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Authors: Cooke, Merritt T., and Xia, Liyiran

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Conservation Issues

Impacts of Land-Based Recreation on Water Quality

Merritt T. Cooke[1,2] and Liyiran Xia[1]

[1]Fox Leadership International, University of Pennsylvania, 3814 Walnut Street, Philadelphia, PA 19104

[2]Corresponding author: mterrycooke@gmail.com; 610-504-2245

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ABSTRACT

The impact of land-based recreational activities on water quality in rivers and streams is an important topic for land stewardship. It is not a topic that has been yet systematically studied. This paper surveys the scientific literature on the topic and offers preliminary conclusions for ecologists, trail and park managers, and outdoor enthusiasts. The review examines three categories of recreational activity—hiking and jogging; horseback riding, dog-walking, picnicking and camping; and biking and off-road vehicle riding—in terms of three broad dynamics of ecological impact that directly affect water quality: (1) soil compaction and associated soil loss into waterways; (2) reduction of ground cover and runoff of organic litter with associated soil loss into waterways; and (3) fecal contamination and its impact on waterways. Preliminary conclusions suggest that the greatest impacts on water are a function of trail placement and design (siting, grading, contouring, surface composition, and immediate surroundings). Type of trail use is also highly salient, especially in the case of off-road vehicles when specified restrictions on trail use are absent or when certain behavioral attributes are present. There are important commonalities of water impact stemming from all types of recreation reviewed and relative impacts sometimes defy simple comparison (e.g., motorbikes appear to have greater impact uphill than hiking and horseback riding but less impact downhill). Frequency of trail use is also examined in connection with water quality as are the significant effects of fecal contamination associated with overnight camping, horseback riding, and dog-walking.

Index terms: literature review; recreation; riparian ecosystems; trails; water quality

INTRODUCTION

This article surveys the scientific literature regarding the impacts of land-based recreational activities—in particular, trail-based recreational activities—on water quality along the rivers, streams, and creeks of a watershed.

The impact of land-based recreation on water systems is an important topic for land stewardship; however, the scientific literature covering it is, to date, heterogeneous and spotty. Most studies of land-based recreation focus on land-based ecological effects and there is little direct investigation of the impact of these land-based activities on water quality or quantity. Also, there is considerable variation in the methodological focus of the mostly trail-oriented studies that do address the nexus of recreational activities and their impacts on water quality and quantity. Some studies ignore specific uses of the trails and focus on the geomorphic processes occurring in different trail landscapes. Some studies focus on only one specific trail segment. Many studies focus narrowly on only the effects of a single trail use and offer little data that is comparatively useful in analysis of multi-use trail recreation.

Because this article is intended to be useful to researchers, land stewardship managers, and recreationists, some introductory comments are called for in setting the scope for this review.

First, for researchers, it is important to set out the criteria for what is covered and what is not:

- With the term "land-based recreation," we are including certain activities, excluding others, and then categorizing those activities under discussion into a few broad categories.
- The types of recreational activity to be included are hiking, jogging, horseback riding, dog-walking, picnicking, camping, biking, and off-road vehicle driving.
- The types of recreational activity to be excluded, for reasons explained immediately below, are field sports, birdwatching, fishing, and on-road vehicle driving.

We will set out briefly here the rationale and the implicit assumptions used in our process of inclusion and exclusion. Most pertinently, we have tried to allow the availability of scientific research to inform our relative focus on those land-based recreational activities that have documented effects on water quantity. As such, we have focused on trail-based recreational activities as opposed to, for example, the impact of field-based organized sports.

Also on the basis of this rationale, we are not treating birdwatching as a recreational activity in its own right. While birding is clearly a land-based form of recreation that takes place on trails and near waterways, there is virtually no scientific literature covering birding as separate from a more general category of hiking. (Both birding and hiking involve uni-directional movement along a trail at various and intermittent speeds with no augmented weight- or foot-loads and no exceptional biological waste impacts.) Similarly, we have excluded recreational activities such as swimming and fishing that are not primarily land-based. Finally, we have excluded recreational vehicle impacts, which are primarily associated with asphalt roads as opposed to taking place on fields and trails proximate to streams, creeks, and rivers since the latter belongs to a different research literature.

For nonscientist readers and for recreational enthusiasts who wish to understand the ecological impacts of their recreational activities, it is worthwhile clarifying some of the key ecological elements and concepts that will underpin this article. We will do so in the remainder of this Introduction by (1) describing some of the characteristics of soil and sediment and then by (2) relating the role of soil and sediment to several important ecological processes involving water (Artiola et al. 2004).

Properties of Soil and Sediment

Sediment is categorized into six groups according to grain size (measured by the diameter of the particle). These are boulders, cobbles, gravel, sand, silt, and clay. Sediment of all sizes can be transported and settled across aquatic and terrestrial ecosystems slowly or rapidly.

Healthy soil typically consists of half pore space (25% water and 25% air), with the other half being 45% mineral (sand, silt, and clay) and 5% organic matter. Clay, silt, and sand are the three building blocks of soil texture varying in size. Clay particles are less than 0.002 mm, silt particles are 0.002–0.05 mm, and sand particles are 0.05–2 mm. Particles larger than 2 mm are categorized as gravel. Loam combines clay, silt, and sand particles. The prevalence of clay particles is largely determinative of the capacity of soil to retain or hold water. Silt particles are susceptible to wind and water erosion (Kalev and Toor 2017).

Ecological Processes

Compaction: Soil compaction is the reduction of soil volume, making soil more dense with less pore space available for air and water. Compaction can occur naturally or due to anthropogenic factors such as being subjected to vehicle/equipment and/or foot/hoof traffic. Change in soil structure through compaction is typically associated with bulk density and porosity. The more compacted the soil, the less porous, with less space available for air and water. Compaction typically has negative effects on watershed ecosystems. These effects include decreased ability of soil to absorb rainfall (i.e., reduced infiltration rates), increased surface water runoff, and soil erosion.

Erosion: Soil erosion is the loss of soil due to natural or anthropogenic factors. The process of soil erosion involves soil particles being detached from the soil mass and being moved by transporting or detaching agents such as water, ice, and wind. The most important agent in detaching soil is rainsplash; weathering processes such as wetting/drying and freezing/thawing also loosen soil particles. Human/livestock/animals trampling and tillage as well as running water and wind further detach soil particles. The severity of erosion hinges on the quantity of soil being detached and the capacity of the transporting/eroding agents. Erosion has become a global environmental concern as the effects pertain to not only forestry and recreation but also to soil productivity and agriculture. While the natural rates of soil loss are in the range of 0.0045–0.45 ton per hectare per year, the annual rates from agricultural land are between 45 and 450 ton per hectare, which is 1000 to 10,000 times the natural rates (Morgan 2005).

Sediment Deposition: This is a process following erosion and involves settling of the sediment (i.e., loose soil particles and organically derived matter such as decomposition of plants and animals) that has been transported. Sediment can contribute to waterbed (the bottom of a body of water) or land mass. Deposition of sediment has positive and negative effects—it can contribute to fertile farmland if sediment is deposited on the banks and floodplains of a river; it can degrade water quality for drinking and damage the riparian ecosystem, where cloudy water makes it harder for animals to seek food and murky water prevents growth of vegetation in water; sediment deposition can also disrupt or destroy habitat for fish and other aquatic organisms.

Eutrophication: Eutrophication is nutrient enrichment as a result of excess nutrient inputs into freshwater, marine, and terrestrial ecosystems due to primarily human activities, altering the function and structure of those ecosystems. An excess supply of the most essential nutrients, nitrogen (N) and phosphorus (P), into water bodies leads to an abundance of algae and aquatic plants, which results in degradation of water resources, most notably by harmful algal blooms, with consequences on drinking water sources, fisheries, and recreational water bodies. The sources of excess nutrients from human activities include fertilizers, detergents, and sewage (Smith et al. 1999).

I. GENERAL OBSERVATIONS

All forms of land-based recreation, to varying degrees, rework soil structure and composition in ways that affect what, where, and how much material enters local waterways. The primary effects of recreational activities, according to one meta-analysis, include (a) soil compaction, reduced soil moisture, and associated soil loss into waterways, and (b) reduction of ground cover and runoff of organic litter with associated impacts on waterways (Pickering et al. 2010).

(A) The pressure, literally speaking, of recreational activity tends to compact soil, reducing its porosity and saturation capacity while increasing its bulk density (i.e., its dry weight per unit volume of soil). These effects are exacerbated by forms of recreation that bring heavier loads on the trail (e.g., horseback riding, all terrain vehicle [ATV] riding). However, even sites with lower-impact use, such as picnicking, experience significant soil compaction, reduced saturation capacity, and increased presence of fine soil (Cakir et al. 2010). As we will see in the following sections, these processes of soil compaction, de-moisturization, and runoff of fine soils into waterways are harmful to water quality in various ways.

(B) Ground cover (low-growing and spreading plants generally helpful in reducing weed penetration) and organic litter (largely fallen leaves and the detritus from higher-growing bushes and trees) are both important to maintaining healthy terrain alongside trails and waterways. Processes whereby recreational activity results in loss of organic litter and ground cover vegetation are varied:
  - Recreational treading on or trampling along streambanks (such as caused by streambank fishing or streamside jogging trails) can lead to elimination of the riparian

protective cover afforded by bank vegetation and contribute to altered stormwater runoff into streams. The result is increased sedimentation and turbidity (i.e., the state of being being cloudy, opaque, and/or thick with suspended matter) caused by water runoff across denuded surfaces. (Cole and Landres 1995)
- Whether caused by foot/hoof traffic or by wheeled vehicles, recreation alongside rivers and creeks tends to reduce ground cover and thereby tends to alter the volume of natural litter input into streams (Naiman et al. 1988; Risser 1995). As a result, substantial changes in the aquatic ecologies of these streams can occur. One example of such change is the striking variation in the biomass of macroinvertebrates (shredders feeding on coarse particulate organic matter such as leaf detritus) in direct correlation with variance in the input of litter into streams. (Cummins et al. 1989; Cole and Landres 1995)
- In a related way, recreational activities can impair the availability of important food sources for arthropods, amphibians, and fish to the extent that they reduce riparian vegetation which, in turn, increases runoff and soil erosion. The resulting sedimentation can cover and kill the periphyton community in streams. (Cordone and Kelly 1961; Murphy et al. 1981)
- Finally, sedimentation also increases the turbidity of water. In one researched case, rising water turbidity has been shown to cause up to a 50% reduction in bluegill (*Lepomis macrochirus*) feeding rates (Gardner 1981). Both the concentration of suspended sediments and the duration of their suspension can have large impacts on aquatic ecosystems (Newcombe and MacDonald 1991; Cole and Landres 1995; Reilly et al. 2016).

The following sections explore land-based recreations by reviewing hiking and jogging in Section II; horseback riding/dog-walking/picnicking/camping activities in Section III; and findings specific to biking (mountain and other)/ATV and off-road-vehicle recreation in Section IV.

II. HIKING AND JOGGING RECREATION

Hiking and jogging both tend to compact the underfoot soil. Compacted soil interrupts groundwater flow paths, redirecting water along trail corridors until it is eventually deposited at stream crossings. These more concentrated water flows create muddy patches more susceptible to erosion. The result is damaged trail contouring and compromised maintenance regimes, which cumulatively contribute to higher-velocity water flows eroding adjacent land and increasing the likelihood of flooding and landslides (Coffin 2007).

In addition to these compaction effects, hiking and jogging tends to reduce local litter cover and hence the proportion of organic matter in the topsoil, thereby increasing the amount of fine soil present on trails (Cakir et al. 2010). The increased proportion of fine soils on trails heightens the processes of runoff into streams and sedimentation in streambeds described above since finer soils have higher mobility.

Soil eroded by hiking and jogging through these various processes may not make its way directly into rivers, streams, or creeks, unless the trail crosses or runs close to those waterways (Marion and Wimpey 2007). However, in assessing how a limited quantity of eroded soil does make its way directly into waterways as a result of hiking, attention to not only proximity of the paths but also soil type of the paths is important. Finer sands are the most susceptible to erosion in these situations—and thus, likelier to make their way into waterways—while coarser or mixed soils are less susceptible (Goeft and Alder 2001). As previously noted, both low- and high-impact recreational use of trails tend to increase the presence and proportion of fine soils.

It is the cumulative and more indirect consequences of the phenomena of soil compaction, litter reduction, and erosion that lead to the most dramatic impacts of hiking and jogging activities on watersheds. This is measured by the degree to which increased volumes of local water flow (as well as the increased susceptibility to landslides that increased water flows engender) lead to the mass deposition of sediment in water bodies. Mass deposition of sediment in water bodies, in turn, leads to a spectrum of secondary consequences:

- **Stream morphology changes**: These changes, which largely involve the creation of shallow pools, increase turbidity and local water temperature which, in turn, lead to stress on aquatic ecosystems.
- **Burying of fish nests**: Mass deposition of sediment in the waterbeds of streams, creeks, and rivers can bury nests of fish eggs before they have the opportunity to hatch. In one study, magnetically tagged particles were used to demonstrate the deleterious effect of flood-induced dispersion of coarse bed material on sockeye salmon fish nests in the Stuart-Takla region of British Columbia, Canada (Gottesfeld et al. 2004).
- **Eutrophication of waters**: Eutrophication triggers excessive algal growth as a result of decreased light penetration, shifts in trophic balance, decreased dissolved oxygen, tainted drinking water, and increased water temperatures (Ursem et al. 2009).

In this general landscape of research findings, a rich vein of relevant applied research focuses on the importance of trail positioning and drainage in mitigating effects on erosion and sediment deposition in nearby streams, creeks, and rivers.

Trail Placement and Positioning

Trail placement and positioning emerges from the literature as one of the primary factors affecting water quality and quantity as a result of hiking- and jogging-type recreational activity. Olive and and Marion (2009) identify trail position as the single most determining factor accounting for soil loss across various models. They recommend (1) that trails not be sited in floodplains, (2) that valley-positioned trails be sited above frequent flood levels and designed with good drainage, and (3) that more highly erosive types of recreational use (e.g., horseback riding, ATV/off-road-vehicle use) be barred from riparian area trails.

Additionally, trails routed across slopes (closer to the contour) have significantly less soil loss because the terrain on one side of the trail is always lower, allowing easier tread drainage. The same study finds that "as determined by the best regression model, CSA (Contingency Space Analysis) soil loss increases 23 cm^3 for every 1% increase in trail grade" (Olive and Marion 2009).

Drainage Characteristics:

- **Soil Composition:** Broadly speaking, the type and texture of soil and the drainage characteristics of the soil matrix can greatly diminish the effect on erosion of trail grade. Trails with steeper grades can avoid significant erosion when tread soils have heterogeneous textures, such as loam, and when substantial amounts of gravel or rock are also present. Olive and Marion's (2009) study found consistently in all regression models that clay soil textures experienced greater soil loss than the other soil types, especially as compared to sandy loam and organic soils. This is a result of the fact that, as a homogeneous-texture soil, clay compacts more tightly and causes greater runoff than other soil textures. Even soils with higher organic content than found in clay were found to erode quickly from trail treads, except in flat terrain and areas receiving substantial deposits of eroded soils.
- **Soil Compaction and Erosion:** Soil compaction leads to lowered water infiltration rates and increased detachment of surface soil particles. On trails, this produces increased surface runoff and trail erosion and increased introduction of sediments into trailside creeks with sediment deposition and turbidity occurring particularly at stream crossings. Olive and Marion (2009) noted a number of specific conditions under which this general dynamic is accentuated: (1) trails with low slope alignment angle (Leung and Marion 1996) tend to be susceptible to degradation because their flatter side slopes offer little resistance to trail widening and because they hinder or block the drainage of water from incised trail treads; (2) trails that ascend slopes are difficult to drain water from so they tend to become highly susceptible to erosion; and (3) trails that intercept streams or seeps and have running water along their treads were found to be particularly prone to muddiness and erosion (Olive and Marion 2009). As a method for mitigating these effects, Olive and Marion (2009) recommend aligning trails to topographical contours.
- **Tread Drainage Features:** Tread drainage features can generally be effective against erosion when placed with sufficient density and maintained with regular cleaning. One rigorous study cites the lack of tread drainage features as a specific reason why the park being researched lost so much soil. The specific finding in that study was that well-graveled trails reduced soil loss on the steepest trails (with grades from 18% to 48%) by approximately 75%. (This finding derived from precise measurements using the Variable CSA method making possible efficient measurement of soil loss using a point-sampling method based on fixed intervals and a random start; Olive and Marion 2009.)
- **Grade Reversals:** Grade reversals, also known as Coweeta dips or rolling grade dips, are considered among the most effective and sustainable methods for removing water from trails (Birchard et al. 2000; Hesselbarth et al. 2007). Grade reversals are constructed by reversing the trail's grade periodically to force all water off the tread (Marion and Wimpey 2007). A principal advantage of grade reversals is that, in contrast to water bars, they typically do not require any onward maintenance to ensure effectiveness. However, installation of grade reversals does require careful planning during the design and construction phase of trails to ensure that the descending trail's grade levels off and then ascends briefly before resuming a descent.
- **Rainfall and Erosivity:** Ramos-Scharrón and colleagues (2014) led a rigorous study to examine the correlation between rainfall and erosivity along trails in a pristine environment where trails represent the sole anthropogenic source of disturbance. A salient finding was that low erosion was measured for abandoned trails with a dense vegetation cover, while the highest rates were associated with devegetated trails immediately following construction or restoration. Measuring trail erosion as a function of rainfall, slope, and vegetation cover density, their research found that annual erosion rates on trails were one to three orders of magnitude higher than measured surface erosion rates on undisturbed hillslopes.
- **Seeding and Other Measures to Promote Vegetation Growth:** Since Ramos-Scharrón et al. (2014) were able to establish a strong correlation between declining erosion rates and progressive increase in vegetation cover along trails, they offered in their analysis a number of specific recommendations to minimize the effects of trailside erosion in neighboring waterways. These recommendations include:
  - Seeding and other measures to promote vegetation growth on abandoned trails;
  - Undertaking construction and restoration activities during relatively dry periods so as to minimize soil exposure; and
  - Avoiding steep routes and installing water bars to stabilize and protect trail surfaces.

III. HORSEBACK RIDING/DOG-WALKING/ PICNICKING/CAMPING RECREATION

Hiking- and jogging-type recreational activity involves humans passing along a trail at varying rates of speed. The activities described in this section—horseback riding, dog-walking, picnicking, and camping—all represent activities with a recreational focus other than simply passing along a trail. From the perspective of environmental impact, these latter forms of recreation all involve trail-related activity that is associated either with heavier weight loads (horseback riding), a greater number of foot impacts per observed unit (dog-walking), or repetitive treading over the same unit of trail or recreational surface area (picnicking and camping). Finally, and importantly, this category of recreational activity entails a significantly higher degree of water-related impact as a result of the higher incidence of animal waste, human waste, and food waste.

Because the literature is limited and because the biological waste concomitants of these four activities represent a significant common denominator in assessing the impact of recreation on water quality, we will not attempt to treat these four activities separately in the following summary review.

Generalized Findings

In a rigorously controlled experiment, horse-frequented trails were found to generate more sediment when compared to trails used for hiking and jogging. This effect disparity was further elevated when trails were wet. For instance, Wilson and Seney

(1994) determined that, when measured by control plots after 100 passes, horse plots produced significantly more sediment than bicycle, hiker, or control plots. The greater amounts of sediment produced on horse trails then becomes available to enter waterways, leading to the range of stresses to aquatic ecosystems noted in the General Observations section. Accordingly, the measurably higher levels of sediment production found with horse-riding trails means, as suggested in Marion and Olive (2006), that trail and park managers need to acknowledge the high potential for eroding soil and sediment runoff into waterways when siting trails and planning trail use.

As to other effects on the soil which, in turn, influence water quality and quantity, even sites with as low-impact use as picnicking experience significant soil compaction, reduced saturation capacity, and increased presence of fine soil (Cakir et al. 2010). This is consistent with the findings for hiking and jogging described in the previous section. These effects are correspondingly greater with high-impact recreational use such as horseback riding and ATV driving. An early study found that horses caused greater increases in soil compaction, litter, trail width and depth compared to hikers and motorcycles. Horse traffic applies the greatest force (weight per unit area) among hikers, horseback riders, off-road bicyclists, and motorcyclists (Weaver and Dale 1978).

The measurably greatest impact of horse-related recreation and dog-walking on water systems is also attributable to fecal nitrification runoff into streams, creeks, and rivers (Pickering et al. 2010). In fact, it is with respect to fecal contamination of water that horseback riding and dog-walking, and picnicking and camping, all can have broadly similar and deleterious impacts on water quality. In sufficient quantities, fecally nitrified soils entering into water systems can facilitate algal blooms and lead to eutrophication. Additionally, these soils can introduce pathogens into water, with the most harmful consequences involving water used in recreational swimming or for drinking (Dodds et al. 2009; Vesterinen et al. 2010; Hammitt et al. 2015).

Coliform bacteria prevalence is a reliable indicator of fecal contamination and waterborne disease risk. Ursem et al. (2009) analyzed coliform bacteria and *E. coli* levels in streams adjacent to (1) pristine areas rarely traversed by humans, (2) backpack off-trail areas not traversed by pack or stock animals, and (3) multi-use areas with backpacker and animal use over an eight-week period during the summer season. They found a significantly higher prevalence of *E. coli* in multi-use sites (including horseback riding) as compared to pristine and backpack-only sites. Chlorophyll *a* concentration (a measure of algal presence) changed negligibly in pristine sites but changed significantly in backpack and multi-use sites. The highest prevalence of coliform bacteria was found in multi-use sites. The authors cite a variety of sources, singly or in combination, as responsible for producing coliforms in wilderness areas: (1) wild animals native to the area, (2) humans visiting during daylight (sometimes with pets), (3) backpackers who camp overnight, (4) stock or pack animals, such as horses and mules, and (5) cattle or sheep grazing. The authors also note that significant increases in chlorophyll *a* concentration and *E. coli* were found at sites that saw both human hiker and pack animal use (Ursem et al. 2009).

As suggested by, but not fully distinguished in, the above-cited study, coliform pollution of wilderness areas by humans is a result of two different types of practice. On the one hand, a hiker or recreationalist may inadequately bury fecal waste at a site that is otherwise appropriate for ecological processing of that waste. On the other hand, a hiker or recreationalist may chose a site for defecation that, given its proximity to surface water or to riparian slopes, is ecologically inappropriate and will lead directly to negative impacts on water quality.

As fecal waste leaches into waterways, complex processes of nitrification and phosphorization affect algae production. Bilotta's research suggests that the processes have differential effects with phosphorus being more limiting in aquatic environments than nitrogen (Bilotta et al. 2007). Hadwen and Bunn (2005) made phosphate and N-enriched ammonium nitrate deposits to shallow lake areas (littoral zone) and, within 5 hr, measured significant increases in periphyton chlorophyll *a* concentrations with no concomitant increase in phytoplankton chlorophyll *a* concentrations. The consumers of these primary food sources also had these enriched N signatures, indicating that the enrichment was passed through trophic levels.

According to Bridle et al. (2006), water quality was found to decrease after rainfall events as a result of fecally contaminated groundwater runoff. Fecal coliform levels continued to be measured in the high range as late as 2 wk following major rainfall events. The authors estimated that 30% of contamination in this study originated from humans and 30% from other animal herbivores. Water samples were taken from behind the main toilet area of a "hut" campsite where human feces were supposed, at the least, to be buried. The authors cite shallow and dense burying as one potential contributor to coliform spikes in the observed area (Bridle et al. 2006).

Resulting from contaminations of this type, some of the most commonly surveyed pathogenic organisms found in backcountry water sources include *Cryptosporidium* spp., *Giardia* spp., and *Campylobacter jejuni* (Taylor et al. 1989; Abbaszadegan et al. 1999). The occurrence of these pathogenic organisms is less of a concern in areas where trail use is predominantly day-oriented, and where waste issues can be avoided through installation of toilet facilities or by posting and enforcing "Leave No Trace" practices (i.e., digging catholes for waste away from water resources) (Marion and Wimpey 2007).

Water contamination has been found to be most problematic, as measured by coliform levels, in areas where camping is common. As a behavioral attribute, individuals typically grow attached to and return to the same campsite, and this pattern of repeated use produces heightened ecological impacts (Price et al. 2018). In addition to water contamination impacts, the repeated use of single campsites leads to measurable reductions in tree cover due to the twin factors that visitors procure firewood by cutting down both on- and off-site trees and that human activity (trampling) around the campsite eliminates the chance for tree seedlings to germinate and survive. In campsites studied between 1982 and 2014, the change in tree cover was found to be a 44% decrease (Eagleston and Marion 2017).

Some success has been reported in mitigating these environmental impacts by concentrating use to a few facilities/campsites. As a related approach, the implementation of booking fees to facilitate managerial maintenance of trails and trail infrastructure has also been shown to mitigate these impacts. More study is, however, encouraged for this fee-based mitigation strategy since it restricts access to those who can afford the fees and may encourage the creation of "rogue campsites" by those who cannot afford or choose not to pay the fees (Dixon 2017).

IV. BIKING (MOUNTAIN AND OTHER)/ATV AND OFF-ROAD-VEHICLE RECREATION

When compared to the impacts of hiking, the impacts of mountain biking on water quality and quantity are similar in type, but different in degree.

Soil Compaction, Erosion, and Reduction in Local Plant Cover

The studied effects of mountain biking on water quality do not lend themselves to a single interpretation. There appears to be some variance of impact on the different processes affecting water quality and also a significant difference is noted depending on whether the direction of mountain biking is uphill or downhill. One study suggests that mountain biking appears to compact and erode soils less than hiking; however, the compacting and eroding effects of both activities are significantly exacerbated when soils are wet (Wilson and Seney 1994). A separate study, conducted in Australia, found that mountain biking had relatively greater effect on the immediate trail surface and relatively less effect on the trailside and surrounding area than hiking. This was attributed to the fact that, with mountain biking, relatively light impacts of soil compaction and erosion were found to directly affect the trail itself whereas, with hiking, the comparably light effects of soil compaction and erosion were spread more extensively to include not only the trail but its periphery as well (Goeft and Alder 2001). The authors of the Australian study noted, however, that the severity of the physical impacts in their study appears markedly less than the impacts recorded from other studies. They attributed this disparity to the drier climate, lateritic (less erosive) soil, and less extensive use in southwestern Australia (where their study was conducted) as compared to Wisconsin and Germany where the Bjorkman (1996) and Wöhrstein (1998) studies were conducted.

In comparing motorcycle erosion with hoof and foot erosion, Weaver and Dale (1978) found that motorcycle erosion had the widest range of differential effects when uphill and downhill movement were cross-compared. According to their research, motorcycles moving uphill tend to establish a narrow rut, which increases the velocity and sediment transport capacity of trail runoff. The development of this linear channel was seen as a direct result of the imprint of the tire and and the torque of the spinning wheels. However, motorcycles moving downhill, when torque is not needed, caused less erosion than hikers and horses. This is presumably due to the fact that rolling wheels tend to loosen less soil when descending a steep trail in comparison to the force applied by footwear and hooves in breaking a descent (Weaver and Dale 1978).

A later study on experimentally applied mountain biking and hiking found that moderate to intense trail use by both hikers and bikers drastically reduced vegetation cover; however, the same study found that, one year after biking and hiking trampling stopped, ground cover was found largely restored to the state of adjacent, undisturbed areas. One methodological caveat: the treatment area for this study was 4 m × 1 m. Not only is that not representative of the width or length of a normal trail, but the degree to which it is so densely surrounded by other vegetation able to seed the trampled (and semi-bare) soil is much greater than found in traditional trails. But, with this caveat noted, the research does tend to support the conclusion that dispersed use of trails may be sustainable (Thurston and Reader 2001).

Goeft and Alder (2001) conclude that consequences such as soil compaction, erosion, and local plant cover reduction can occur as a result of mountain biking, but they can also be mitigated via trail design and management, such as restricting cyclist access from steeper slopes and discouraging trail use in wet conditions. Specifically, injudicious siting and poor maintenance of biking trails is associated with higher water erosion impacts and with tread sediments being carried off by runoff. However, with installation of water control features such as grade reversals and outsloped treads, these impacts can be mitigated. As a result of installation of these features, water runoff tends to drop more of its sediment close to trails, where it is trapped and held by organic litter and vegetation. Soils eroded from biking trails with water control features installed were found rarely to enter water bodies, unless trails were poorly sited and crossed streams or ran close to stream or lake shorelines (Marion and Wimpey 2007).

Sediment Production and Runoff

Results from the control plot study cited in the previous section indicate that motorbikes create significantly more sediment than hikers after 100 passes but create only insignificantly more sediment than bikes (Wilson and Seney 1994). As previously noted, these effects become more pronounced for both types of vehicle when the plots were wet (Weaver and Dale 1978).

As to direct impacts on water quality, trail-related impacts to water resources were found to include the introduction of soils, nutrients, and pathogenic organisms (e.g., *Giardia*), and to alter the patterns of surface water drainage. The authors note, however, that there is very little research to draw from on these topics, and that none that is particularly focused on mountain biking (Marion and Wimpey 2007).

In order to prevent negative impacts to the reproductive cycle of aquatic communities, the siting of paths used recreationally plays a particularly important role. Since many recreational activities (such as fishing, swimming, boating, picnicking, and viewing waterfalls and other river features) will draw visitors and trails to the vicinity of water resources, it is often necessary to route trails to water resources because, otherwise, visitors will simply create their own informal trails. As we have seen, biking trails that are close to water resources require special consideration in their design and maintenance to prevent the introduction of tread sediments into bodies of water. Eroded soil that enters water bodies increases water turbidity and causes sedimentation that can affect aquatic organisms (Fritz et al. 1993). For instance, trout and other fish that lay their eggs in gravels on the bottom of streams and lakes can experience the smothering of their egg nests by these sediments and thereby have reduced reproductive success. Sedimentation in these water bodies can also hurt invertebrate organisms, which serve as food for fish and other creatures. Also, some sediment may contain nutrients that will contribute to algal blooms that deplete the dissolved oxygen in water bodies as the blooms die off (Marion and Wimpey 2007).

Biking trails require particularly judicious siting in order to minimize disruptions to acquatic communities and to help maintain water quality. It is, for instance, ecologically disruptive when biking trails intercept and divert water from seeps or springs. In those situations, water can sometimes flow along the tread, leading to muddiness or erosion. In the case of "cupped" and other types of uneven tread wear, the water may flow for a distance before it is diverted off the trail with concomitant changes to the ecology of small wetland or riparian areas (Marion and Wimpey 2007). As previously noted, it is best to avoid siting biking trails close to water resources. Where biking trails are in close proximity to water, minimization of harmful water impacts can be achieved by minimizing the number of stream crossings, by including grade reversals, by regularly maintaining outsloped treads, and by installing drainage features to divert water off the trail before and after stream crossings. These measures help prevent large volumes of water and sediment from flowing down the trail and from being introduced into the stream. They also promote the ability of trailside organic litter, vegetation, and soils to slow and filter water (Marion and Wimpey 2007).

Finally, special attention should be given to siting streamside paths for horseback and mechanized vehicle use due to their relatively higher impact. As Olive and Marion (2009) recommend, horse and ATV access should be restricted to resistant trails. Since horses and ATVs cause significantly greater soil loss than hiking and mountain biking uses, the authors urge the managers of these outdoor spaces to be more rigorous in the planning and in their establishment of maintenance regimes if they wish to accommodate horse and ATV use.

While most ATV riders may be as sensitive to the environment as horseback riders generally are, a subset of ATV riders are heedless of or even flaunt a flagrant disregard for the environmental impact of their riding practices—gouging fields with tight turning in circles, driving down (not across) streambeds, and powering through fragile understories. Websites belonging to informal clubs of ATV and 4×4 owners who promote this style of driving are not hard to find on the internet but tend to be short-lived.

V. PRELIMINARY CONCLUSIONS

The preceding four sections of scientific literature review underscore the basic conclusion that the nexus of trail use and impacts on water quality is environmentally significant. Further, the fact that so little of the research has been replicated (under different conditions or in different geographies) or can be quantifiably described underlines the importance of further study.

A limited number of preliminary conclusions can be drawn, however. The most important general conclusion to emerge through the review is that trails along watershed waterways—specifically, the type of use of trails, the amount of use of trails, the siting and grading and contouring of trails, the composition of trail surfaces, and the immediate surroundings of trails—have the most significant impact on water quality and quantity when land-based recreation is considered. Some of the preliminary conclusions that can be drawn directly relating to trails follow.

General Salience of Trail Use Impacts

- "The substantial loss of soil is considered an essentially irreversible form of recreational impact as the soil cannot be returned or easily replaced" (Olive and Marion 2009).
- "Study findings reveal a trail system with substantial soil erosion problems, with estimated soil loss of... 34,687m^3 for the entire trail system... They are considered conservative estimates of soil loss" (Olive and Marion 2009).

Type of Trail Use

- Many impacts are similar across recreation types, with differences in severity (Pickering et al. 2010).
- Type of use was found to be a substantially greater determinant of trail degradation than amount of use" (Olive and Marion 2009 and other studies).
- "Impacts of biking and hiking measured here were not significantly different" (Thurston and Reader 2001).
- "ATV and horse use are significantly greater contributors to soil loss than are hiking and mountain biking use . . . (and accordingly) managers seeking to accommodate horse and ATV uses should acknowledge their higher potential for eroding soil" (Olive and Marion 2009) as well as for adversely impacting streams, creeks, and rivers with sedimentation, increased turbidity, aquatic community disruption, etc.
- To mitigate the most pronounced impacts of ATV use, and to a lesser extent mountain biking use, it is recommended that access from steeper slopes be limited and trail use in wet conditions be proscribed (Goeft and Alder 2001).
- Given the behavioral and social attributes of some ATV riders and rider clubs, managers seeking to accommodate ATV use need to anticipate the higher level of ecological destruction that can result from wanton ATV use. Proactive and anticipatory steps—involving design, oversight, and community outreach—can minimize this risk.

Amount of Trail Use

- Some researchers consider reductions in trail use to be an ineffective solution, due to the asymptotic growth of trail consequences with use. In their view, deciduous forest trail areas that have experienced high levels of vegetation loss will struggle to recover even when activity levels are significantly curtailed (Thurston and Reader 2001).
- Others, however, find that while reductions in continuous use may only have limited value, there is nonetheless evidence to suggest that allowing for "fallow periods" (i.e., noncontinuous use) may bring measurable benefit: "Our results support Cole's suggestion that deciduous forest understory plants have high resilience when the recreational activity is not continuous" (Thurston and Reader 2001).

Siting, Grading, and Contouring of Trails

- Trail grade was a "significant predictor of soil loss in all three study areas... particularly when grades exceeded 15%" at one site, "segments with low grades (0–4%) had similar low levels of soil loss." Of apparent secondary importance to reducing soil loss are trail drainage features (e.g., drainage dips) and the presence of gravel (to make trail soils coarser). These drainage features do, however, require semi-frequent maintenance in order to retain their efficacy (Marion and Wimpey 2016).

Composition of Trail Surfaces

- Sand and fine soils on trail surfaces have greater erodibility than coarse and mixed soils. Homogeneity of particle size on trail surfaces, especially of fine soils, also further adds to erodibility.

Immediate Surroundings of Trails

- Most "problematic" trails closely parallel streams (Leung and Marion 1999). Creating buffering zones between trails and streams may reduce sediment deposition and all its negative consequences.

Fecal Waste Impacts

A second set of impacts on water quality involve human, animal, and food waste left along trails.

- "Our results indicate that ongoing low-level nutrient additions by tourists to oligotrophic lakes could lead to increased primary (periphyton) and secondary (consumer) production. However, increases in periphyton production and biomass accrual could eventually escape control by grazers, leading to adverse ecological and aesthetic effects" (Kidd et al. 2014).

While the topic of the impact of land-based recreation on water quality and quantity would benefit across the board from greater research focus and attention, a few specific recommendations for needed study appear in the literature reviewed here:

- Godtman Kling et al. (2017) identified a particular paucity of research examining the impact of horseback riding and biking, with a majority of research examining the impacts of hiking (representing 51.3% of the literature that they surveyed).
- "Much of the research on hiking impacts in the USA and in Australia has focused on easily observable soil and vegetation change with *little research on indirect and cumulative effects*" (emphasis ours; Pickering et al. 2010).

FINAL OBSERVATIONS

Our use of the outdoors for recreational purposes is varied and frequently brings us in proximity to watershed waterways. This is because the land surrounding rivers, streams, and creeks is less easy to develop and is frequently accorded some protection by government authorities and conservation associations. While a quantifiable understanding of the precise impacts of different types of recreation activity on water quality and quantity is not yet generally available across the range of recreational activities, the general dynamics are available in the scientific literature for several key types of recreation. One of our goals with this review article has been to bring those key findings from that literature together in one place. Another has been to point out areas where additional research can help fill in holes in this picture. Our abiding and most important goal is to provide land stewardship managers and recreationists with a useful tool with which to gauge broadly the impacts of their professional work and private activities. We hope that this paper can make a difference in improving water quality and aquatic ecosystem integrity—and, conversely, help minimize the degradation—as readers apply the findings from this review.

Merritt T. (Terry) Cooke is Visiting Professor and Instructor for the International Master of Public Administration program at the University of Pennsylvania. He is also the Founder and Executive Director of the China Partnership of Greater Philadelphia, a 501c3 non-profit bringing clean water and low-carbon solutions to northeast China. Terry was the Panel Facilitator for the panel of scientists convened in 2016 by Roger Latham with multi-year funding from the William Penn Foundation to study issues of Land Stewardship from a Water Resource Perspective. This article belongs with that body of research, which was memorialized in a Special Issue of the Natural Areas Journal (Volume 39, No. 1). Terry and his family steward a 37-acre conserved property in the western suburbs of Philadelphia comprising mostly wetlands and floodplain. He received his PhD in Cultural Anthropology (1985) and MA (1981) from the University of California at Berkeley and his BA from Princeton University in 1981.

Liyiran Xia is Co-Instructor for the International Master of Public Administration program at the University of Pennsylvania. She is also an Environment and Clean Energy Project Manager at China Partnership of Greater Philadelphia. She holds a BA in environmental science from Franklin and Marshall College and an MA in international affairs with a focus on environment, energy, and sustainable development from Penn State University.

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