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RESEARCH

Impacts of Experimentally Applied Mountain Biking and Hiking on Vegetation and Soil of a Deciduous Forest

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ABSTRACT / Many recent trail degradation problems have been attributed to mountain biking because of its alleged capacity to do more damage than other activities, particularly hiking. This study compared the effects of experimentally applied mountain biking and hiking on the understory vegetation and soil of a deciduous forest. Five different intensities of biking and hiking (i.e., 0, 25, 75, 200 and 500 passes) were applied to 4-m-long × 1-m-wide lanes in Boyne Valley Provincial Park, Ontario, Canada. Measurements of plant stem density, species richness, and soil exposure were made before treatment, two weeks after treatment, and again one year after treatment. Biking and hiking generally had similar effects on vegetation and soil. Two weeks after treatment, stem density and species richness were reduced by up to 100% of pretreatment values. In addition, the amount of soil exposed increased by up to 54%. One year later, these treatment effects were no longer detectable. These results indicate that at a similar intensity of activity, the short-term impacts of mountain biking and hiking may not differ greatly in the undisturbed area of a deciduous forest habitat. The immediate impacts of both activities can be severe but rapid recovery should be expected when the activities are not allowed to continue. Implications of these results for trail recreation are discussed.

Managers of natural areas consider recreational impacts along trails and on campsites to be their most common management problem (Godin and Leonard 1979, Washburne and Cole 1983). The field of recreation ecology, which developed to address this problem, initially focused largely on the impacts of hikers (Cole 1987a). Impacts of recreation on trails can vary between activity types (e.g., hikers, horses, and motorcycles) (Weaver and Dale 1978), so it is important to know the impacts of new forms of recreational activity, such as mountain biking.

The addition of mountain biking to trails in recreation areas has caused considerable concern. Some hikers feel that bikers should be excluded from existing trails because of the potential damaging effect of moving wheels (Cessford 1995). The Sierra Club cited potential degradation of the environment as a reason for developing guidelines and policies on biker access to trails (Coello 1989). Some park supervisors and managers have also attributed trail damage to mountain biking (Chavez 1996, Schuett 1997). A number of factors may contribute to trail degradation following the addition of mountain bikes, including biker behavior and the physical impact of bikes.

Numerous studies have focused on the behavior basis for mountain biking impacts (Watson and others 1991, Chavez and others 1993, Ruff and Mellors 1993, Cessford 1995, Schuett 1997, Goeft 1999, Symmonds and others 1999, 2000). Much less research has focused on the physical impacts of mountain biking. One study (Wilson and Seney 1994) appears in the primary literature and several others are unpublished (Petit and Pontes 1987, Goeft 1999). Wilson and Seney (1994) compared the soil erosion caused by mountain bikes, hikers, horses, and motorcycles using experimentally applied passes in Montana. They found that horses made more sediment available to erosion than mountain bikes, hikers or motorcycles, which did not differ significantly from each other or from the control. Their experiment was conducted on an existing trail with a history of prior, multiple use. Additional studies are needed to answer questions about how mountain bikes impact vegetation and soils at early stages of trail formation and how these impacts compare with those caused by other activities (e.g., hiking).

In areas with established trail systems, a common problem reported by managers is the tendency of users to go off-trail, creating impromptu paths (Cole 1985). Off-trail use can result in parallel tracks or trail widening where the main trail is more difficult to traverse

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*Author to whom correspondence should be addressed. e-mail: rreader@uoguelph.ca than adjacent surfaces (Bayfield 1973, Lance and others 1989), or may result in new, informal trails where users cut through undisturbed vegetation as a shortcut or to gain access to attractions (Coello 1989, Cessford 1995). Because it becomes difficult to discourage the use of obvious impromptu trails, managers need to know how many off-trail passes are needed to create a trail and if this threshold differs for biking and hiking. If the effects of biking and hiking are similar, then managers can make use of previous hiking studies (Cole and Schreiner 1981) to predict where and when biking impacts are likely to occur.

The purpose of this study was to compare the effects of mountain biking and hiking on the soil and understory vegetation of an undisturbed deciduous forest at the initial stage of trail formation. To isolate the physical impacts of each activity, the behavior of bikers and hikers was standardized. By measuring soil and vegetation parameters before and after experimentally applied biking and hiking passes, we assessed differences between effects of biking and hiking, under the unique circumstances of the experiment. The study was conducted in a deciduous forest for two reasons. First, deciduous forests with sensitive, forb-dominated understories are among the most susceptible terrestrial habitats to damage by recreational activity (Kuss 1986, Cole 1987b, 1995c). Therefore, potential differences in the amount of impact from biking and hiking should be more easily observed in this vegetation type than in more resistant types. Second, forest is the preferred environment of mountain bikers (Ruff and Mellors 1993) and is therefore a likely setting for future bicycle paths.

Materials and Methods

Study Area

The study was conducted in Boyne Valley Provincial Park (44°05′N, 80°08′W), located 60 km northwest of Toronto, Ontario, Canada. A site was selected within the park that satisfied two criteria: (1) a mature deciduous forest with continuous canopy, and (2) absence of timber harvesting. The site occupies an area of approximately 270 ha, at an elevation of 420–470 m. The dominant tree cover is sugar maple (*Acer saccharum* L.), and the predominant soil type is a well-drained fine sandy loam of the Hillsburgh soil series (Hoffman and others 1964).

Experimental Design

The experiment consisted of two treatments: activity type (hiking or biking) and pass intensity (0, 25, 75, 200, and 500 passes), resulting in ten treatment combinations. A maximum of 500 passes was chosen based on the finding of Cole and Bayfield (1993) that 500 passes was sufficient to cause at least a 50% reduction in vegetation cover for most vegetation types. Each of the ten treatment combinations was randomly assigned to one of ten treatment lanes within a 50-m-long × 5-m-wide block. Lanes were 5 m long and 1 m wide (Figure 1A). Lanes were separated by a buffer zone of 5 m to avoid potential treatment carryover effects and to allow access for taking measurements. The 50 cm at each end of the 5 m lane were used as buffer zones so that the sampled portion was 4 m long × 1 m wide. The meter-wide plots were divided into three zones (center, middle, and outer) to allow for spatial variation in biking and hiking impacts (Figure 1B). The ten blocks were set up at least 5 m away from one another and at least 25 m from the edge of the forest.

Treatment Application

Each block was positioned on a slope so that the treatment lanes ran perpendicular to slope contours. An effort was made to position each block so that terrain microtopography was as homogeneous as possible from one end to the other. Slopes were measured with a clinometer at each of the ten lanes along the base of each block. The mean slope measurements for the ten chosen blocks ranged from 9.0° to 14.7°. Block locations were also selected to share the same southerly aspect. The centerline of each lane was marked by five wire pegs tied with flagging tape to indicate the path to be followed by bikers and hikers.

Biking and hiking treatments were applied by the same four participants, weighing between 57 and 73 kg. To apply hiking passes, three hikers wore lug-soled hiking boots and one wore rubber-soled running shoes. Three mountain bikes, two Norco Kokanees and one Raleigh Legend, each weighing 13.5 kg, were used to apply biking passes. All three bikes had 18-inch chrom-alloy frames, with heavily lugged tires (65.4 cm diameter, and 4.9 cm width), with 21 speed Shimano front and rear derailleur gears, and Shimano cantilever hand brakes. The total weights of bikes plus riders ranged from 70.5 to 86.5 kg.

Biking and hiking treatments were applied from the start of the last week of June to the middle of the second week of August 1997. The total number of passes required for an individual block (1600) was scheduled to be completed over a one-week period. The number of passes to be completed on a particular lane was distributed over the same number of days so that on a given day a 25-pass lane might receive two passes per person while a 500-pass lane would receive

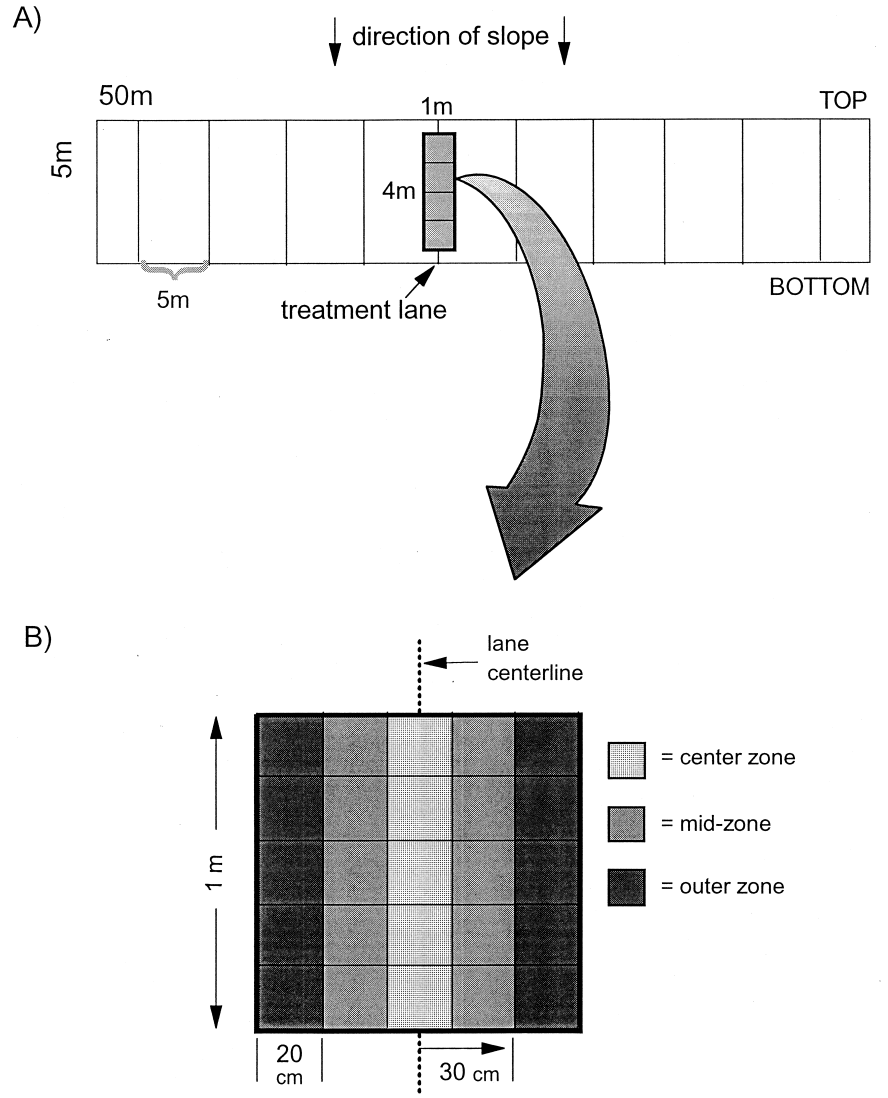


Figure 1. (**A**) Location of the ten treatment lanes per 50m × 5m block. (**B**) Enlargement of a 1-m × 1-m quadrat showing the three quadrat zones (center, middle, outer).

40. As well, the number of passes scheduled to be completed on a given day were distributed among all participants in order to balance weight differences.

A pass was a one-way walk or bike trip down a lane following the premarked centerline path. Bikers could not make uphill passes, even in the lowest of 21 gears, due to slope, rough terrain, and tree sapling density, so passes by both hikers and bikers were only made downhill. Hikers moved at a natural gait, adjusting their pace on steeper slopes and over rough terrain to maintain balance. During the initial passes down a given lane, hikers would occasionally stumble away from the lane centerline, or slide their boots over steeper sections, until a path developed. Bikers traveled at a moderate speed, usually allowing bicycles to roll down lanes without pedaling where the slope would allow. Brakes were applied as needed to keep bicycles under control. Over rough terrain, some firm braking, occasional skidding, and some side-to-side movement of the front tire was required to maintain balance until a path developed. Once participants reached the bottom of a lane, they would turn and circle around the nearest end of the block back to the top of the lane to make a second pass. Treatment application schedules were adjusted to avoid heavy rain events for the safety of bikers and hikers. Blocks received approximately 19 mm of rain during treatment application.

To calculate the surface area covered by one pass of a hiker or bicycle, and the contact pressure applied by each, boot sole and tire measurements were taken. Hiker footwear had a mean single sole contact area of 215.1 cm^2 (range 200.0–228.8 cm^2). The surface area contacted by two bicycle tires on the ground at any given moment (without a load being applied) was calculated as 224.3 cm^2 from an equation based on the tire geometry of agricultural vehicles: $S = 0.7 \times$ undeflected tire radius $\times$ tire width (Soane and others 1981a, 1981b), where S is the contact area of one tire, radius = 32.7 cm, and tire width = 4.9 cm. The total surface area contacted by a hiker would therefore be (assuming six steps per 4 m of lane) 1290.6 cm^2, and that by a biker would be tire width $\times$ 4 m $\times$ 2 wheels = 3920 cm^2. The pressure applied over one foot step was calculated as the weight of each hiker divided by the area covered by their boot sole. Hikers applied a mean pressure of 0.29 kg/cm^2 (range 0.27–0.32 kg/cm^2). A similar approach was used to calculate the pressure applied over two bicycle tires at rest. Using bike plus biker weights and the contact area calculated above, the mean pressure applied by bicycle and rider was 0.35 kg/cm^2 (range 0.31–0.39 kg/cm^2).

Response Variables

Three variables commonly used to assess recreational impacts were measured. First, the loss of vegetation following treatment application was measured by the change in vascular plant stem density from pretreatment stem density. Second, the loss of species richness was measured by the change in the number of plant species present. Third, the increase in the amount of soil exposed was measured.

Measurements were made immediately before biking and hiking passes were applied, and then two weeks after treatment application and again one year after treatment application.

Pretreatment measurements. A 1-m^2 wooden frame quadrat was positioned on the ground so that the lane centerline marked the center of the quadrat as well. String was attached to the 1 m^2 frame to divide it into twenty-five 20-cm $\times$ 20-cm cells (Figure 1B). To accommodate the presence of saplings and other obstacles in the sampling area, a second quadrat was prepared that used removable thin wooden planks, instead of string, to outline the 25 cells. To consider the spatial differences in treatment effects from the center of the lane to its edges, the five columns of quadrat cells were grouped into three categories, or quadrat zones. The center column of five cells was referred to as the center zone, the two columns on either side of the center (i.e., ten cells) were called the middle zone, and the two outside columns of cells (i.e., ten cells) became the outer zone (Figure 1B). Measurements were made and recorded for each individual cell before being summarized for the three zones. Once measurements were completed for a quadrat, its position was marked at four corners using pegs tied with flagging tape so that the same exact spot would be used again during posttreatment sampling.

Vascular plants present in a cell were identified to species and species were each categorized as one of six growth forms: tree-seedlings (stem <1 cm diameter, height <1 m), tree saplings (stem >1 cm diameter, height >1 m), shrubs and vines, ferns, forbs (broad-leaved herbaceous plants), and graminoids (grasses and sedges). Mature trees were not encountered within the sampled lane areas. Once identified, the plants in each quadrat cell were counted. To avoid the problem of how to define individual plants (complicated by clonal growth), plants were counted by their aboveground stems only. Due to the dense clustered growth of the graminoids, they could not be enumerated as discrete stems with confidence. Instead, each graminoid species was simply observed as either present or absent in a given quadrat cell. Graminoid data were therefore only used in species richness calculations.

Exposed soil was defined as bare ground of the A_1 horizon, free of macroscopic vegetation, leaf litter, twigs, moss, or humus. Soil exposure was visually estimated for each quadrat cell using a five-point scale: 0 (0–20%), 1 (21–40%), 2 (41–60%), 3 (61–80%), and 4 (81–100%).

Two weeks after treatment application. Effects of biking and hiking were first measured two weeks after treatment application. A two-week waiting period was recommended by Cole and Bayfield (1993) as the amount of time required to allow damage to vegetation to become apparent. Quadrats were repositioned using corner markers to ensure identical placement and the procedure used to measure pretreatment conditions was repeated during posttreatment sampling. Vascular plant stems present were classified as intact, damaged, dead, or absent. Intact stems were those found in their original condition. Damaged stems were those found with evident tissue loss (missing leaves), with impact-induced injury (broken stems, crushed plant body), or with yellowing or wilting plant parts. Dead stems were those with no green pigment and were brittle to the touch. Absent stems were simply missing. New shoots (<10 in total) were not included in the posttreatment vegetation survey. Soil exposure was estimated visually as in the pretreatment sampling, using the same five-point scale (0–4).

One year after treatment application. Posttreatment sampling was repeated one year after treatment application. A one-year period was recommended by Cole and Bayfield (1993) as the amount of time required for damage to either diminish or become more apparent, depending on the resiliency of the vegetation type.

Vascular plant stems were classified as present or absent. Soil exposure was estimated visually as in pretreatment sampling, using the same five-point scale (0–4).

Treatment Effects

Measurements taken during pretreatment and posttreatment sampling were used to calculate the following response variables. For each variable, data for the four quadrats per treatment lane were summed for each quadrat zone (center, middle, outer).

Loss of vegetation after two weeks. This was defined as the percentage of original vegetation found damaged, dead, or absent two weeks following treatment application. It was calculated as follows:

$$\frac{\text{number of original stems found damaged, dead, or absent 2 weeks after}}{\text{number of stems present before}} \times 100\%$$

where the words before and after refer to pre- and posttreatment measurements.

Loss of vegetation after one year. This was defined as the percentage of original vegetation that was absent one year following treatment application. It was calculated as follows:

$$\frac{\text{number of original stems found absent 1 year after}}{\text{number of stems present before}} \times 100\%$$

Treatment lanes where no plant stems were present initially (14 of 300 lanes) were not included in the analysis.

Loss of species after two weeks. This was defined as the percentage of initial species that were not present (i.e., all stems were dead or absent) two weeks following treatment application. It was calculated as follows:

$$\frac{\text{number of species found dead or absent 2 weeks after}}{\text{number of species present before}} \times 100\%$$

Loss of species after one year. This was defined as the percentage of initial species that were absent one year following treatment application. It was calculated as follows:

$$\frac{\text{number of species found absent 1 year after}}{\text{number of species present before}} \times 100\%$$

Increase in soil exposure after two weeks or one year. This was defined as the difference in cover estimates before and either two weeks or one year after treatment application. It was calculated as follows:

$$\%\text{ exposed soil (2 weeks or 1 year) after} - \%\text{ exposed soil before}$$

Statistical Analysis

To determine whether there were any preexisting differences among lanes assigned to different treatments, pretreatment (before) values for each response variable were compared using a three-factor split-plot analysis of variance (ANOVA). The two whole-plot factors were activity type (biking or hiking) and pass intensity (number of passes made). The split-plot factor was quadrat zone. This analysis was carried out using the PROC MIXED procedure of SAS (SAS Institute Inc., 1996). Data were square-root transformed to help meet assumptions of normality and equality of variance. This analysis revealed no significant pretreatment effects (Thurston 1998).

To assess statistical significance of posttreatment (after) effects, the three-factor analysis described above was repeated for each of the three response variables. Significant interaction terms involving quadrat zone made it necessary to analyze treatment effects for each zone separately. Data for each zone were analyzed with a two-factor ANOVA for a randomized complete-block design, using the PROC GLM procedure of SAS (SAS Institute Inc., 1996). The two treatment effects were activity type (biking and hiking) and pass intensity (0, 25, 75, 200, and 500 passes). Data were arcsine square-root-transformed for loss of vegetation and loss of species data after two weeks, square-root-transformed for soil exposure data, and log-transformed for loss of vegetation after one year data.

Results

Vegetation Composition

Fifty-five vascular plant species were encountered in pretreatment sampling (Appendix 1). The most common species were two forbs, *Arisaema triphyllum* (L.) Schott. (20 stems per lane), and *Caulophyllum thalictroides* (L.) Michx. (11 stems per lane), and seedlings of the tree *Acer saccharum* (7 stems per lane). A total of six different growth forms were encountered: forbs, tree seedlings, ferns, shrubs and vines, tree saplings, and graminoids. Based on total stem density, forbs ranked first with 77% of all stems, followed in turn by tree seedlings (17%), ferns (3%), shrubs and vines (2%), and tree saplings (1%).

Treatment Effects After Two Weeks

Loss of vegetation. Vegetation loss was significantly affected by pass intensity, by quadrat zone, and by the

Table 1. Analysis of variance results for treatment effects on loss of vegetation, species richness, and increase in soil exposure after two weeks in three quadrat zones (Combined or Separated)[a]

	F value		
Source of variation	Loss of vegetation	Loss of species richness	Increase in soil exposure
Combined			
Activity type (A)	0.6	0.5	2.3
Pass intensity (P)	40.1**	16.3**	53.7**
$A \times P$	1.8	0.8	0.8
Quadrat zone (Z)	223.2**	188.6**	186.6**
$A \times Z$	2.4	1.1	0.9
$P \times Z$	11.8**	6.0***	25.0**
$A \times P \times Z$	0.9	0.4	0.3
Separated			
Center zone			
Activity type	0.01	3.0	0.7
Pass intensity	48.7**	19.4**	37.8**
$A \times P$	1.6	0.6	0.3
Middle zone			
Activity type	3.6	0.04	0.3
Pass intensity	20.9**	6.5**	5.5*
$A \times P$	0.6	0.3	33.7**
Outer zone			
Activity type	0.3	0.07	0.2
Pass intensity	2.0	1.2	2.3
$A \times P$	1.5	0.6	1.0

[a] Blank = $P > 0.05$, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

interaction effect of pass intensity × zone. This interaction reflects the significant pass intensity effect detected in the center and middle zones but not in the outer zone (Table 1, Separated). In contrast, neither activity type nor any interaction effect including activity type was significant (Table 1).

Vegetation loss generally increased with increasing pass intensity for the two activity types combined (Figure 2a). In the center zone, mean vegetation loss increased significantly from 16%–31% on control lanes (0 passes), to 86%–100% on treated lanes (25–500 passes). In the middle zone, vegetation loss increased significantly from 14% on control lanes (0 passes) to 58%–79% on treated lanes (25–500 passes). In the outer zone, vegetation loss did not differ significantly with the number of passes made, ranging from 14% to 28%.

Mean vegetation loss did not differ significantly between biking and hiking treatments (Table 1, Combined). Nor were there any significant interactions between activity type and pass intensity, in any zone (Table 1, Separated). Mean vegetation loss over all pass intensities was greatest in the center zone (80% for biking, 81% for hiking), moderate in the middle zone (55% for biking, 47% for hiking), and least in the outer zone (19% for biking, 22% for hiking) (Figure 3a).

Loss of species. Species loss was significantly affected by pass intensity, by quadrat zone, and by the interaction effect of pass intensity × zone (Table 1, Combined). Again, this interaction effect reflects the significant pass-intensity effect detected in both the center and middle zones but not in the outer zone (Table 1, Separated). Species loss was not affected by activity type or by any other interaction (Table 1).

Species loss generally increased with increasing pass intensity for the two activity types combined (Figure 2b). In the center zone, species loss increased significantly from 28% on control lanes (0 passes) to 74%–99% on treated lanes (25–500 passes). In the middle zone, species loss differed significantly from 4% on control lanes (0 passes) to 22%–41% on treated lanes (25–500 passes). In the outer zone, no significant treatment effects were found, with species loss ranging from 6% to 14%.

Mean species loss did not differ significantly between biking and hiking treatments (Table 1, Combined), or were there any significant interactions between activity type and pass intensity in any zone (Table 1, Separated). Mean species loss over all pass intensities was greatest in the center zone (80% for biking, 71% for hiking), moderate in the middle zone (27% for biking, 26% for hiking), and least in the outer zone (8% for biking, 11% for hiking) (Figure 3b).

Increase in soil exposure. Soil exposure was significantly affected by pass intensity, by quadrat zone, and by the interaction of the two (Table 1, Combined). The interaction resulted from the significant pass intensity effect being detected in both the center and middle zones but not in the outer zone (Table 1, Separated). Neither activity type nor any interaction involving activity type was statistically significant when all three zones were considered together (Table 1).

In the center zone, mean soil exposure increased gradually and significantly from 1% on control lanes (0 passes) to 49% on treated lanes (Figure 2c). In the middle zone, mean soil exposure increased significantly with pass intensity but to a lesser extent than in the center zone, ranging from 1% for control lanes (0 passes) to a maximum increase of 21% for treated lanes. In the outer zone, no significant treatment effects were found. Mean increase in soil exposure ranged from −0.2% to 1%.

Mean soil exposure did not differ significantly between biking and hiking treatments in any zone (Table 1, Separated). Mean soil exposure over all pass intensities was greatest in the center zone (30% for biking lanes, 23% for hiking lanes), moderate in the middle

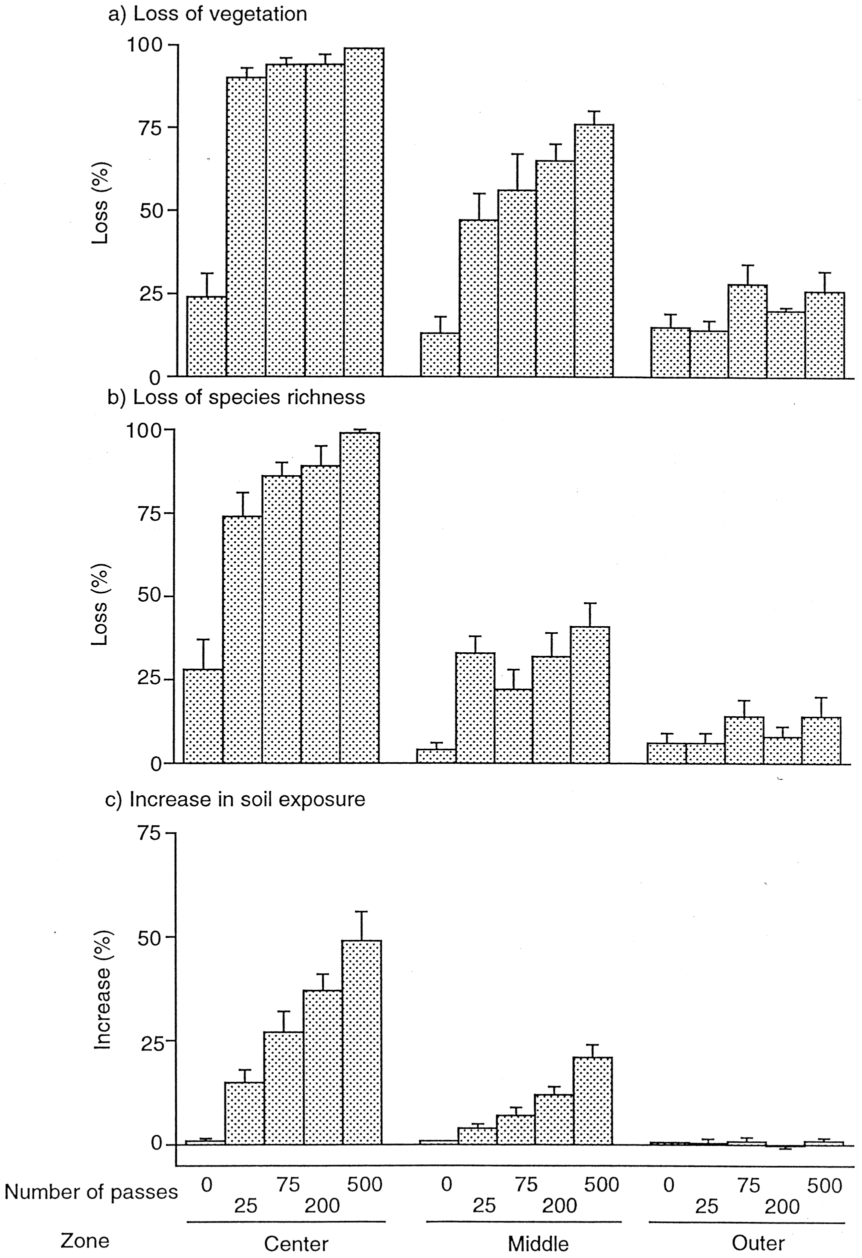


Figure 2. Effect of increasing pass intensity on the mean (±1 SE) loss of vegetation, loss of species richness, and increase in soil exposure two weeks after treatment in the three quadrat zones for the two activity types (biking and hiking) combined.

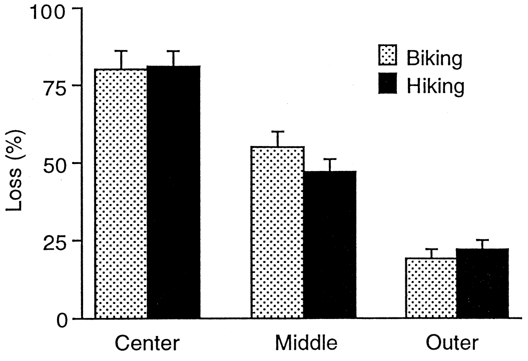
zone (10% for biking lanes, 8% for hiking lanes), and least in the outer zone (0.6% for both activities) (Figure 3c).

Analysis of variance results for soil exposure in the middle zone indicated a significant interaction between activity type and pass intensity (Table 1, Separated). This interaction was due to the fact that soil exposure following biking was only significantly greater than hiking at one pass-intensity (i.e., 500 passes) (Thurston 1998).

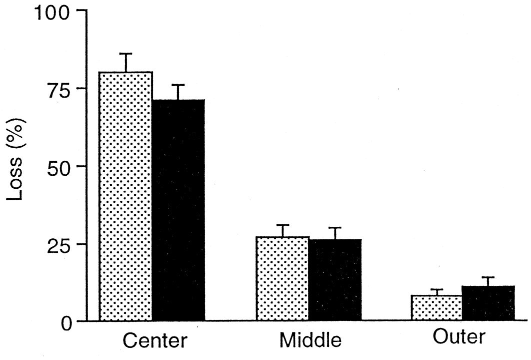
Treatment Effects After One Year

Loss of vegetation. Vegetation loss did not differ significantly between activity types or among pass intensities (Table 2). There was a significant difference among zones, however. Mean vegetation loss in the outer zone (7%) and in the middle zone (11%) were significantly less than in the center zone (31%) for all pass intensities and activity types combined. None of the interaction effects involving zone, activity type or pass intensity were statistically significant.

a) Loss of vegetation



b) Loss of species richness



c) Increase in soil exposure

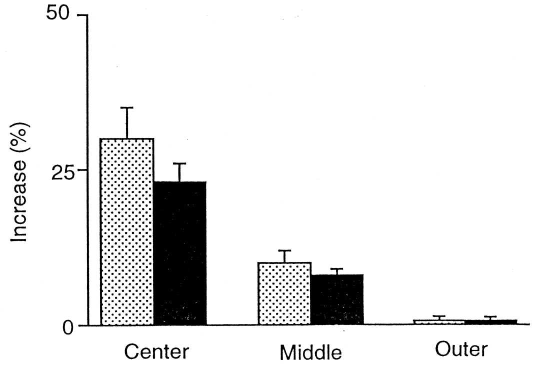


Figure 3. Effect of activity type (biking or hiking) on the mean (±1 SE) loss of vegetation, loss of species richness, and increase in soil exposure two weeks after treatment in the three quadrat zones for the five pass intensities combined.

Table 2. Analysis of variance results for treatment effects on loss of vegetation, species richness, and increase in soil exposure after one year in the three quadrat zones (Combined or Separated)[a]

	F value		
Source of variation	Loss of vegetation	Loss of species richness	Increase in soil exposure
Combined			
Activity type (*A*)	0.07	0.9	0.2
Pass intensity (*P*)	0.8	0.6	1.8
$A \times P$	1.1	1.6	4.1**
Quadrat zone (*Z*)	6.1**	6.1**	9.0***
$A \times Z$	1.0	0.6	0.2
$P \times Z$	0.3	0.4	0.9
$A \times P \times Z$	0.3	0.4	0.5
Separated			
Center zone			
Activity type	1.0	0.4	0.03
Pass intensity	0.8	0.6	2.1
$A \times P$	0.7	1.2	0.7
Middle zone			
Activity type	0.8	1.3	0.4
Pass intensity	0.5	0.7	2.2
$A \times P$	0.5	0.5	1.9
Outer zone			
Activity type	0.04	1.0	0.3
Pass intensity	0.5	0.3	0.9
$A \times P$	0.9	0.8	1.5

[a] Blank = $P > 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

Mean vegetation loss for all pass intensities combined ranged from 1% in the outer zone to 34% in the center zone (Figure 4a). Mean vegetation loss for activity types combined ranged from −2% in the outer zone to 42% in the center zone (Figure 5a). The negative value indicates an increase in posttreatment stem density over pretreatment stem density.

Species loss. Species loss did not differ significantly between treatments but it did differ among zones (Table 2, Combined). Mean species losses in the outer zone (6%) and in the middle zone (8%) were significantly less than species loss in the center zone (24%) for all pass intensities and activity types combined. None of the interaction effects involving zone, activity type or pass intensity were statistically significant.

Mean species loss for activity types combined ranged from −3% in the outer zone to 30% in the center zone (Figure 4b). Mean species loss for all pass intensities combined ranged from 2% in the outer zone to 25% in the center zone (Figure 5b).

Increase in soil exposure. Soil exposure did not differ significantly between activity types or among pass intensities (Table 2, Combined). However, the interaction of activity type × pass intensity was significant. This interaction resulted from soil exposure being greater on biking 500 pass lanes than hiking 500 pass lanes but not at lower pass intensities (0–200 passes) (Thurston 1998). There was also a significant difference in soil exposure among quadrat zones, with the center (4%) and middle zones (2.4%) greater than the outer zone (0.2%). None of the other interaction effects involving zone, activity type, or pass intensity were statistically

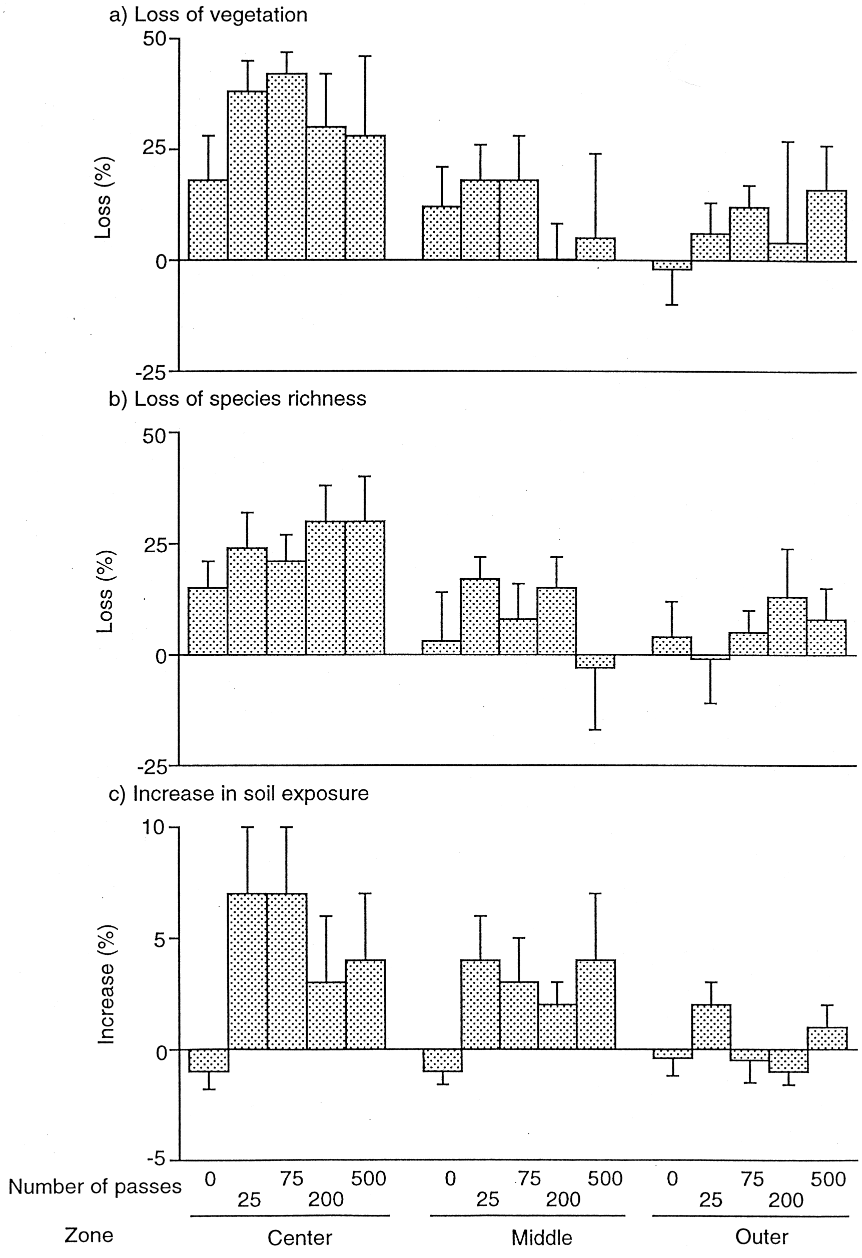


Figure 4. Effect of increasing pass intensity on the mean (±1 SE) loss of vegetation, loss of species richness and increase in soil exposure one year after treatment in the three quadrat zones for the two activity types (biking and hiking) combined.

significant. Mean values for exposed soil over both activity types ranged from −1.1% to 7.0% (Figure 4c). Mean soil exposure for all pass intensities combined ranged from −0.6% to 4% (Figure 5c).

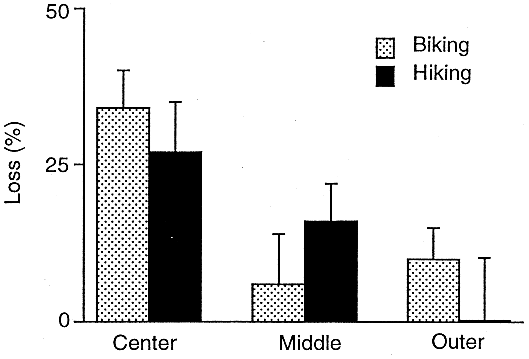
Discussion

Three principal findings emerged from this study. First, impacts on vegetation and soil increased with biking and hiking activity. Second, the impacts of biking and hiking measured here were not significantly different. Third, impacts did not extend beyond 30 cm of the trail centerline. These findings are discussed in turn below, followed by suggestions for future research and the management implications of our results.

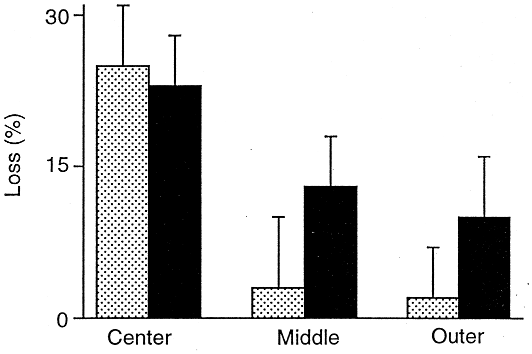
Pass-Intensity Effects After Two Weeks

In the center zone, both vegetation loss and species loss occurred rapidly with biking or hiking activity. After only 25 passes nearly every plant stem present in the center zone was damaged. Effects were less pronounced in the middle and outer zones because bikers and hikers only came in contact with vegetation when they strayed from the lane centerline. The asymptotic

a) Loss of vegetation



b) Loss of species richness



c) Increase in soil exposure

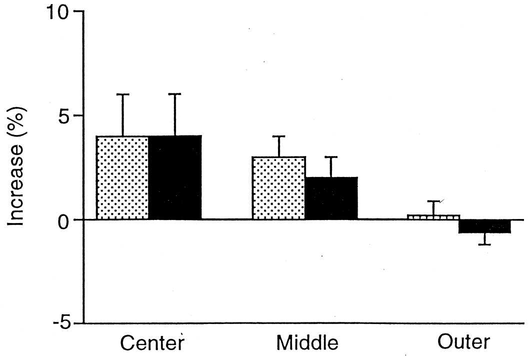


Figure 5. Effect of activity type (biking or hiking) on the mean (±1 SE) loss of vegetation, loss of species richness and increase in soil exposure one year after treatment in the three quadrat zones for the five pass-intensities combined.

pattern of vegetation loss with increasing amount of recreational activity found here is characteristic of deciduous forests with understories dominated by erect forbs. Numerous studies have identified closed-canopy forests among the habitats most susceptible to recreational impact (Kuss 1986, Cole 1979, 1987a, b, 1995a, b). The loss of species due to recreational activity is likely controlled by several species attributes. First, growth forms with tall, succulent stems and broad leaves, such as the erect forb species observed in this study, are easily crushed and broken by recreational activity, while growth forms with narrow leaves and flexible stems, such as graminoids, are more resistant (Sun and Liddle 1993a, b). Second, rare species are more likely to be lost than common species. Both attributes may have contributed to species loss in this study because erect forbs dominated the sampled lanes and approximately one third (35%) of the species present initially in treatment lanes were represented by five or fewer stems.

Soil exposure increased almost linearly from the lowest pass lanes to the highest rather than asymptotically, as was observed for vegetation loss. Mean values for increased soil exposure did not exceed 49% on the 500 pass lanes of the center zone, whereas vegetation loss reached 99% on the same lanes. These results indicate that the loss of organic horizons does not occur as rapidly or does not become as severe at low trampling intensities as does vegetation loss. This is explained simply by the fact that as vegetation is damaged and killed by low levels of use, surface organic layers (i.e., leaf litter) are only just beginning to be scuffed away (Cole 1987a). Cole (1987b) found that soil exposure below 100 passes per year was negligible, and Quinn and others (1980) observed that bare ground did not appear until after at least 250 passes were made.

Pass-Intensity Effects After One Year

One year following treatments, neither vegetation loss nor species loss was significantly greater on treated lanes than on control lanes. Most of the herbaceous plant species at the study site were perennials, with their perennating buds located at or below the soil surface (Gleason and Cronquist 1991). In these species, aboveground stems may be damaged or removed in a given season, but if the perennating organ remains intact, plants should be able to replace lost stems in following seasons. Presumably, resprouting from dormant buds would account for the absence of any treatment effect after one year. Our results support Cole's (1987a, 1995b) suggestion that deciduous forest understory plants have high resilience (i.e., the ability to subsequently recover) when the recreational activity is not continuous.

The amount of soil still exposed after one year in treated lanes did not differ significantly from control lanes. The absence of a detectable treatment effect was likely due to the addition of deciduous tree leaves to the forest floor in the autumn following treatment application. Over-winter reduction in exposed soil has been attributed to leaf fall by a number of investigators (e.g., Legg and Schneider 1977, Cole 1987b, Hammitt and Cole 1987).

Activity-Type Effects

For the response variables measured in this study, there were no significant differences between hiking and mountain biking treatments. One possible explanation is that when vulnerable plants are directly contacted by a weight-bearing surface they will be affected no matter what the weight-bearing surface is, once a certain weight threshold is met. If weights of user groups are only slightly different, as with hikers (e.g., 60 kg) and mountain bikers (e.g., 75 kg, bike and biker included), there should be little difference in their impact on vegetation and soil. In this study, the weight applied per unit area of ground contacted (i.e., contact pressure) was very similar. Biker contact pressure (0.35 kg/cm^2) was only 0.06 kg/cm^2 more than the contact pressure of a hiker balanced on one foot (0.29 kg/cm^2). However, when the weights of two user-groups are considerably different, as with hikers (e.g., 85 kg) and horses (e.g., 550 kg), the magnitude of damage to vegetation is clearly greater for the larger weight-bearing activity (Weaver and Dale 1978).

Spatial Dependency of Effects

The magnitude of biking and hiking effects on vegetation and soil declined sharply with distance from the center of the treatment lane. After a maximum of 500 passes, visible impact was concentrated within a narrow zone, no greater than 30 cm from the lane centerline. The center zone of a treatment zone received the most concentrated use, and consequently, revealed the most severe impact even at low pass intensities. The middle zone received only occasional passes of bikers and hikers when they strayed from the lane centerlines, therefore revealing only moderate impact. In the outer zone almost no foot or bike tire contacted the ground and no changes in parameters could be detected after treatments were applied.

Identifying the scale of impact for recreational activities puts into perspective the relative amount of damage they cause.

Future Research

Our study compared the impacts of biking and hiking under a particular set of conditions so additional studies conducted under other conditions are needed to test the generality of our findings. In these studies, it would be useful to compare impacts for (1) a maximum of more than the 500 passes applied here, (2) uphill rather than downhill passes, (3) established rather than new trails, (4) habitats other than deciduous forest, and (5) wet rather than dry conditions.

If future research confirms our finding that the physical impacts of mountain biking on vegetation and soil seem to be no worse than those of hiking, then there must be other reasons for the belief that mountain biking is to blame for recent trail degradation problems. One possibility is that behavioral differences between bikers and hikers are responsible for reports of greater biking impact. Bikers, in general, enjoy the challenge of obstacles on the trail, such as bumps and jumps, gullies, roots, rocks, and surface water (Symmonds and others 1999, 2000). Many of these features are the result of erosion. If mountain bikers seek out eroded areas, and hikers do not, then bikes will in fact contribute further to soil erosion problems. A second possibility is that mountain bikers simply contribute further to the overuse of trails. In other words, it may not be the activity of mountain biking per se that is to blame for these problems but rather the addition of this user group to hikers and others that has exacerbated overuse problems on already crowded trails (Ruff and Mellors 1993).

Mountain bikes are also be alleged to cause damage because of the inherent conflict between recreational user groups sharing the same space. Conflicts between user groups that differ in technology and methods of travel are common, such as between cross-country skiers and snowmobilers, or canoeists and those using motorboats (Watson and others 1991). Bikers move faster than hikers and equestrians, and these slower-paced users have complained that bikers startle them and present a safety hazard (Keller 1990). Mountain bikes have also been characterized as mechanized by hikers and managers and are therefore judged as inappropriate in a natural setting (Cessford 1995). In recreational conflict research, conventional wisdom states that users of more physically obtrusive technologies are resented by users of less obtrusive technologies (Devall and Harry 1981). Since mountain bikes are visually obtrusive, objectionable to other users, and leave easily identifiable evidence of their passing in the form of tire marks, they are commonly assigned as the cause of environmental damage (Cessford 1995).

Management Implications

Resource managers have no objective basis for managing biking activity in natural areas without research results. If further research on mountain biking impacts confirms our finding that biking and hiking can have similar physical impacts, then managers should be able to use results of past hiking impact studies to predict where and when biking impacts are likely to occur.

Appendix 1. Species composition and mean stem density of vascular plants present in the 100 experimental lanes before treatments were applied[a]

Species	Mean stem density (stems per lane)
Forbs	
Arisaema triphyllum	20.05
Caulophyllum thalictroides	11.43
Other species	14.84
Total	46.32
Tree seedlings	
Acer saccharum	6.86
Fraxinus americana	1.76
Other species	1.53
Total	10.15
Ferns	
Dryopteris carthusiana	0.54
Athyrium filix-femina	0.40
Other species	0.82
Total	1.76
Shrubs and vines	
Cornus alternifolia	0.55
Solanum dulcamara	0.51
Other species	0.08
Total	1.14
Tree saplings	
Acer saccharum	0.62
Ostrya virginiana	0.12
Other species	0.05
Total	0.79
Graminoids	
Carex pedunculata	4.21
Carex radiata	0.42
Other species	0.44
Total	5.07

[a] Species are grouped by growth form. Nomenclature follows Gleason and Cronquist (1991). Other species include: Forbs—*Maianthemum canadense*, *Trillium* spp., *Circaea quadrisculata*, *Veronica officinalis*, *Taraxacum officinale*, *Polygonatum pubescens*, *Geranium robertianum*, *Ranunculus abortivus*, *Smilacina racemosa*, *Viola pubescens*, *Hieracium aurantiacum*, *Waldstenia fragariodes*, *Actaea pachypoda*, *Ranunculus recurvatus*, *Galium triflorum*, *Epipactus helleborine*, *Thalictrum pubescens*, *Aralia nudicaulis*, *Aquilegia canadensis*, *Allium tricoccum*, *Oxalis stricta*, *Scrophularia marilandica*, *Asarum canadense*, *Aster lanceolatus*, *Impatiens pallida*; Tree seedlings—*Prunus serotina*, *Tsuga canadensis*, *Ostrya virginiana*, *Ulmus rubra*, *Populus grandidentata*, *Thuja occidentalis*, *Fagus grandifolia*, *Tilia americana*; Ferns—*Onoclea sensibilis*, *Matteuccia struthiopteris*, *Dryopteris marginalis*; Shrubs and vines—*Sambucus canadensis*, *Vitis riparia*, *Ribes cynosbati*; Tree saplings—*Fraxinus americana*, *Prunus serotina*, *Fagus grandifolia*; Graminoids—sedges: *Carex arctata*, *Carex deweyana*; grasses: *Poa alsodes*, *Elymus hystrix*, *Glyceria striata*, *Schizachne purpurescens*.

Managers of natural areas also need to know how quickly impromptu or informal trails can form when people leave the main path and whether this threshold number of passes differs for hiking or biking. From the results of this study, it would appear that informal trails should not form any more quickly for biking than for hiking. However, managers should be aware that the immediate impacts of both activities can be severe, and obvious trails will form after relatively very few passes (i.e., less than 500). If these initial trails are not allowed to persist, rapid recovery should be expected in a deciduous forest habitat with a forb-dominated understory, at least for the range of use intensities employed here.

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Literature Cited

Bayfield, N. G. 1973. Use and deterioration of some Scottish hill paths. *Journal of Applied Ecology* 10:635–644.

Cessford, G. R. 1995. Off-road impacts of mountain bikes: A review and discussion. Science and Research Series Report No. 92. Department of Conservation, Wellington, New Zealand, 38 pp.

Chavez, D. J., P. L. Winter, and J. M. Baas. 1993. Recreational mountain biking: A management perspective. *Journal of Park and Recreation Administration* 11:29–36.

Chavez, D. J. 1996. Mountain biking: Direct, indirect, and bridge building management styles. *Journal of Park and Recreation Administration* 14:21–35.

Coello, D. 1989. Vicious cycles? *Sierra* 74:50–54.

Cole, D. N. 1979. Reducing the impact of hikers on vegetation—an application of analytical research methods. Pages 71–78 *in* R. Ittner, D. R. Potter, J. K. Agee, and S. Anschell (eds.), Recreational impact on wildlands. R-6-001-1979. USDA Forest Service, Pacific Northwest Region, Portland, Oregon.

Cole, D. N. 1985. Management of ecological impacts in wilderness areas in the United States. Pages 138–154 *in* N. G. Bayfield and G. C. Barrow (eds.), The ecological impacts of outdoor recreation on mountain areas in Europe and North America. Recreation Ecology Research Group Report No. 9.

Cole, D. N. 1987a. Research on soil and vegetation in wilderness: A state-of-knowledge review. Pages 138–154 *in* R. C. Lucas (comp.) Proceedings, national wilderness research conference: Issues, state-of-knowledge, future directions. General Technical Report INT-220. USDA Forest Service, Intermountain Research Station, Ogden, Utah.

Cole, D. N. 1987b. Effects of three seasons of experimental trampling on five montane forest communities and a grassland in western Montana, USA. *Biological Conservation* 40: 219–244.

Cole, D. N. 1995a. Experimental trampling of vegetation. I. Relationship between trampling intensity and vegetation response. *Journal of Applied Ecology* 32:203–214.

Cole, D. N. 1995b. Experimental trampling of vegetation. II. Predictors of resistance and resilience. *Journal of Applied Ecology* 32:215–224.

Cole, D. N. 1995c. Disturbance of natural vegetation by camping: Experimental applications of low-level stress. *Environmental Management* 19:405–416.

Cole, D. N., and N. G. Bayfield. 1993. Recreational trampling of vegetation: Standard experimental procedures. *Biological Conservation* 63:209–215.

Cole, D. N., and E. G. S. Schreiner. 1981. Impacts of backcountry recreation: Site management and rehabilitation—an annotated bibliography. General Technical Report INT-121. USDA Forest Service, Intermountain Forest and Range Experiment Station.

Devall, B., and J. Harry. 1981. Who hates whom in the great outdoors: The impact of recreational specialization and technologies of play. *Leisure Sciences* 4:399–418.

Gleason, H. A., and A. Cronquist. 1991. Manual of vascular plants of northeastern United States and adjacent Canada. The New York Botanical Garden, New York, 910 pp.

Godin, V. B., and R. E. Leonard. 1979. Management problems in designated wilderness areas. *Journal of Soil and Water Conservation* 34:141–143.

Goeft, U. 1999. Managing mountain bike impacts in the south west of Western Australia: Combining biophysical impact studies with rider preferences for better trail design. BS thesis. Edith Cowan University, Perth, Australia.

Hammitt, W. E., and D. N. Cole. 1987. Wildland recreation: Ecology and management. John Wiley & Sons, New York, 335 pp.

Hoffman, D. W., B. C. Matthews, and R. E. Wicklund. 1964. Soil survey of Dufferin County, Ontario. Soil Research Institute, Research Branch, Canada Department of Agriculture, Ottawa.

Keller, K. J. D. 1990. Mountain bikes on public lands: A manager's guide to the state of practice. Bicycle Federation of America, Washington, DC.

Kuss, K. R. 1986. A review of major factors influencing plant responses to recreation impacts. *Environmental Management* 10:637–650.

Lance, A. N., I. A. Baugh, and J. A. Love. 1989. Continued footpath widening in the Cairngorm Mountains, Scotland. *Biological Conservation* 49:201–214.

Legg, M. H. and G. Schneider. 1977. Soil deterioration on campsites: Northern forest types. *Soil Science Society American Journal* 41:437–441.

Petit, B., and P. Pontes. 1987. "Kepner-Trego analysis": Mountain bicycle situation on Santa Barbara front trails managed by the USDA Forest Service. Unpublished report. Santa Barbara Ranger District, Los Padres National Forest, USDA Forest Service (in Chavez and others 1993).

Quinn, N. W., R. P. C. Morgan, and A. J. Smith. 1980. Simulation of soil erosion induced by human trampling. *Journal of Environmental Management* 10:155–165.

Ruff, A. R., and O. Mellors. 1993. The mountain bike—the dream machine? *Landscape Research* 18:104–109.

SAS Institute Inc. 1996. SAS Software Release 6.12. SAS Institute Inc., Cary, North Carolina.

Schuett, M. A. 1997. State park directors' perceptions of mountain biking. *Environmental Management* 21:239–246.

Soane, B. D., P. S. Blackwell, J. W. Dickson, and D. J. Painter. 1981a. Compaction by agricultural vehicles: A review. I. Soil and wheel characteristics. *Soil and Tillage Research* 1:207–237.

Soane, B. D., P. S. Blackwell, J. W. Dickson, and D. J. Painter. 1981b. Compaction by agricultural vehicles: A review. II. Compaction under tires and other running gear. *Soil and Tillage Research* 1:373–400.

Sun, D., and M. J. Liddle. 1993a. Plant morphological characteristics and resistance to simulated trampling. *Environmental Management* 17:511–521.

Sun, D., and M. J. Liddle. 1993b. Trampling resistance, stem flexibility and leaf strength in nine Australian grasses and herbs. *Biological Conservation* 65:35–41.

Symmonds, M. C., W. E. Hammitt, and V. L. Quisenberry. 1999. Mountain biking and soil erosion: User preference of factors of erosion and management techniques. Pages 89–94 *in* D. Harmon (ed.), On the Frontiers of Conservation: Proceedings of the tenth conference on research and resource management in parks and on public lands. The George Wright Society Biennial Conference, Asheville, North Carolina.

Symmonds, M. C., W. E. Hammitt, and V. L. Quisenberry. 2000. Managing recreational trail environments for mountain bike user preferences. *Environmental Management* 25: 549–564.

Thurston, E. 1998. An experimental examination of the impacts of hiking and mountain biking on deciduous forest vegetation and soil. MS thesis. University of Guelph, Guelph, Canada.

Washburne, R. F., and D. N. Cole. 1983. Problems and practices in wilderness management: A survey of managers. Research Paper INT-304. USDA Forest Service, Intermountain Research Station, Moscow, Idaho.

Watson, A. E., D. R. Williams, and J. J. Daigle. 1991. Sources of conflict between hikers and mountain bike riders in the Rattlesnake NRA. *Journal of Park and Recreation Administration* 9:59–71.

Weaver, T., and D. Dale. 1978. Trampling effects of hikers, motorcycles and horses in meadow and forests. *Journal of Applied Ecology* 15:451–457.

Wilson, J. P., and J. P. Seney. 1994. Erosional impact of hikers, horses, motorcycles and off-road bicycles on mountain trails in Montana. *Mountain Research and Development* 14:77–88.