Trail degradation as influenced by environmental factors: A state-of-the-knowledge review

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Human use and misuse of land has been causing extensive degradation of the very natural resources on which we depend. National parks, wilderness and other protected natural or semi-natural areas (referred to as natural areas hereafter) represent efforts to preserve our natural heritage from further exploitation. Such areas also provide outstanding recreational, research, and educational opportunities. However, resource impacts resulting from overuse and inappropriate management increasingly threaten these protected areas and erode their natural and cultural values.

Among the many forms of recreational impact, those associated with trail development and use are often a major concern of natural area managers and visitors. Such impacts impair and degrade the functions that trails serve, including (1) protecting resources by concentrating traffic on a hardened tread, (2) providing recreational opportunities along aesthetically pleasing trail routes, and (3) facilitating recreational use by providing a transportation network. The extensive distribution of trails and their degrading condition in many natural areas can have pervasive environmental effects through alteration of natural drainage patterns, erosion and deposition of soil, introduction of exotic vegetation, and increasing human-wildlife conflicts. Degraded trails also threaten the quality of visitor experiences by making travel difficult or unsafe, or by diminishing visitors' perceptions of naturalness.

The proliferation of unintended trails and the degradation of trail resources therefore compromise management goals for these natural areas. In response to such concerns, research on trail impact problems have been carried out for several decades. This line of research is an integral component of recreation ecology: an emerging field in natural resources research which seeks to understand the human-nature ecological relationships in recreation contexts, including identification of recreational impacts on ecosystems and the landscape, the influence of use-related and environmental factors, and the roles management can play in modifying these factors (Cole 1987; Cole 1990; Kuss et al. 1990).

The objectives of this paper are threefold: (1) to clarify terms used in trail condition research; (2) to assess the development of trail degradation research; and (3) to review and summarize the influence of environmental factors affecting trail degradation. Emphasis for objectives two and three is placed on research that examines the relative influence of environmental attributes on trail degradation.

Some definitions

Trail degradation has often been used interchangeably with other terms such as trail impact, trail erosion, trail wear, and trail deterioration. No clear definitions and distinctions have been given in previous studies. A classification system that differentiates these trail condition terms based on the scope of the problems they comprise is presented in Table 1. Such classification also reflects different lines of trail research and their relationship with one other.

Trail impact is the most general term, encompassing all physical, ecological, and aesthetic effects resulting from the construction and use of trails. Trail surveys conducted by Bayfield and Lloyd (1973) in Britain and by Mortensen (1989) in the United States provide good examples of this type of trail studies. In addition to biophysical effects, trail impact studies are also concerned with environmental nuisance and social impacts caused by the depreciative behavior of visitors, such as littering and vandalism.

Other trail research terms reflect differences in specific types of trail problems. Trail deterioration studies are distinguished by their inclusion of trail proliferation and vegetation assessments, and their general focus at a landscape scale. These studies often consider the very existence of trails as a form of impact on the natural landscape. Bayfield's (1986) study of the penetration of user-created trails in the mountain areas of Britain is illustrative of this line of trail research.

Trail degradation studies are, however, more specifically focused on the effects of trail use on the tread surface after they are constructed or created. This line of trail research generally accepts the necessity of trails in natural areas as a means of resource protection. The research then focuses on how trails as a resource can be protected from degrading.

Finally, trail erosion, the most restrictive term, refers specifically to assessments of processes and consequences of soil erosion on the trail tread.

From a management standpoint, trail degradation studies address the most critical problems associated with trails: soil compaction, trail widening, trail incision, and resultant soil loss. Soil loss is particularly important because it is not self-limiting, unlike many other forms of trail impact. Once a trail is established, the soil comprising its tread is subject to the continuing erosional forces of rainfall, running water, wind, freeze/thaw cycles, gravity, and visitor traffic. However, variability in environmental characteristics often endow different trails and even disparate sections of the same trail with varying susceptibility to the impacting forces. Identifying specific environmental attributes and the role they play in controlling trail

Table 1. A classification of trail research terms based on the scope of trail problems included

	Trail condition term			
Trail problem	Trail impact	Trail deterioration	Trail degradation	Trail erosion
Depreciative behavior	✔			
Trail proliferation	✔	✔		
Vegetation cover loss or compositional change	✔	✔		
Soil compaction	✔	✔	✔	
Trail widening	✔	✔	✔	
Trail incision and soil loss	✔	✔	✔	✔

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degradation is vital because it permits the avoidance of sensitive locations and/or the establishment of preventive measures.

Trail degradation research

Research on vegetative effects of trampling has dominated the recreation ecology literature since Meinecke (1928) and Bates (1935) published their studies, while published work on trail degradation did not emerge until the 1970s (Ketchledge and Leonard 1970; Root and Knapik 1972; Bayfield 1973). During this decade trail degradation research originated from many different but fragile montane and alpine/subalpine areas of North America and Western Europe [Canada (Root and Knapik 1972), United States (Ketchledge and Leonard 1970; Helgath 1975), England (Chappell et al. 1971; Bayfield and Lloyd 1973; Crawford and Liddle 1977), Wales (Liddle and Greig-Smith 1975), Scotland (Bayfield 1973), Sweden (Bryan 1977)]. More recently, the geographic range of these studies has expanded to other regions and continents [Australia (Sun and Liddle 1993), Hong Kong (Leung 1992), New Zealand (Stewart and Cameron 1992), Norway (Pounder 1985), South Africa (Garland et al. 1985; Garland 1987)].

Trail degradation research can be classified into four topical concentrations with descending order of the volume of literature: descriptive studies of the type and magnitude of degradation (Root and Knapik 1972; Bratton et al. 1979), analytical studies of the use-degradation relationship (Teschner et al. 1979; Kuss 1986), analytical studies of the environment-degradation relationship (Bryan 1977; Jubenville and O'Sullivan 1987), and evaluative studies of the effectiveness of trail management actions (Cole 1983; Doucette and Kimball 1990). Many studies include more than one concentration.

Previous studies have employed one or a combination of three research designs. A cross-sectional approach is used to assess or compare various forms of trail degradation to use-related or environmental attributes (Helgath 1975; Bratton et al. 1979; Cole 1983). More sophisticated cross-sectional studies analyze differences between trail and off-trail measurements, attributing differences to the construction and use of trails (Teschner et al. 1979; Summer 1980). A longitudinal approach supplements the cross-sectional design with replicated assessments over time, permitting the documentation and evaluation of temporal changes in trail condition (Fish et al. 1981; Cole 1991). Experimental trampling, which is commonly used in trail deterioration and trampling ecology studies, is the third and the most rigorous type of trail degradation research design. This approach seeks to assess relationships between degradation and the amount and type of use, and the influence of various environmental factors under controlled field or laboratory environments (Weaver and Dale 1978; Quinn et al. 1980; Wilson and Seney 1994). The most common trail degradation variables examined in these studies are trail width (total trampled width; bare width), trail incision depth, trail erosion (cross-sectional area loss; sediment yield), the existence of multiple treads and soil compaction (penetrability; bulk density). One major weakness in trail degradation research is the lack of standardization for both the variables studied and the research methods employed. This often hinders comparisons between studies, impeding development of an improved understanding of trail degradation processes.

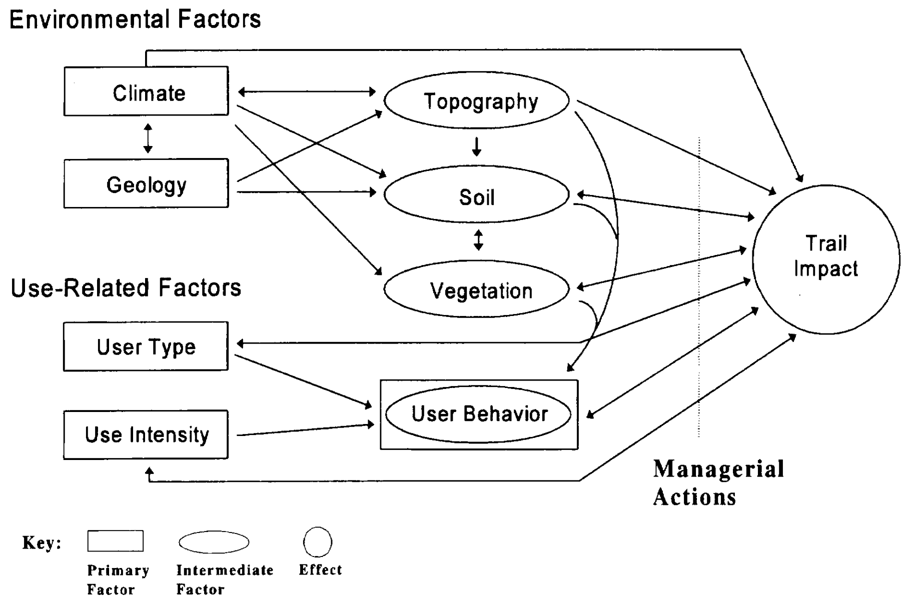

Figure 1. Interrelationships between environmental, use-related, and managerial factors affecting trail degradation

Despite this limitation, several general findings can be drawn based on previous studies. First, the majority of environmental changes occur with initial trail construction (Cole 1990). Second, environmental factors are an important determinant of the type and severity of trail degradation (Cole 1987, Kuss et al. 1990). To illustrate, consider any single trail, which while receiving approximately the same type and amount of use, typically exhibits segments in both good and poor condition. Third, most forms of trail degradation and vegetative changes are related to use intensity in a curvilinear fashion (Weaver et al. 1979; Cole 1983; Sun and Liddle 1993). The majority of post-construction changes occur with initial or low levels of use, with changes diminishing, on a per-capita basis, with increasing use. Subsequent degradation on established trails is mostly a function of site durability and other use-related factors such as type of use and use behavior.

Model of trail degradation

A model of the principal groups of environmental and use-related factors, including interrelationships and the influence of managerial actions, is presented in Figure 1. Primary environmental factors include climate and geology, which act on each other as well as the intermediate elements of topography, soil, and vegetation. The characteristics of these intermediate elements are important determinants of trail degradation. For example, climate and geology may act to determine topography, but it is the topographic characteristics of a landscape which most directly influence the layout of trails and their susceptibility to trail degradation.

Primary use-related factors include user type, use intensity, and user behavior (Figure 1). User behavior also plays an intermediate role because it is influenced by user type, use intensity and the three intermediate environmental factors. All use-related factors are also subject to influence

Table 2. Principal findings relating the influence of geologic and climatic factors on trail degradation

Factor	Method*	Summary of finding	Citation†
Elevation	fo	Trails at higher elevations eroded more severely	(US: Willard and Marr 1970; Marion 1994)
	fm	Positive relationship: trail depth	(US: Burde and Renfro 1986)
Precipitation	fm	Positive relationship: trail depth, soil loss	(US: Burde and Renfro 1986)
	fe	Soil loss related to several rainfall parameters	(SA: Garland 1987)
Seasonal effect	fo	Highest level of trail erosion occurred in summer	(US: Dale and Weaver 1974)

* Method: fo - field observation, fm - field measurement, fe - field experiment
† Citation: SA - South Africa, US - United States

by the extent of trail degradation. For example, excessive trail incision or muddiness can alter hiker behavior, causing hikers to spread laterally in their efforts to avoid eroded or muddy sections (Bayfield 1973). This behavior would lead to other forms of trail degradation, trail widening or multiple treads.

Very few studies have examined the influence of managerial actions, though they have enormous potential for mitigating or modifying the roles of both environmental and use-related factors, with the exception of climate (Figure 1). Through trail layout and design, managers can minimize trail degradation by selecting routes through more resistant and resilient soil and vegetation types and by avoiding sensitive landforms and topography (Price 1983). Through their influence over use-related factors, managers can reduce amount and type of use or modify visitor behavior that contribute to excessive trail degradation (Doucette and Kimball 1990). Finally, through trail construction and maintenance actions, managers can harden treads to sustain use while minimizing water and wind erosion (Proudman and Rajala 1981).

Environmental factors affecting trail degradation

This section summarizes research findings describing relationships between environmental factors and both general and specific forms of trail degradation. An improved understanding of these environmental factors and their influence on the process of trail degradation can aid natural area managers seeking to minimize the extent, degree, and the rate of degradation.

Climate and geology. Climate and geology are two basic groups of factors which affect trail degradation primarily through their influence on other factors. Their effects are typically indirect and are mediated by intermediate elements such as vegetation and soil characteristics. One notable exception is precipitation, which directly erodes tread surfaces from raindrop impact and water runoff.

Research findings relating the influence of these factors on trail degradation are summarized in Table 2. Landscape, established by structural geology, is shaped by climate and manifests its effects on trail degradation through differences in climatic factors. One of the relationships between these factors is illustrated by the research finding that trails at high elevations exhibit greater soil loss than those at lower elevations (Burde and Renfro 1986). This may be attributed to higher precipitation rates and extended periods of snowmelt in the mountains, which create muddy soils and a higher potential for erosion. Additionally, loose soil from more severe freeze/thaw cycles and higher erosion rates on steep trail slopes, and increased exposure to wind erosion, may also contribute to these findings.

Vegetation. The effects of trampling on vegetation are well documented (Cole 1987; Kuss et al. 1990). However, the emphasis here is the influence of vegetative factors on trail degradation (Table 3). In general, understory vegetation with high density, resistance to trampling, and resilience, inhibit trail widening, though these attributes are less important in reducing soil loss. Dense trailside vegetation confines the lateral spread of trail users while segments crossing open meadows often widen or split to form multiple treads (Figure 2). At low use levels, vegetation types with high trampling resistance and resilience can sustain use with little degradation. The influence of these attributes diminish with increasing use and are relatively unimportant at high use levels (Cole 1988).

Topography. Characteristics of topography have been the most intensively investigated influences on trail degradation (Table 4). Numerous studies have documented strong positive relationship between trail slopes and soil loss. The greater velocity and erosivity of surface runoff on steep slopes is the predominant cause but other influences, such as the slippage of feet and hooves, are also likely contributors.

The orientation of the trail to the prevailing slope, termed the trail angle by Bratton et al. (1979), is an important factor that is often overlooked by both trail designers and researchers. We prefer the more descriptive term slope alignment angle for the following discussion. Trails that more directly ascend the fall line of a slope, irrespective of its steepness, have a low slope alignment angle: they are paral-

PHOTO BY JEFFREY L. MARION

Figure 2. Open trailside vegetation and flat sideslopes invite hikers to wander off the trail tread, resulting in trail widening and multiple treads

Figure 3. Trails with low slope alignment angles (lower portion of photo) are more susceptible to different forms of trail degradation than those with high slope alignment angles (upper portion of photo)

lel to the slope. Sideslopes, the terrain adjacent to either side of the trail, are typically not very steep with low slope alignment angles, relative to the plane of the trail tread. Consequently, trails with a low slope alignment angle are susceptible to degradation because their flatter sideslopes offer little resistance to trail widening, and hinder or block the drainage of water from incised trail treads (Figure 3). Trails which more closely follow the contour have a high slope alignment angle: they are perpendicular to the slope. Their steeper sideslopes confine use to the constructed tread and facilitate tread drainage. The importance of slope alignment angle increases in its significance as trail slope increases. This is probably applicable to trails in most topographic positions, including trails that directly ascend valley bottoms, mountainsides, and ridges.

Proximity to groundwater discharge areas or streams can also increase the susceptibility of trails due to excessive wetness and periodic flooding of trail treads. Unless adequate and effective drainage and hardening features are provided in these areas, trails with compacted, eroded, puddled, and muddy tread surfaces are unavoidable. In summary, degradation can be minimized by midslope trail positions with low trail slopes, high slope alignment angles, and moderate to steep sideslopes.

Soil and surface characteristics. Researchers have investigated a number of physical soil properties to evaluate their influence on trail degradation (Table 5). Trails on soils with fine and homogeneous textures have been found to have greater tread incision. Poorly drained soils contribute significantly to excessive trail widening due to users seeking to circumvent muddy areas (Figure 4). Wet muddy

Table 3. Principal findings relating the influence of vegetative factors on trail degradation

Factor	Method*	Summary of finding	Citation†
Vegetation type	fm	Wider trails in forested areas than in meadow	(UK: Bayfield and Lloyd 1973)
	fm	Wider trails in forested areas than in meadow at low use levels; at high use level this pattern reversed	(US: Dale and Weaver 1974)
	fm	Trails are more susceptible to erosion in mesic than in xeric forest types	(US: Helgath 1975; Bratton et al. 1979; Cole 1983; Burde and Renfro 1986)
Vegetation density	fm	Negative relationship: soil loss	(US: Teschner et al. 1979)
	fo	Hikers more confined on trails in dense vegetation	(US: Bright 1986)
Succession stage	fm	Trails in mature forest had greater impact than those in successional forest	(US: Bratton et al. 1979)

* Method: fo-field observation, fm-field measurement
† Citation: UK-United Kingdom, US-United States

Figure 4. Muddy soil on the tread surface contributes to trail widening and multiple treading as hikers seek to circumvent the muddy areas

soils are also more susceptible to erosion, especially when trail slopes are steeper. Highly organic soils retain water long after rains and with traffic become mucky. In many instances wet soils present only seasonal limitations, as during times of the year when rainfall or snowmelt are particularly high. However, these problems can be exacerbated if trails are located near streams and groundwater discharge areas.

Surface characteristics generally refer to the roughness of trail treads, such as stoniness and the presence of large rocks. Trails on soils with a high rock or gravel content have been found to be less susceptible to soil erosion. Rocks and gravels are less easily eroded by water or wind, and these materials can act as filters, retaining and binding finer soil particles. In general, small rocks and stones should not be removed from trail treads as their presence tends to slow the velocity of water runoff and protect underlying soils (Summer 1980, 1986).

Management and research implications

This review of the environmental factors affecting trail degradation offers a number of management and research implications. For managers, an improved understanding of the influence of this group of factors can aid in identifying the contributing causes of specific trail problems. Such knowledge will also help in the selection of appropriate and effective actions to resolve problems. The environmental factors reviewed represent inherent resource capabilities that are typically not subject to manipulation by managers. Rather, their relationships, positive and negative, to trail degradation must be identified and accommodated during original trail design or subsequent relocations. The capacity of a trail to sustain recreational use is greatly increased by avoiding routes through areas particularly susceptible to degradation and favoring areas that are resistant to such changes (Price 1983; Garland 1990).

Most trails in protected natural areas were originally designed to serve nonrecreational purposes, including logging roads, fire access routes, wagon roads, railroad grades, and access routes to former homesteads or fire towers. Though such routes were designed to be serviceable, resource protection objectives were rarely a concern. Route selection was commonly based on finding the shortest distance between two points or done by individuals who either lacked or did not fully apply knowledge of environmental factors. A common error by managers who inherit such trails has been to ignore such environmental deficiencies in their attempts to control trail degradation. The resulting trail problems are often ignored or addressed through restrictions on trail users and/or increased trail maintenance. Such solutions are often unnecessarily restrictive to trail users, ineffective, and costly. A principal recommendation is that managers conduct careful evaluations of all trail degradation problems to identify environmental deficiencies. Where indicated, such problems should be resolved through trail or segment reroutes, or through additional engineering.

Research findings also reinforce the importance of trail maintenance in address-

Table 4. Principal findings relating the influence of terrain and topographic factors on trail degradation

Factor	Method*	Summary of finding	Citation†
Trail slope	fm	Positive relationship: soil loss	(US: Helgath 1975; Weaver and Dale 1978; Bratton et al. 1979; Teschner et al. 1979) (UK: Bayfield 1973; Coleman 1981) (CAN: Welch and Churchill 1986) (NWY: Pounder 1985) (HK: Leung 1992)
	fm/fo	Trail widening on slope due to hiker's lateral spread	(UK: Bayfield 1973) (NWY: Pounder 1985) (HK: Leung 1992) (US: Marion 1994)
Trail sideslope	fo	Hikers tended to walk on side with less acute sideslope	(UK: Bayfield 1973)
	fm	Trails on interfluves (sharp ridges) had narrower treads	(HK: Leung 1992)
Trail alignment	fm	Trails that directly ascend slope were more degraded	(US: Bratton et al. 1979) (HK: Leung 1992)
Slope position	fm	Wider trail treads at upper slope positions	(HK: Leung 1992)
Proximity to water	fm	Greater trail widths at lower slope positions due to wet soils	(US: Marion 1994)
	fo	Trails close to streambanks and areas of groundwater discharge were more damaged	(CAN: Root and Knapik 1972) (US: Marion 1994)

* Method: fo-field observation, fm-field measurement
† Citation: CAN-Canada, HK-Hong Kong, NWY-Norway, UK-United Kingdom, US-United States

Table 5. Principal findings relating the influence of soil and surface factors on trail degradation

Factor	Method*	Summary of finding	Citation†
Soil texture	fo/fm	Soil with finer texture had greater incision	(SWD: Bryan 1977) (CAN: Welch and Churchill 1986)
	fo	Soil with homogeneous texture had greaterincision	(SWD: Bryan 1977)
Soil type	fo	Organic soil related positively with muddiness	(SWD: Bryan 1977)
	fm	Soil with organic topsoil was subject to profile truncation and more compaction	(NZ: Stewart and Cameron 1992)
	fo	Trails in permafrost areas were subject to subsidence-related soil loss	(US: Jubenville and O'Sullivan 1987)
	fo	Trails on colluvial fans had higher occurrence of muddiness	US: Summer 1986)
	fo	Trails on alluvium and till were more eroded than those on colluvium and bedrock	(CAN: Root and Knapik 1972)
Soil moisture	fm	Positive relationship: trail width	(UK: Bayfield 1986)
		Positive relationship: erosion	(US: Willard and Marr 1970)
Infiltration capacity	fm	Positive relationship: trail width	(US: Burde and Renfro 1986)
Stoniness	fm	Negative relationship: trail depth	(SWD: Bryan 1977) (US: Weaver and Dale 1978)
Roughness	fm	Roughness of adjacent areas had negative relationship with trail width	(UK: Bayfield 1973)
	fo	Large rock on trail encouraged lateral spread and increasing trail width	(NWY: Pounder 1985)

* Method: fo - field observation, fm - field measurement
† Citation: CAN - Canada, NWY - Norway, NZ - New Zealand, UK - United Kingdom, US - United States, SWD - Sweden

ing trail degradation problems. Limiting soil erosion on trails is particularly significant as soil loss is not self-limiting, has negative environmental consequences, impairs trail use, and contributes to trail widening. An ongoing program of trail maintenance is essential to both install and maintain an adequate number of tread drainage features. Maintenance actions can also improve and focus use on a single tread to reduce trail widening or the formation of multiple trails.

There are also several implications pertaining to research topics and methodology. Nearly all existing trail degradation studies have emphasized environmental and use-related factors with only brief reference to managerial factors. For example, the densities and/or effectiveness of tread drainage features have not been examined until very recently (Marion 1994). Studies of the effectiveness of alternative trail designs or the suitability of different environments for different types of trail use are also conspicuously absent from the literature. Future trail degradation research should include evaluations of such managerial actions.

Similarly, among environmental factors, another notable omission are studies which examine the role of rainfall events in the process of trail erosion. The significance of soil loss, and the fact that it is primarily caused by water runoff, suggest that an improved understanding of rainfall events is needed. Though no data exists, managers commonly observe that soil loss from a single major storm event can greatly exceed that of many years of more typical weather and trail use. Additionally, because erosion processes on trails are more similar to those of gully erosion, modeling and prediction of trail erosion using the concepts of surface and rill erosion may not be relevant (Morgan 1985). Rather, models of gully development (Bucco 1991) developed in geomorphological studies might be more appropriate for examining the channelized form of erosion common to trails.

Relatively few trail studies have incorporated landform or landscape components (Pounder 1985; Summer 1986; Tinsley and Fish 1985) or concepts in landscape ecology (Benninger-Truax et al. 1992). A potential new area for research is the relationship between landscape heterogeneity and trail system condition and stability. The spatial analytical capabilities of geographic information systems may be useful for these types of studies. Finally, additional experimental and longitudinal research is needed to more thoroughly investigate trail degradation interrelationships and processes. Additional emphasis is also needed on multivariate analyses and the development of trail degradation models.

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