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Approaches to estimating pathway erosion on the Coast Walk, Royal National Park, New South Wales

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Abstract

Natural area conservation has become more challenging with the worldwide growth in tourism. Increasing numbers of visitors lead to trampling of vegetation and soils with accompanying erosion and adverse ecological impacts. Although visitors accelerate erosion rates and can cause ecological damage, visitor amenity is in turn negatively affected by eroded pathways. Effective and timely management intervention requires information on which to act but conducting detailed track deterioration assessments places heavy demands on data sources and/or skills of personnel. A simple indicator of track erosion may provide a workable interim measure. In a preliminary investigation along the Coast Walk in Royal National Park, twenty sites were selected and assessed within a three-category erosion severity classification which included visitor-generated deterioration. Erosion losses were estimated using measured cross-sectional area and a soil erosion model. We found reasonable convergence between the erosion severity classification and results from the cross-sectional area and erosion model, although both needed interpretation of outlying data. A measure of maximum erosion depth emerged as the simplest general indicator of erosion loss. This indicator also places the least demand on personnel and data resources, an important consideration for budget-challenged park managers tasked with simultaneously providing environmental protection and visitor amenity.

Introduction

The worldwide growth in natural area tourism has led to increasing concern about potentially adverse and unintended environmental impacts, especially in protected areas. These impacts include pathway (track) erosion. Managing natural resources to meet the dual objectives of conservation and recreation provision is complex and dynamic (Bushell, 2003), and involves responding to environmental, policy, attitudinal, social and economic changes. Use of protected areas like Royal National Park for leisure activities has been encouraged by the State government (State of NSW and Dept of Environment and Climate Change, 2008) and similar approaches have been adopted internationally (e.g. Ministry of Tourism and Creative Economy of the Republic of Indonesia, 2012; Kingdom of Morocco, 2017). Policies are frequently framed within the paradigm of "sustainable tourism" or "ecotourism," generally with the stated intention of ensuring visitor satisfaction, minimal environmental impact, and economic and social benefits for local communities (e.g. Robinson and Picard, 2006; Director of National Parks Australia, 2011; UNESCO, 2016). Achieving such a combination of positive outcomes is challenging.

Pathway erosion results from visitor use of informal (Barros and Pickering, 2017) and formal access routes. Trampling of vegetation in the absence of raised or constructed walkways/surfaces is inevitable and impacts tend to increase with higher visitor (Marion and Leung, 2001; Nepal, 2003) and/or associated livestock numbers (Nepal, 2003; Ostoja et al., 2014). Well-known detrimental environmental consequences include accelerated rates of erosion and the degradation of soils, vegetation and water quality (e.g. Bayfield, 1973; Cole, 1995; Cole and Landres, 1996; Bhuju and Ohsawa, 1998; Arocena et al., 2006; Kissling et al., 2009). These impacts represent indicators which contribute adversely to ecological functioning, and also relate to erosional outcomes which disturb visitors' experience (Pietilä and Fagerholm, 2016). Consequently, erosion generated by vegetation loss and path deterioration becomes a concern for both ecosystem health and visitor experience (Lynn and Brown, 2003).

Management of pathways involves responding to existing deterioration (path condition), predicting future damage at these or other sites on existing or projected tracks, and monitoring visitor satisfaction (Table 1). Path condition can be assessed qualitatively in the form of a complete condition inventory, or by assessing deterioration at predetermined distance intervals, or by applying a combined approach of an initial qualitative categorisation followed by a quantitative investigation. Most quantitative methods adopt a sampling procedure within previously assessed condition categories. However, qualitative sampling points alone, or a combination of point-based qualitative assessment and measurement at within-category sampling sites, may both produce an under-estimation of path deterioration, as the extent of specific impacts between sampling locations is unknown (Marion and Leung, 2001). As would be anticipated, longer sampling intervals were found to reduce accuracy in estimating the extent of impacts (Leung and Marion, 1999).

The approximately 30-km long Coast Walk in Royal National Park has long been popular with visitors. It has a history of severe erosion, followed by pathway repair involving infilling of gullies, and subsequent re-erosion of the same sites. In 1981, for example, part of the Walk had been gullied to a depth exceeding 3 m (Young and Young, 2006); and in 1991 a gully more than 2 m deep — later infilled — had led to visitors creating an adjacent informal path (Figure 1). This continuing interaction of erosion processes with visitor impacts and management responses produces changing track conditions over time. Any pathway assessment thus represents conditions at the time of the study, and does not take into account the timeframe over which the observed erosional features developed.

Figure 1: A previously in-filled and subsequently deeply gullied section of the Coast Walk, 1991.

The Coast Walk had been deteriorating for some years before the government announced funding of $2 million over three years from 2014 to repair the most damaged sections (Galvin, 2014). As this activity commenced slowly, the current study was completed before these management interventions had altered the general condition of the Walk. By mid-2018, upgrading of a 9-km section was in the planning stage (Visentin, 2018). Conducting track deterioration assessments often involves heavy demands on data and/or skills and time of personnel, so a simple indicator of pathway erosion would benefit park management. The purpose of this investigation was to determine whether different approaches (one qualitative and two quantitative) to assessing pathway erosion produced similar and useful indicators of erosional loss. The approaches considered were qualitative categorical assessment, field estimates of erosion using measured cross-sectional area, and soil loss estimates using an erosion model.

Study area

Established in 1879, Royal National Park (RNP) is the world's second oldest national park and now covers an area of 15,080 ha on the southern fringe of metropolitan Sydney, Australia (latitude 34°04'16"S, longitude 151°03'21"E). Annual visitor numbers to RNP are estimated to be around 4 million, about 80,000 of whom walk all or part of the approximately 30-km-long pedestrian-only Coast Walk (Galvin, 2014). People are attracted to the natural scenic views, availability of family-oriented picnic and recreational facilities, and proximity to metropolitan areas with easy access by road and public transport. A high priority in the Park's most recently published Plan of Management (NPWS 2000) was to "restore the Coast Walk" and "review the system of walking tracks," some specific funding for which was finally provided in 2014–2017.

RNP experiences a warm temperate climate with moderate winter temperatures and warm summers. Over a 30-year period of records at Audley near the centre of the Park, most rainfall occurred during autumn (353 mm) and least during spring (215 mm). The annual average over the period was 1114 mm (Australia, Bureau of Meteorology, 2017). The Park has an internationally acclaimed flora collection with more than 1000 recorded plant species, of which 26 are classified as nationally rare or threatened (NPWS, 2000).

Geologically, the Park lies within the Sydney Basin, and lithology in this area is dominated by Hawkesbury sandstone, a fine-to-coarse-grained quartzose sandstone occasionally interbedded with shale. Underlying the sandstone is the Narrabeen shale series that emerge in the south. Both the sandstone and underlying shale are nearly horizontally bedded, so much of the Park forms a low plateau bounded by a cliffed shoreline with some rock platforms on headlands and occasional intervening beaches. With the exception of relic cliff-top sand dunes (Fairley, 2000) most soils have a loamy texture. Soils developed on shale have a heavier texture and range from loam to clay loams at the surface and medium to heavy clays in the subsoil. Where Hawkesbury sandstone forms the parent material, soils are mainly loams, ranging from coarse sandy loams to clay loams (Hazelton and Tille, 1990). Most soils in RNP have poor structure and are highly erodible.

Table 1: Approaches to managing paths in protected areas

Assessment (qualitative)	**Method / approach**	**Path characteristics**	**Author/s**
Qualitative assessment	4-category rating system	89 km	Nepal and Nepal (2004)
Qualitative inventory	Sample at each 100 m	4 km	Mende and Newsome (2006)
Qualitative broad assessment	Sample at each 20 m (recommended interval)	Can assess 5–7 km of track per day	Hawes et al. (2006)
Qualitative plus quantitative	5-category rating system; 5x6 sites measured	25 km	Gager and Conacher (2001)
Prediction (planning)	**Method / approach**	**Path characteristics**	**Author/s**
Predicting potential deterioration	Monitoring pre-classified path types (8 years)		Dixon et al. (2004)
Identifying relevant environmental variables	Analysis of field measurements	25 km; track type assessment for 1,700 km system	Gager and Conacher (2001); Hawes et al. (2013)
Using GIS to design 'optimum' path locations	5-category resilience classes (erosion susceptibility)	70 km^2 area	Tomczyk (2011); Tomczyk and Ewertowski (2013a)
Using GIS to plan visitor travel routes	Time and energy costs for visitors	22 km^2; 16 trails (182–8145 m long)	Chiou et al. (2010)
Monitoring — visitor behaviour and response	**Method / approach**	**Path characteristics**	**Author/s**
Noticeable erosion	On-site and web-based surveys	Eroded paths	Pietilä and Fagerholm (2016)
Erosion and diminished visitor satisfaction Erosion and visitor response	Self-administered questionnaire Questionnaire	Impacted paths Eroded paths, trampled vegetation	Lynn and Brown (2003) Dragovich and Bajpai (2012)

Methods and Materials

Erosion severity assessment

Physical measurement of the entire Coast Walk for a complete census of trail problems was not attempted. Rather, twenty sample sections (sites) were selected after reconnaissance which involved walking the length of the Coast Walk and ensuring that sample sites represented the range of erosion scenarios present. This directed-sampling approach was further constrained by sections where management had installed stairs or raised walkways, or concrete-hardened path surfaces; by rock outcrops; and by visitor use patterns, in that most walkers and erosion-affected surfaces are concentrated in two approximately 5-km sections at either end of the Walk where public access roads terminate. For practical purposes, it was assumed that recreational impact (trampling) was similar on both end sections of the Walk. A three-category erosion severity classification of high, moderate or low severity was devised for sections not modified by management. Based on field observation of erosion patterns, all sections categorised as moderately or highly eroded were measured. The remaining unmodified sections were classed as low severity and only some of these sections were measured.

Erosion severity assessment was based on the three key indicators, of channel (path) depth, surface roughness, and presence of stones, with higher values for measured or observed indicators signifying increased erosion severity. Measured channel depth was the primary indicator applying to all paths while uneven surfaces and stones were not always present. Channel depths were differentiated to broadly reflect the magnitude of water erosion in the form of sheet erosion, rill development and gullying (channels). A threshold channel depth of 30 cm was applied, as this represents the practical difference between rills and gullies (New South Wales Dept. of Primary Industries, 2015).

Rills or shallow channels of ≤30 cm in depth were arbitrarily sub-divided into those of <10 cm (low erosion severity) and of >10 cm (medium erosion severity), while gullied surfaces were those having channel depths >30 cm (high erosion severity) (Figure 2). Wind- and water-eroded sandy sections were characterised by pathway hollowing rather than channel development, but the same depth criteria for low, medium and high erosion severity were applied.

Surface roughness was categorised as even, uneven, or very uneven. Uneven walking surfaces are created by erosion, although shallow channels <10 cm deep allow path-

Figure 2: Examples of (A) high, (B) medium and (C) low erosion severity categories.

way surfaces to remain reasonably even, with sheet erosion being the dominant water erosion mechanism. As channels become deeper but occupy only part of the track, surface unevenness increases. Associated with this increased erosion is a higher probability of subsoils, bedrock or a lag of gravel or boulders being exposed, creating pathway surfaces that become increasingly uneven and potentially hazardous for walkers.

Evidence of uneven/unsafe walking surfaces, multiple tracks and near-path trampling of vegetation was described as user-generated degradation. As trampling may lead to soil compaction and increased runoff through reduced infiltration, a field penetrometer (Humboldt) was used to measure soil compaction within and adjacent to measured path sections.

Soil loss estimates

Cross sectional area (CSA) field measurements

Individual sites varied in size. Site length was defined as a stretch of the track where erosion severity was fairly uniform but became noticeably different from the adjacent upslope and downslope path sections. Site length ranged from 6.5 m to 30 m. Site width was defined as the distance between pathway edges or banks beyond which a marked disparity in erosion was evident, with site widths ranging from 0.92 m to 4.23 m.

Soil loss at each of the twenty sites was calculated using the Cross Section Area (CSA) method (Helgath, 1975; Gager and Conacher, 2001; Olive and Marion, 2009). A string was tied connecting four nails demarcating the site boundaries, with a further string inserted midway along the section where a soil sample was also collected. Depending on the depth of erosion, pathway samples might have represented the A or B horizon. Depth to the ground below each across-site string was recorded to the nearest 0.5 cm at 20 cm intervals. The area below each surface profile line was calculated by multiplying the total depths recorded by 20 and converting the result from cm^2 to m^2, and the total volume of soil loss was estimated by averaging the three values and multiplying by the site length. Soil loss per m^2 was estimated by dividing the calculated volume of soil loss by the surface area of the track surface (m^3/m^2).

Erosion modelling using SOILOSS

Estimated sheet and rill erosion rates were obtained by using SOILOSS (Rosewell, 1993), a program adapted from RUSLE for Australian conditions. The soil loss equation is:

$$A = R \times K \times L \times S \times P \times C \qquad (1)$$

where A is average annual soil loss in tonnes per hectare; R is rainfall erosivity; K is soil erodibility; L is length of slope; S is angle of slope; P is erosion control practices; and C is cover (vegetation) management.

Values for the individual parameters were determined by a combination of field recording, laboratory analysis and lookup tables. Rainfall erosivity (R) was based on the map accompanying the SOILOSS software (Rosewell, 1993). Slope length (L) and angles (S) were measured. For the soil erodibility (K) parameter, soil structure and permeability were assessed in the field, and laboratory results were used for texture and organic matter. Soil samples were analysed for texture using a Mastersizer 2000 and organic matter content was determined by loss on ignition (organic matter = loss on ignition × 0.7). Based on field observation, erosion control practices were assumed to be absent (P =1 from lookup tables in Rosewell, 1993). Bare pathway surfaces were most common, but because incomplete grass cover or leaf litter was in some cases present on the less trampled edges of pathways, and rocks occurred on some paths, soil loss estimates were calculated using a value of *C*=0.45 (lookup tables in Rosewell, 1993). SOILOSS output was converted to kg/m^2 before comparing modelled SOILOSS estimates and CSA field measurements, with each retaining their respective measurement units.

Results and Discussion

Length, depth and width of measured sites

Individual sites varied within and between erosion categories in length, width and depth. On average, individual low erosion category sites extended over shorter distances, and were narrower and shallower than sites classified as having medium and high erosion severity (Table 2; Figures 2 and 3). Although sites in the medium erosion category were longer and wider on average than the highly eroded sites, the latter had a considerably greater average maximum depth (59.8 cm compared with 25.2 cm).

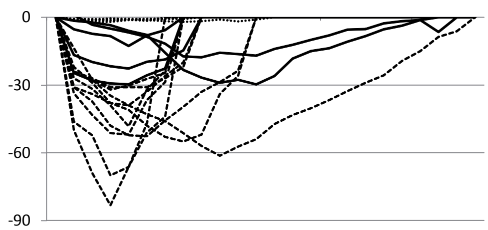


Figure 3: Path cross sections by erosion category (High = broken line; Medium=solid line; Low = dots, overlapping at this scale). Each path is represented by the average of three cross sections. Vertical scale in cm. Widest path = 4.6 m.

Soil compaction

The trampled pathway sites were often compacted and soils were not penetrable at nine of the 20 sites, with seven of these nine being high erosion category paths and one each of the medium and low categories. None of the 20 on-path sites was easily penetrable and in total these trampled sites recorded a mean value of 1.36 kg/cm^2 (Table 2). Untrampled areas were generally less compacted than paths and six untrampled areas had zero resistance recorded ('easily penetrable'). Two of the three trampled sites in the high erosion category were on sandy soils which would have contributed to pathway compaction being below that for adjacent untrampled areas (on sandy soils, footfalls churn the loose surface material rather than compacting it). This contrasts with loamy and clayey soils where trampling leads to compaction, a use-generated feature which compounds erosion susceptibility following initial vegetation loss.

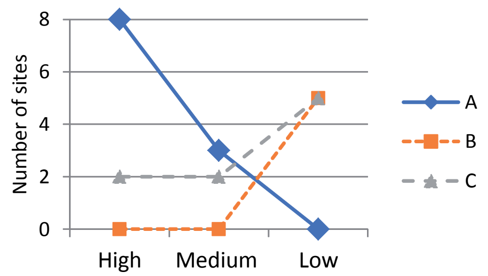


Figure 4: Use-generated degradation and erosion severity. A = multiple paths, vegetation trampled; B = minimal degradation; C = no extra tracks.

At each site vegetation in the central part of the path had been completely destroyed by trampling. With one exception, management interventions appeared on high and medium erosion severity sections (Table 3), suggesting that visual assessment was being

Table 2: Physical characteristics of sampled sites

Characteristic/ property	High severity	Medium severity	Low severity
Erosion severity criteria			
Channel depth (cm)	1+ XS value >30 cm	>10 cm and ≤30 cm	0 to <10 cm
Path surface	Very uneven	Uneven	Even
Stone size	5 – 10 cm	2 – 8 cm	<2 cm
Site dimensions (range)			
Average length (m) [(a)]	13.9 (7 – 30)	16.5 (6.5 – 20)	11.9 (6.5 – 17)
Average maximum depth (cm)	59.8 (34 – 85)	25.2 (15 – 30)	1.64 (1.2 – 2)
Average width (cm)	162 (92 – 423)	231 (110 – 395)	138 (101 – 205)
Average width:depth ratio	2.8 (1.2 – 5.9)	9.0 (4.3 – 15.2)	84.9 (67.3 – 116.7)
Sample sites — path slope and soils			
Mean path slope (range) (degrees)	7.2 (3 to 15)	6.6 (3 to 11)	1.4 (1 to 2)
Surface soil texture (no. of sites)	Sand (3); Loamy sand (5); Silty loam (3)	Loamy sand (5)	Loamy sand (4); Silty loam (1)
Mean gravel (range) (%)	13.9 (0.9 – 24.4)	15.2 (2.5 – 47.7)	11.5 (4.2 – 18.7)
Mean organic matter (range) (%)	2.2 (0.6 – 4.0)	2.5 (0.7 – 5.0)	3.0 (1.3 – 4.5)
Mean silt content (range) (%)	17.5 (3.7 to 36.9)	18.0 (13.6 to 22.7)	17.2 (9.7 to 31.8)
Mean clay content (range) (%)	2.9 (0.4 – 8.7)	2.5 (1.8 – 4.1)	2.2 (1.7 – 2.9)
Soil compaction (no. of sites)			
Trampled (not penetrable) (no.)	n=7	n=1	n=1
Trampled (no.) (mean kg/cm^2)	n=3 (1.3 kg/cm^2)	n=4 (1.5 kg/cm^2)	n=4 (1.25 kg/cm^2)
Untrampled (easily penetrable) (no.)	n=3	n=0	n=3
Untrampled (no.) (mean kg/cm^2)	n=7 (1.75 kg/cm^2)	n=5 (0.90 kg/cm^2)	n=2 (0.75 kg/cm^2)

(a) The length of path upslope of each site was not recorded. All other factors being equal, longer slopes have more erosion than shorter slopes

used by managers to identify potentially uncomfortable or hazardous pathway conditions for walkers. Only the low erosion sites recorded an absence of multiple tracks, uneven surfaces and walkers encroaching onto near-path vegetated areas (Figure 4). Natural waterlogging occurred at three sites and this can lead to uncomfortable walking conditions which may also encourage visitors to develop alternative routes.

Erosion estimates: SOILOSS

A summary of path slope angles and soil analyses for texture, gravel, organic matter and clay contents is provided in Table 2. Most soils were loamy sands, with three being classified as sands and the remainder as loamy sands or silty loams. Clay content of surface soils was generally low, between 0.4 and 4%, with only two samples recording amounts of more than 5%. Organic matter was also generally low, averaging between 2.2% and 3% for the three erosion categories. The gravel component contributed more than 10% at thirteen sites, with three of these recording amounts exceeding 20%.

Soil loss estimates for the high erosion severity group ranged from a minimum of 0.33 to a maximum of 7.20 kg/m^2/yr; for the moderate severity group, from 1.30 to 11.10 kg/m^2/yr; and for the low severity group from 0.22 to 0.78 kg/m^2/yr (Table 4).

Table 3: Use-generated degradation, path condition and management intervention

Use degradation and path condition	No. of sites [(a)]	Erosion severity category [(b)]
Track use pattern –		
Multiple tracks (5) plus initial phase (3)	8	5 H; 3 M
Walkers utilising near-path vegetated area	3	3 H
No additional tracks	9	2 H; 2 M; 5 L
Natural waterlogging	3	1 H; 2 M
Uneven/unsafe walking surface (on path, not adjacent)	11	10 H; 1 M
Minimal degradation	5	5 L
Management – degraded geoplastic and channel formation	2	2 M
Management – planks (now dislodged) along path banks	5	4 H; 1 M

(a) Sites may record >1 form of degradation
(b) Erosion severity category: H=high; M=medium; L=low

Erosion estimates: CSA measurements

CSA field measurements of estimated soil loss for each erosion category showed both within- and between-group differences (Table 4). Mean soil loss values increased 10-fold between the low to medium severity category, and another 2.8 times from the medium to high severity category. This regular increase in erosion estimates for low, medium and high severity sites contrasted with the pattern of SOILOSS estimates in which medium severity sites recorded the greatest amount of erosion. However, the patterns of between-method differences showed that for both CSA and SOILOSS, moderate and high erosion categories had substantially higher estimated soil losses than the low erosion category sites (Table 4). CSA registered the greatest soil losses for the high erosion category, contrasting with SOILOSS which recorded both the highest erosion loss and greatest between-site variability (95.6%) for the medium severity group.

CSA and SOILOSS estimates

Erosion estimates using the CSA and SOILOSS methods were compared by using erosion categories (Mann-Whitney *U* test, one-tailed) and linear regression of all-site data. Erosion losses between low and medium categories, and between low and high categories, had the same significant differences for both CSA (U=0, p<0.004 and U=0 p of 0.001 respectively) and SOILOSS. CSA recorded a significant difference between medium and high erosion categories (U=0 p of 0.001) but no significant difference occurred for SOILOSS (U=31, p>0.05).

Table 4: Mean and variability of erosion estimates using measured CSA (m^3/m^2) and estimated SOILOSS ($kg/m^2/yr$) grouped by erosion severity classes

	High severity	Medium severity	Low severity
Measured (CSA) soil loss in m^3/m^2 (sd)*	0.416 (0.143)	0.158 (0.071)	0.013 (0.005)
CV (%)**	34.5	44.9	38.5
Estimated SOILOSS in $g/m^2/yr$ (sd)	3.033 (2.321)	5.400 (5.162)	0.542 (0 276)
CV (%)	76.52	95.6	50 9

* Standard deviation in parentheses
** Coefficient of variation

When CSA and SOILOSS erosion results were compared by ignoring erosion severity categories, no significant correlations were noted between the two methods for all sites

(R^2 = 0.015, p >0.1) (Figure 5) or for the ten high severity sites (R^2 = 0.001, p>0.1). Two pairs of sites registering major anomalies were identified in Figure 5: sites 6,7 and 16,17. Excluding these outliers, the remaining 16 sites recorded a significant linear correlation (R^2 = 0.600, p<0.001). The outliers registered the highest values for SOILOSS (6,7) and CSA (16,17) (Table 5) and thus warranted further investigation as contributors to identifying potentially high-risk erosion sites. Two possible explanatory environmental variables were considered, namely slope and soil texture.

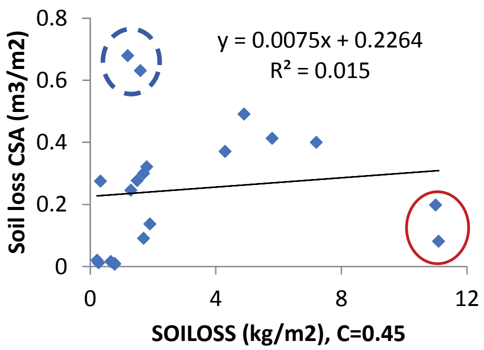


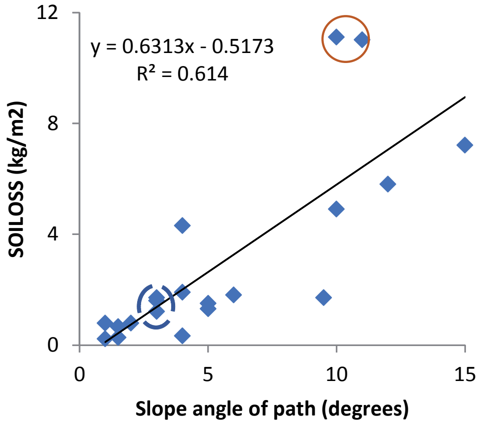
Figure 5: SOILOSS and CSA at all sites (n=20). Circled outliers 6,7 = solid line; outliers 16,17 = broken line.

(a) Slope

Average slope angles for sites categorised as high, moderate and low erosion severity were 7.2, 6.6 and 1.4 degrees, respectively (Table 2). In this study, slope angle explained more than half the variation in estimates of soil erosion using SOILOSS (R^2 = 0.61 p<0.001), partly because slope is a variable included in the equation; but slope was not a significant variable using the CSA method (R^2 = 0.13 p>0.1). Sites 6 and 7 were categorised as medium erosion severity (Table 5), even though they occurred on steeper slopes (11 and 10 degrees respectively) than high erosion severity sites 16 and 17 (both on slopes of 3 degrees). In accounting for the lower than expected measured soil loss (CSA) of outliers 6 and 7, two factors may have contributed: these sites had stones of varying sizes adjacent to and within the path; and management had installed a now-degraded geoplastic material over the trampled area. In estimates using SOILOSS, no adjustment was made for management/natural factors — thus SOILOSS estimates on these slopes were high (Figure 6a). The CSA method reflected the depth-limiting outcome of both stones and management intervention, producing erosion estimates that were more comparable to sites on slopes of less than 5 degrees (Figure 6b).

Table 5: Characteristics of 'outlier' sites

Site no.	Erosion severity category	Erosion estimate high for:	Average slope (⁰)	Mean max. depth (cm)	Stones present	Intervention (geoplastics)	Silt content (%)	Penetrometer (trampled) (kg/cm²)
6	Medium	SOILOSS	11	25	Yes	Yes	<25	1.0
7	Medium	SOILOSS	10	15	Yes	Yes	<25	1.5
16	High	CSA	3	70	No	No	>30	Not penetrable
17	High	CSA	3	85	No	No	>30	Not penetrable



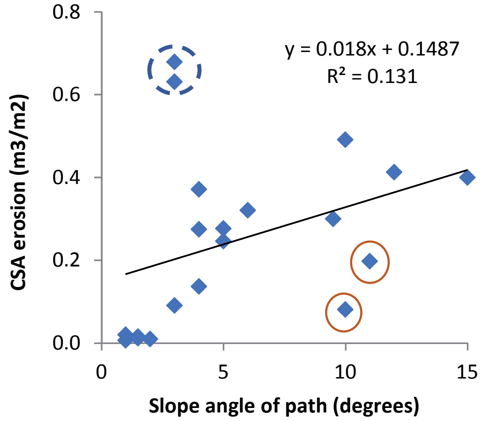


Figure 6a: SOILOSS and slope angle. Figure 6b: CSA and slope angle.
Circled outliers 6,7=solid line (geoplastics); outliers 16,17=broken line (high silt content)

(b) Soil texture

Sites 16 and 17 were categorised as having high erosion severity (Table 5) and, although located on gentle slopes, they nevertheless registered high CSA estimates but did not appear as outliers for SOILOSS. For these sites the substantial silt content (>30%, the highest of all sites) is the most probable explanation for the high erosion estimates for CSA. Silty soils are highly erodible (USDA Natural Resources Conservation Service, no date) and silt can maintain steep cohesive path banks, which in sites 16 and 17 resulted in deep and narrow sections having the lowest width to depth ratio (1.2 and 1.3) of all sites. Trampling had compacted the pathway surface making it impenetrable with a hand-held penetrometer (Table 5) and had thereby increased overland flow by reducing infiltration. In SOILOSS estimates, the silt factor would have been offset by the gentle slope angle.

Another three sites recording loose sandy soils, which are readily detached and transported by water and wind, were categorised as having high severity erosion but did not contribute to outliers (sites 1, 4 and 11). Slope angles for these sites were 4, 12 and 10 degrees respectively, indicating that regardless of slope, sands are likely to be highly susceptible to pathway erosion. Trail width:depth ratios were 4.1, 3.3 and 1.8 respectively, compared with a mean of 2.8 (Table 2). At these three sites, depth of erosion (34, 60 and 57 cm respectively) was associated with reasonably wide trampled areas (mean of 147 cm).

CSA, SOILOSS and maximum path depth

Measured CSA represents erosion that has occurred. Modelling may describe existing erosion and predict future outcomes, as well as being applied as a comparative benchmark against which to assess the effectiveness of conservation measures. Both measured and modelled approaches have value within their respective contexts and yield useful information when combined. However, the relative influence of individual factors, and therefore their management value as erosional indicators, will vary between specific physical environments and visitor usage patterns. In relation to variables considered here, the erosional detail provided by CSA shows a strong correlation with mean maximum path depth (R^2 = 0.869 $p<0.001$, Figure 7), a single measure which is simple and relatively quick to estimate and record. A much weaker but still significant correlation (R^2=0.487 $p<0.001$) was noted between CSA erosion and maximum depth:width ratios. Maximum path width was not significant ($p>0.5$) as a single variable for the CSA method (R^2=0.018), and none of the depth, width or depth:width ratios correlated with SOILOSS estimates (R^2=0.037, R^2=0.000 and R^2=0.164 respectively).

The advantages and disadvantages of the methods of assessing pathway erosion loss examined here are summarised in Table 6.

Table 6: Advantages and disadvantages of methods used for estimating pathway erosion

Estimation method	Advantages	Disadvantages	Examples
Use-related degradation	Trail modifications easy to observe and record (qualitative assessment).	Exact edge of trampled vegetation may be unclear in places; comparability between different observers' categorisations would need to be checked.	Explanatory variable often incorporated within qualitative and quantitative methods.
Qualitative erosion severity assessment (sampling frequency dependent on path length)	Simple classification criteria can be used; low cost to implement; observers readily trained; depth and other estimates easily made; only one person required to make assessment.	High input of labour time for lengthy tracks; boundaries between simple categories in erosion severity classification may be uncertain; extent of impacts between sampling points unknown.	Nepal and Nepal (2004); Mende and Newsome (2006); Hawes et al. (2006); Marion and Leung (2001)
Quantitative erosion severity assessment (cross sectional area measurements)	Simple to set up and record.	More time-consuming than qualitative assessments; precision of measurements may be affected by lateral slope	Jewell and Hammitt (2000); Olive and Marion (2009); Gager and Conacher (2001)
SOILOSS/RUSLE modelling	Effective erosion indicator at a broad scale; knowledge of the model allows for explanation of variations in local output values	Broad-scale modelling may not adequately represent track deterioration at a local scale; the model incorporates only water erosion and excludes wind erosion	Kuss and Morgan (1984); Vinson et al. (2017)

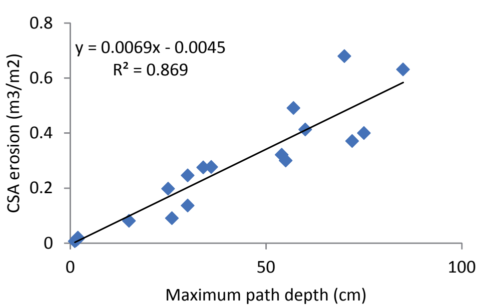


Figure 7: Mean maximum path depth and soil loss (CSA).

Caution needs to be exercised in relation to potential limitations of extrapolating our study to other environments. First, the number of sites we investigated is small statistically, and such a sample may produce anomalous outcomes which are not supported by larger data sets. However, we noted congruence between approaches that were expected to reflect that relationship and were able to point to factors likely to generate anomalies even in the small data set.

Second, variables other than those considered here may be critical to erosion in other environments, requiring adequate local knowledge to assess which physical variables are relevant and whether maximum track depth would be a suitable erosion indicator. Third, even though maximum track depth data correlated significantly with measured CSA erosion, the depth data were means of three CSA values recorded at each site and therefore underestimated individual maximum depths at specific points within each site. Finally, the composition of the visitor population may change over time, with accompanying differences in attitudes and behaviour, leading to altered patterns of use-generated erosion.

Conclusion

Soil erosion is a key variable in assessing track deterioration although it is not necessarily the sole useful indicator for pathway management in all environments. Irregular shallow bedrock, waterlogging or tree root exposure may also be responsible for walking discomfort — but not substantial depth increases — that prompt formation of multiple tracks and associated vegetation trampling. In this study, estimated quantity of soil loss was prioritised over walking comfort in the rare instances where either rock exposure or waterlogging was present.

The presence of pathways is an essential component of both proactive and reactive management of protected areas which contain valuable or rare ecosystems and are accessible to the general public for enjoyment of a variety of leisure activities. In the study area we applied several approaches to assessing pathway erosion and these converged to produce a reasonably consistent result. At the time of the study, sites classified qualitatively as having high erosion severity and without management intervention had the most visitor-generated pathway degradation and, on average, the greatest amount of measured soil loss (CSA) as well as high estimated (modelled) erosion rates. Both erosion indicators were more reliable when slope and soil texture factors were incorporated. We found that qualitative categorical assessment of pathway degradation can be combined successfully with use-generated deterioration and the erosion-estimating approaches of CSA or an erosion model, with field knowledge of physical track conditions being necessary for the interpretation of both qualitative and quantitative information. Maximum path depth provided a simple single indicator of relative erosion losses.

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