant composition (Barros et al. 2013; Leung et al. 2011), introduction of weeds (Barros and Pickering 2014b; Wells and Lauenroth 2007; Wolf and Croft 2014), and soil loss and compaction (Deluca et al. 1998; Lucas-Borja et al. 2011; Ólafsdóttir and Runnström 2013; Tomczyk et al. 2016). Some of these impacts are from trails formally designed, constructed, and maintained by land managers (Hill and Pickering 2006; Pickering and Norman 2017), while others are from informal trails created by visitors (Ballantyne and Pickering 2015; Barros et al. 2013; Nepal and Nepal 2004).

Recreational trails can also be formed and used by pack animals, including horses and mules (Barros et al. 2013), which are increasingly used in some protected aras to support tourism and management (Barros et al. 2014a; Barros et al. 2015; Walden–Schreiner et al. 2017). Horses and mules on trails can damage vegetation by trampling and grazing, increase soil erosion and compaction, add nutrients to soils and waterways from manure and urine, and increase the potential introduction and dispersal of weeds through seed attached to hooves, fur and in dung (Ansong and Pickering 2013; Barros and Pickering 2014b; Loydi and Zalba 2009; Pickering et al. 2010). In addition to these trail impacts, pack animals can contribute to broader-scale impacts when they leave trails (Barros and Pickering 2015; Newsome et al. 2004; Walden–Schreiner et al. 2017).

Assessing landscape level impacts from recreation trails (formal and informal) is an area of increasing interest for researchers and managers, including the fragmentation of plant communities by trail networks (see recent review by Ballantyne and Pickering 2015a of trail impacts). Internal fragmentation can occur when formerly contiguous areas of vegetation become separated by areas of bare compacted soils due to the creation and use of trail networks (Ballantyne et al. 2014; Leung et al. 2011). As a result there is a reduction in the total amount of undisturbed habitat in a given area (Ballantyne et al. 2014). Internal fragmentation from trail networks can alter hydrology and soil moisture regimes, restrict movement of some native animals and plants among fragments, and enhance the movement of some invasive species along the trails (Leung et al. 2012; Pickering and Mount 2010; Wimpey and Marion 2011). Along with the direct effects of fragmentation due to trails, more damage occur when visitors and pack animals leave trails and trample vegetation in the fragments (Walden–Schreiner et al. 2017; Ballantyne et al. 2014; D'Antonio and Monz 2016; D'Antonio et al. 2013).

Networks of informal trails often form around the start of popular routes particularly when low growing vegetation does not impede movement off-trails (D'Antonio and Monz 2016; Leung et al. 2011; Monz et al. 2010b; Walden–Schreiner and Leung 2013). This facilitates visitor off-trail access to viewpoints, meadows, rivers, and lakes, as well as the off-trail movement of pack animals when grazing (Barros et al. 2014b; Walden–Schreiner et al. 2017). Assessing these more diffuse impacts remains a challenge for many protected areas, in particular those with limited resources for implementing larger-scale monitoring programs (Hill and Pickering 2008; Magro and Barros 2004; Monz et al. 2010b).

To evaluate how extensive these impacts could be from unregulated use, we assessed damage in the most popular area of Aconcagua Provincial Park in the Andes of Argentina, where a network of informal trails has formed near the main entrance to the Park in the Horcones Valley (the Valley hereafter) (Barros et al. 2015) (Fig. 1). Specifically, we quantified: (1) the lineal extent and types of trails (formal and informal) and other visitor infrastructure in the Valley, (2) the area of vegetation lost due to the trails, and the extent to which they fragment the remaining vegetation, and (3) the level of disturbance to vegetation off-trails. By doing so we can assess if networks of informal trails have landscape level impacts affecting the ecological integrity of this area of high conservation value, which is also a popular tourism destination. We also show how park agencies can use relatively rapid Global Information System (GIS) and visual assessment methods to document these impacts, and hence are able to identify key sites for management and remediation.

Materials and Methods

Study Area

Aconcagua Provincial Park in Mendoza province, Argentina (710 km^2, 2400–6962 m above sea level, 69°56' W, 32° 39' S), is a Category II International Union for the Conservation of Nature Park in the Central Andes. The area was designated as a protected area in 1983 to conserve glaciers, rivers, alpine ecosystems including rare plant communities, and archeological sites around Mt Aconcagua (6961 m) (Barros et al. 2015). As Mt Aconcagua is the highest peak in the southern and western Hemispheres, it has become a very popular destination for mountaineers, hikers, and sightseers (Barros et al. 2013). Due to the limited road access to campsites and roughness of the terrain, most mountaineering involves commercial trips lead by guides

Fig. 1 Different types of recreational trails in the popular Horcones Valley in Aconcagua Provincial Park, in the high Andes. **a** formal natural-surfaced trail, **b** hiker informal trail, **c** mixed use (hiker and pack animals) informal trail, **d** fragmentation caused by networks of formal and informal trails

with pack animals, mostly mules, used to transport equipment for the expeditions (Barros et al. 2015).

The most popular route to the summit of Mt Aconcagua is from the trailhead in the Horcones Valley, just off the international highway “The Paso Los Libertadores” connecting Argentina and Chile (Fig. 2). This valley is also a popular sightseeing destination, with around 27,000 day visitors annually (Barros et al. 2015). Over 4500 mountaineers and hikers traverse the Valley annually (Barros et al. 2015) using over 3000 pack animals to transport their equipment.

The topography of the Valley consists of hummocky, rolling glacial till deposits with intermixed ridges and depressions closest to the trailhead (Espizua and Pitte 2009). There is limited infrastructure in the Valley consisting of a visitor center, 5.2 km of road from the Park boundary to the start of the trails, two small carparks, a helipad, a park ranger station and 2 km of formal trails (Fig. 2).

The Park is in the Andean biogeographic region (Morrone 2006) and is characterized by a cold and dry climate, with low temperatures year round (Departamento General de Irrigación 2011). As a result, vegetation in the Park occurs mainly in the valley floors where conditions are slightly warmer and wetter. The two plant communities in the Park and the Valley are alpine steppe vegetation (29.5% of the 710 km area of the Park), and the very rare alpine meadows (0.4% of the Park) (Barros et al. 2015). Vegetation cover in the alpine steppe is relatively sparse (~ 50% cover) and consists of small shrubs interspersed with tussock grasses and low growing perennial herbs. The rare fragile alpine meadows, in contrast, have near complete

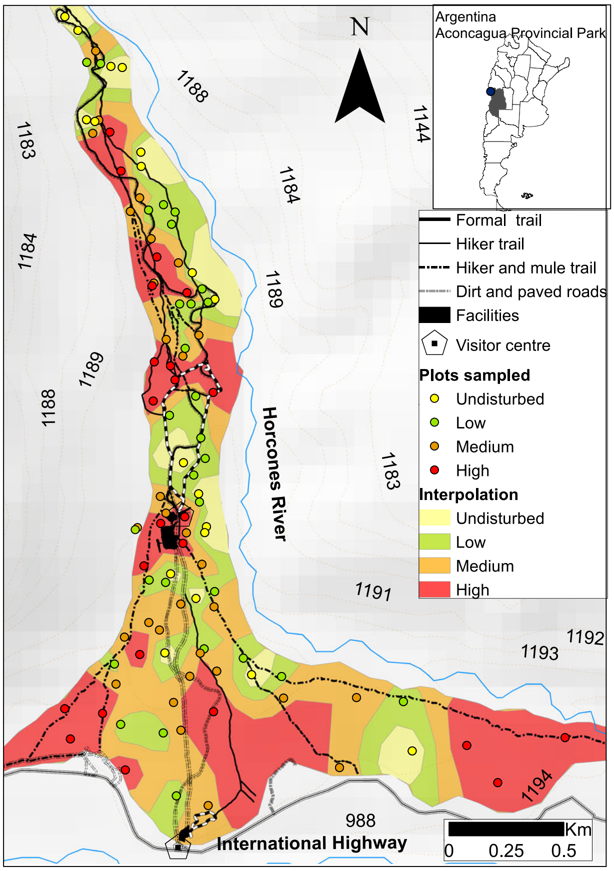

Fig. 2 Map showing the 237 ha area surveyed in the popular Horcones Valley in Aconcagua Provincial Park (69°56’ W, 32°39’ S), in the Andes. The map includes data on trails and other visitor infrastructure features, level of disturbance off-trails in plots surveyed, and the estimated area covered by each disturbance category based on the spline interpolation method in ArcGIS

vegetation cover consisting of low growing sedges, rushes and perennial herbs (Barros et al. 2013; Mendez et al. 2006). Meadows are popular sites for pack animals to graze, resulting in extensive damage to the meadows which evolved in the absence of hard-hooved large grazing mammals (Barros et al. 2014b).

Mapping Trails and Other Visitor Infrastructure

Visitor impacts were assessed in the most popular area of the Park in the Valley. The area to be surveyed in the field was first mapped in ArcGIS (10.1) using a high resolution ALOS satellite image (ALOS 2010). The southern boundary of the survey area (and of the Park itself), is the international highway (2700 m above sea level) between the city of Mendoza in Argentina and the capital of Chile, Santiago. The east boundary was the step edge of the Horcones River, while the west boundary was defined by the ridge line of the Valley. The north boundary was demarcated by the bridge over the Horcones River (3000 m above sea level) which acts as a boundary for day visitors. The total area of the survey area was 237 ha (Fig. 2). Spatial and attribute data for plant communities in this area were obtained from the Park agency in the form of GIS layers (Zalazar et al. 2007). However, due to the small area of alpine meadow in the Valley, the alpine meadows were later remapped in the field using a Garmin Oregon 450 GPS device to increase the accuracy of the data.

To assess the extent of the network of recreation trails in this area, a protocol for mapping trails and fragmentation was used (Monz et al. 2010b; Wimpey and Marion 2011). First, all informal and formal trails and roads were recorded in the field using a hand held Garmin Oregon 450 GPS. Trails were recorded as line features while other types of infrastructure were mapped as polygons. The trails were also classified in the field as: (1) formal trails designed by the Park agency, (2) informal trails used by hikers, and (3) informal multi-use trails used by hikers and pack animals (Fig. 1). The classification was based on field observations and information from Park staff. Where trails were less than 1 m apart, they were treated as a single braided trail due to the accuracy of the GPS receiver (average spatial error 1.8 ± 0.9 m) (Wing 2011). The average width of informal and formal trails was measured with a tape measure and recorded every 100 m along the trails to determine the area without vegetation along the trails. Line feature data recorded with the GPS from the Garmin and field data on the width of trails were then entered in ArcGIS (10.1) and converted into polygons to generate a map of all trails (Fig. 2).

Level of Disturbance Off-Trail

A rapid assessment method was used to assess disturbance to vegetation off-trails (informal and formal). A series of variables reflecting the types of disturbance caused by visitors and pack animals within the Park (Barros 2014), were identified based on consultation with park staff, prior field observations and reference to the recreation ecology literature. These variables were: (1) presence of horse/mule dung, (2) obvious grazing damage by pack animals to vegetation, (3) obvious trampling damage to vegetation and soils, and (4) soil movement (e.g., heavy machinery used for trail/road construction and maintenance) (Table 1). The potential impacts from the variables selected to determine disturbance in this Park have been summarized in recent literature reviews by several authors (Ansong and Pickering 2013; Ballantyne and Pickering 2015; Barros et al. 2014a; Marion et al. 2016; Monz et al. 2010a; Pickering et al. 2010). Although soil movement was not directly caused by visitors and pack animals, it was considered part of the impacts due to the provision of facilities for tourism

Table 1 Definitions for each of the variables selected to assess the level of off-trail disturbance in the 237 ha area surveyed in the Horcones Valley in Aconcagua Provincial Park

Disturbance variable	Description	Disturbance categories			
		Undisturbed	Low	Medium	High
Dung	Evidence of horse/mule dung piles	Not present	1 to 2 dung piles	3 to 5 dung piles	>5 dung piles
Grazing	Evidence of physical disturbance to a plant (e.g., removal of shoot parts from grazing)	No evidence	1 to 2 plants grazed	3 to 5 plants grazed	>5 plants grazed
Trampling	Evidence of footprints and mule/horse hoof prints	No evidence	1 to 2 foot/hoof prints	3 to 5 foot/hoof prints	>5 foot/hoof prints
Soil movement	Evidence of heavy equipment use during trail/road construction	No evidence	No evidence	No evidence	Soil movement

(Godefroid and Koedam 2004; Pickering and Norman 2017).

The disturbance variables were used to assess disturbance to vegetation off the trails in 102 randomly located 5 × 4 m plots within the 237 ha area surveyed in the Valley. The size of the plot was defined based on the general guidelines for plant surveys for these vegetation types (Kent 2012) and to provide a practical scale for the observer to quantify the level of disturbance. Plots were selected off the trail network using the Hawth Tool analysis extension in ArcGIS (Beyer 2004), with a minimum distance of 50 m between points and the edge of the plots at least 1 m from trails and other infrastructure. As a result of the larger area of steppe vegetation in the Valley (217 ha) compared to meadows (20 ha), 91 of the random plots were located within steppe vegetation, and 11 in alpine meadows.

In each plot disturbance to vegetation and soils was rapidly (5 ± 2 min) visually assessed by one observer through an intensive foot search to determine a categorical value for each variable (Table 1). The values ranged from 0 = no evidence, 1 = low, 2 = medium, and 3 = high disturbance (Table 1). To assign a category to each variable, the amount of horse/mule dung present, individual plants grazed, number of footprints (humans), hoof prints (pack animals, e.g., horses and mules) and the extent of any soil movement was recorded in the plot. Each individual dung pile observed in the plot was counted and then a category assigned. The number of hoof/foot prints were recorded, with the highest category given to the plots that have evidence of an undefined trail (i.e., slightly distinguishable trail, with some evidence of trampled and matted vegetation, minimum loss of vegetation cover and/or organic litter) (Table 1). To determine if a plant was grazed, the observer recorded if there was any signal of physical disturbance or damage to a plant such as the removal of shoot parts due to grazing. Soil movement was considered if there was evidence of use of heavy machinery (e.g., small excavator) for the construction and/or maintenance of formal trails or roads and other infrastructure (e.g., visitor center).

To reduce bias in assigning disturbance categories, the values for each category were carefully defined and recorded by the same person (Table 1). The overall level of disturbance in the plot was estimated as the average of these four variables rounded to the nearest whole number. This resulted in four overall disturbance categories: undisturbed, low, medium or high. The variables were not weighted for the overall calculations, but the highest score (3) was given for any evidence of soil movement in the plots due to the potential severity of impacts to soils and vegetation (Godefroid and Koedam 2004; Pickering and Norman 2017). The overall measures of disturbance were found to correlate well with reductions in vegetation cover and changes in composition obtained from previous detailed plant surveys recorded by the authors of the same plots (Barros 2014).

Data Analysis

Area of vegetation lost to trails and extent of fragmentation of plant communities

The cumulative length of trails, roads and the total area affected by the three types of trails (formal, informal hiker, informal mixed trails—i.e., hiker and pack animals) was calculated. To determine if there were any differences in trail features (average width, surface area, length) between the two types of informal trails, a series of One-Way ANOVAs were performed on dependent variables using the statistical package SPSS (Version 21). The assumptions of homogeneity of variance were checked using the Levene's test. As there were only two short formal trails, there were too few replicates of this trail type to use in statistical analyses.

To analyze how the network of trails and other visitor infrastructure have fragmented the plant communities, methods from Leung et al. (2011) were used. The area covered by the alpine steppe and alpine meadows was used as a baselayer. All the trails and infrastructure polygons were then extracted to calculate the total area affected in ArcGIS. This was accomplished by intersecting these

Table 2 Trails and other visitor infrastructure in the 237 ha area surveyed in the Horcones Valley in Aconcagua Provincial Park

Type of trail / infrastructure	No.	Total length (km)	Av. width (m)	Total area affected (ha)	% area affected
Infrastructure	6			1.8	0.8
Roads	6	5.2	6.1 ± 1.1	5.9	2.7
Formal trails	2	2.0	3.3 ± 1.3	1.4	0.6
Hiker informal trail	17	9.6	1.7 ± 0.4	5.1	2.3
Hiker and pack animal informal trail	15	7.2	3.1 ± 0.6	6.4	2.9
Total	46	24	3.0 ± 0.4	20.5	9.4

No., number; Av., average; ±, standard error

Table 3 Impact of trails and off-trail disturbance on two alpine plant communities in the intensively used area of Horcones Valley, Aconcagua Provincial Park

	Area	Area lost from trails & other infrastructure	Area lost to informal trails	Area not disturbed by visitor use[a]	Off-trail level of disturbance[a]			
					Low	Medium	High	Total disturbance
Total	237 ha	20 ha	11.5 ha	24.5 ha	45 ha	67 ha	81 ha	193 ha
Steppe	217 ha	19 ha	10.7 ha	24 ha	35 ha	62 ha	77 ha	174 ha
Meadow	20 ha	1 ha	0.8 ha	0.5 ha	9.7 ha	4.8 ha	4 ha	18.5 ha

[a] area disturbed estimated by the spline interpolation method using the georeferenced data of the plots surveyed.

features with the vegetation shape files (alpine steppe and alpine meadows) to create two shape files representing all the fragmented patches. The shape files were then used to calculate landscape metrics including the number and mean patch size, perimeter/area ratio and weighted mean patch index (WMPI) (Leung et al. 2011; Neel et al. 2004; Wimpey and Marion 2011) (Appendix A). The perimeter/area ratio provides information about the amount of patch area exposed to edges, with patches with elongated shapes or smaller size often having higher perimeter-area ratios than patches with compact shapes (Neel et al. 2004). The WMPI provides an indication of the average size of patches considering overall habitat reduction, with decreasing values indicating increasing degrees of fragmentation (Ballantyne et al. 2014; Leung et al. 2011).

The number of plots in the alpine steppe and meadows in each disturbance category were compared to determine the level of off-trail disturbance. To visualize the spatial patterns of disturbance and estimate the total area damaged in the 237 ha survey area, georeferenced data of each plot were used to interpolate the total area disturbed using the spline method in ArcGIS (Childs 2004). The spline tool uses an interpolation method that estimates values using a mathematical function to minimize overall surface curvature, resulting in a smooth surface passing through the input points (Childs 2004).

To determine if distance to the nearest trail or road was correlated with disturbance categories for a plot, the nearest distance to these features was calculated for each plot using the proximity tool in ArcGIS. The resulting Euclidean distances were then used to determine if distance to the type of trails and roads was a good predictor of disturbance using a multinomial logistic regression (Field 2009). The predictor variables were types of trails and roads while disturbance was the dependent variable with four levels (undisturbed, low, medium, high). The undisturbed category used as the reference category (Field 2009).

Results

Impacts of Trails: Vegetation Loss and Fragmentation

Within the 237 ha area surveyed, there were 34 trails, consisting of two formal trails, and 32 informal trails (Figs 1 and 2, Table 2). The two formal trails are close to the visitor center and park ranger station and are mainly used by day visitors to access viewpoints (Fig. 1a). These two trails were unhardened, but their edges were defined by rocks and logs. They had an average width of 3 m and a total length of 2 km (Table 2) and hence accounted for 1.4 ha of cleared vegetation, or 0.6% of the area surveyed.

The informal trail network consisted of 17 informal trails used by hikers and 15 trails used by hikers and pack animals (Table 2, Figs 1 and 2). All trails were completely barren of vegetation. The average width of informal trails used by hikers and pack animals tended to be greater than those used only by hikers (3 m vs. 1.7 m), but this difference was not statistically significant ($F = 4.102$, $p = 0.052$). There were no differences in length and total area between the two types of informal trails ($p > 0.05$). The informal trails collectively accounted for the loss of 11.5 ha of vegetation, 5.2% of area surveyed. This included 10.7 ha of alpine steppe and 0.8 ha of alpine meadows (Table 3).

In addition to the trails, there was 5.2 km of roads with an average width of 6 m that accounted for the loss of 5.9 ha of vegetation (Table 2). This consisted of a concrete road (1.5 km long) to access the park ranger station, and several sections of old dirt road (3.7 km long) that were previously used to enter the Park (Table 2). Some sections of this old road are now used as a trail by day users and pack animals. Other infrastructure provided for tourism in this part of the Park accounted for the clearing of an additional 1.8 ha (Table 2). The total area of all vegetation lost due to formal and informal tourism infrastructure was 20 ha, consisting of 1 ha of alpine meadows (5%) and 19 ha of steppe vegetation (9%) (Table 3).

In addition to the direct loss of vegetation by trails and other infrastructure, there was extensive fragmentation caused by the trails resulting in 89 separate fragments. While the central sections of the 20 ha of meadows were not directly fragmented, their edges were highly fragmented by the informal trails (Fig. 3). As a result, three large meadows were fragmented into 21 'sub-patches', with an average size of just 0.5 ha. The 198 ha of steppe vegetation was fragmented into 68 sub-patches with a mean patch size of 2.9 ha, again mainly due to the informal trails. Based on the WMPI, the degree of fragmentation was higher in the alpine meadows (WMPI 0.46) compared to the steppe vegetation (WMPI 2.66) (Table 4, Fig. 3). The perimeter-area ratio was also higher for alpine meadows (0.8) compared to steppe vegetation (0.5) (Table 4, Fig. 3).

Disturbance Off-Trail

Visitor use not only resulted in the direct loss of vegetation on the trails and where there was other visitor infrastructure, it also disturbed nearly all of the remaining area surveyed. For the 91 plots in steppe vegetation, 80% were disturbed, with 20% highly disturbed. All 11 plots in alpine meadows were disturbed, with five plots highly disturbed

The main disturbance was off-trail trampling, with obvious damage recorded in 58% of the plots, 40% of them highly trampled. Pack animal dung was recorded in 51% of the plots, grazing damage in 43% and soil movement due to machinery in 21% of the plots. Only 19% of the plots showed no obvious signs of disturbance from trampling, grazing, soil movement and/or pack animal dung, and these were all in steppe vegetation. Based on the spline interpolation method, it is estimated that less than 25 ha (10%) of the Valley was not disturbed by visitor use, with 81 ha (34%) highly disturbed (Fig. 2, Table 3). A total of 45 ha (19%) was estimated to have low levels of disturbance and 67 ha (28%) medium levels of disturbance (Fig. 2, Table 3).

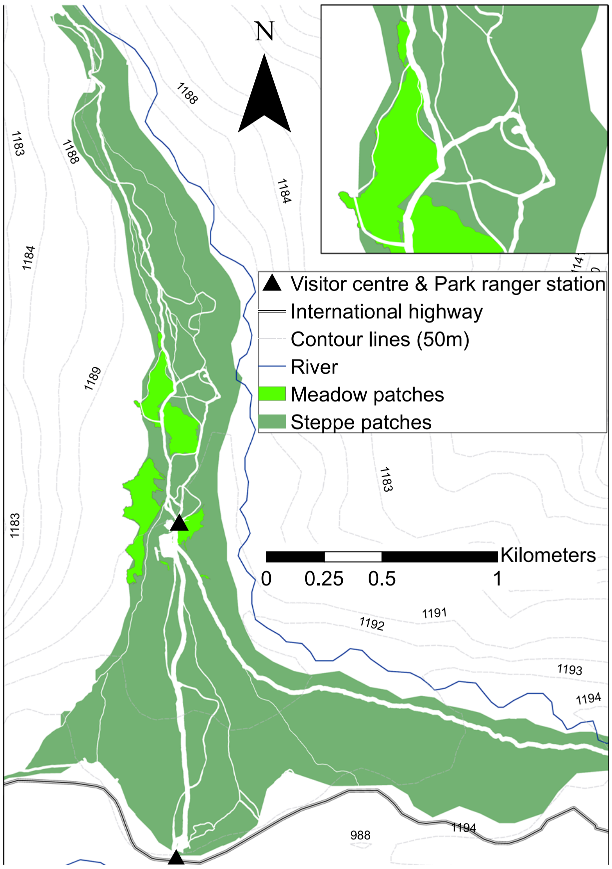

Fig. 3 Fragmented patches of alpine steppe and alpine meadow vegetation in the popular Horcones Valley in Aconcagua Provincial Park, in the high Andes

The level of disturbance varied with distance to the informal trails used by hikers and pack animals (Multinomial logistic regression, $\chi^2 = 11.655$, $p = 0.009$). Plots that were highly disturbed were closer to these mixed use informal trails (75 ± 17 m), than undisturbed plots (274 ± 59 m) ($b = -0.007$, Wald $\chi^2 = 5.952$, $p = 0.015$). There was no relationship between disturbance and distance to hiker only trails or roads (hiker trails, $\chi^2 = 3.050$, $p = 0.384$, roads $\chi^2 = 1.081$, $p = 0.782$).

Discussion

This study highlights how relatively unregulated visitor use can damage large areas of fragile vegetation through the

Table 4 Landscape fragmentation indices for alpine meadows and steppe vegetation in the intensively used 237 ha of the Horcones Valley, Aconcagua Provincial Park

Vegetation type	Area (ha)	No. patches	Mean patch size (ha)	Per/area ratio	WMPI (ha)
Meadow	20	21	0.5 ± 0.2	0.8 ± 0.1	0.46
Steppe	217	68	2.9 ± 1.2	0.5 ± 0.1	2.66

WMPI, weighted mean patch index (Leung et al. 2011); No., number

Values for mean patch size and per/area ratio are the average ± standard error

creation of informal trail networks and off-trail use. In Aconcagua, 20.5 ha of vegetation were directly lost due to trails and other infrastructure (e.g., roads, visitor center) in the most intensively used 237 ha of the Park. The network of trails also resulted in high levels of fragmentation in steppe and alpine meadow plant communities. Off-trail use damaged a further 193 ha of vegetation in the area surveyed. Nearly all the disturbance was due to unregulated use including the creation of informal trails and dispersed use by pack animals and hikers. As a result, only 10% of the area was free of disturbance. The level of disturbance varied across the Valley, with 19% found to have low levels of disturbance, 28% with medium levels of disturbance and 34% highly disturbed.

The drastic difference between the area affected when measuring just trails and other infrastructure (8% of the total area), vs. the area estimated to be affected by off-trail use (81%) emphasizes the importance of including impacts from off-trail use when assessing resource condition in natural areas. The use of rapid (<5 min per plot) visual indicators were a feasible and efficient method to measure dispersed impacts and reflected the changes in important vegetation attributes recorded previously in a more detailed plant survey of the same plots (Barros 2014). For example, plots classified visually as having medium or high disturbance were also found to have less vegetation cover, lower frequency of native shrubs and higher frequency of weeds compared to undisturbed plots (Barros 2014).

The extent of the informal trail network and its impacts in Aconcagua provides additional evidence of the landscape level impacts of informal trails (Ballantyne et al. 2016; Kim and Daigle 2012; Leung et al. 2011; Monz et al. 2010b; Walden–Schreiner and Leung 2013). Other studies, using similar methodology to document impacts of informal trails, have found extensive vegetation loss and fragmentation, including in two different endangered forests in Australia (Ballantyne et al. 2014; Ballantyne et al. 2016), and in mountain meadows (Leung et al. 2011), alpine summit vegetation (Kim and Daigle 2012; Monz et al. 2010b), and forests in the United States (Wimpey and Marion 2011). The degree of fragmentation of alpine meadows based on the WMPI (0.46) in Aconcagua is similar to that for the very popular mountain meadows (>300 visitors daily) in Yosemite National Park (D'Antonio and Monz 2016; Leung et al. 2011), and heavily used remnant forests in peri-urban areas in Australia (Ballantyne et al. 2014).

The decrease in overall vegetation cover and isolation of vegetation patches can have long-term negative effects including on vegetation structure, composition and function (Ballantyne and Pickering 2015; Haddad et al. 2015; Lindenmayer and Fischer 2006). These effects can be exacerbated by the additional loss of vegetation from dispersed use of the remnant patches (Ballantyne et al. 2014; Leung et al. 2011). For example, ecological effects from the creation of trail networks in the Park may affect soil moisture, favor trampling-resistant species and enhance the spread of weeds (Barros 2014; Barros et al. 2013; Mendez et al. 2006; Mount and Pickering 2009). Reductions in plant height and cover due to off-trail grazing and trampling can affect ground nesting birds and native mammals that use these plant communities for shelter and food (Barros et al. 2015; Barros et al. 2014b; Loydi and Zalba 2009). Damage to alpine meadows, such as reductions in plant cover from grazing and trail incision, can alter the depth of the water table thereby affecting meadow productivity and water regulation (Buono et al. 2010; Clymont et al. 2010).

The degradation of alpine meadows is of particular concern due to the higher degree of fragmentation found in this community compared to steppe vegetation, and their high conservation value (Barros 2014; Squeo et al. 2006). Alpine meadows, which are of limited distribution at a local and regional scale, are critical biodiversity hotspots that sustain rare and endemic biota and provide key ecosystem services including carbon sequestration and water regulation (Barros 2014; Buono et al. 2010; Squeo et al. 2006). Alpine meadows are more likely to be subject to fragmentation than steppe vegetation because they have moist soils dominated by graminoids, and visitors were often observed spreading out to avoid muddy areas. Pack animals are also more likely to leave trails in meadows to graze in these more 'lush' communities, resulting in more damage (Barros et al. 2014a; Farrell and Marion 2001; Walden-Schreiner et al. 2017).

In general, factors that can contribute to the creation of informal trails include low growing vegetation that is easy to walk on, limited regulation including off-trail use and inadequate formal trail systems (Ballantyne and Pickering 2015; Park et al. 2008; Turner 2001; Wimpey and Marion

2010). Social factors, such as visitor motivations, can also contribute to the proliferation of informal trails (Park et al. 2008; Turner 2001). For instance, a study assessing visitor characteristics and their association with the creation of informal trails (Walden–Schreiner and Leung 2013), found that visitors were more likely to go off-trails for "stationary activities" such as sightseeing and picnicking, than for more vigorous activities such as hiking or running. In the intensively used area of Aconcagua, the profile of visitors (mainly sightseers and picnickers) (Barros et al. 2015), may have contributed to the creation of informal trails and the increasing levels of off-trail use.

Mixed use of informal trails can contribute to the formation and spread of trails as well as off-trail impacts (Newsome et al. 2004; Newsome et al. 2002; Pickering et al. 2010). In Aconcagua, informal trails used by both hikers and pack animals were often wider than those used only by hikers, and plots closer to the multi-use trails were more likely to show higher levels of disturbance. Based on personal observations and previous research (Barros et al. 2013), off-trail use is more likely when: (1) there are large groups of mules and horses that are untethered as they often leave the trails to graze, and (2) visitors leave the main trails to avoid collisions with herds of pack animals using the trail. Hence, limited regulation of pack animals is of concern because it contributes to visitor impacts. Research has already demonstrated that pack animals tend to do more damage than hikers in this, and other parks (Barros and Pickering 2014a; Barros et al. 2015; Cole et al. 2004; Liddle 1997; Törn et al. 2009).

Management Implications

Given the extent of the impacts of relatively unregulated use in this Park, and other protected areas, managers should concentrate visitor use to a limited set of professionally designed formal trails (Marion and Leung 2004; Marion and Olive 2006; Wimpey and Marion 2010). For Aconcagua and other protected areas this includes separating hiker and pack animal trails, using signage and educational programs to reinforce messages such as stay on track, and visual borders to limit people moving off-trail (Barros and Pickering 2014b; Newsome et al. 2004; Park et al. 2008; Wimpey and Marion 2010). Other regulations could include requiring pack animals to be tethered in lines when traversing intensively used areas.

Results from the assessment methods used here to determine on and off-trail disturbance provide baseline information for longer term monitoring and management in this and other protected areas. The methodology applied in Aconcagua for rapidly assessing off-trail impacts and the level of disturbance can be adapted or modified for other protected areas to reflect impacts from other recreational activities, including from mountain biking, motorized trail biking and horse riding. Such monitoring programs can assist in assessing the effectiveness of management actions for resource protection, as well as identify priority sites for management based on the level of disturbance. For example, it can identify highly disturbed sites needing active remediation and/or exclusion from use by visitors and pack animals.

In addition to monitoring disturbance from trails and off-trail use, additional research assessing patterns of visitor behavior and intensity of use using GPS trackers is important (Beeco and Brown 2013; D'Antonio and Monz 2016). Such research can help to identify areas of high visitor use and where visitors and pack animals disperse off-trail (D'Antonio and Monz 2016; Hallo et al. 2012; Monz et al. 2010b; Wolf et al. 2012). Small GPS trackers can be handed to visitors at the entrance to high use areas and can be attached to pack animals and other types of transport (e.g., mountain bikes) (D'Antonio et al. 2010; D'Antonio et al. 2013; Walden-Schreiner et al. 2017). In Aconcagua and other protected areas where pack animals are used, GPS receivers can also be used to identify sites regularly used by these animals that are likely to be damaged by trampling and grazing. Alternative methods to GPS trackers include direct observations of visitors (Cessford and Muhar 2003; Walden–Schreiner and Leung 2013), or the use of volunteer geographic information on social media uploaded from visitor's devices (Campelo and Mendes 2016; Jankowski et al. 2010; Orellana et al. 2012; Orsi and Geneletti 2013; Santos et al. 2016). To date such information for Aconcagua, and many other remote protected areas, remains very limited.

Conclusions

This study highlights on how trails can internally fragment alpine plant communities and damage large areas of vegetation offtrack. Documenting and mapping such impacts provides important information for park managers to develop better monitoring programs and prioritize management strategies to limit visitor impacts. Implementing rapid assessment methods, such as those used in Aconcagua, is particularly important for mountain protected areas given their popularity for trail-based recreation and their high conservation value.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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