The Science of Sustainable Trail Design & Management

Dr. Jeff Marion,
US Geological Survey &
Virginia Tech University

& numerous graduate students!

American Trails: Advancing Trails Webinar

Presentation Objectives

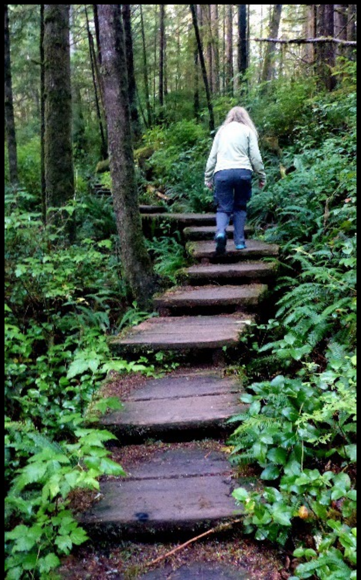
- 1. Review recreation ecology trail impact research findings.

- 2. Review implications for selecting sustainable trail design and management practices.

Presentation Focus

- 1. Native surfaced trails for pedestrian and biking use, with some coverage of tread hardening practices and horse trails.
- 2. Focus on sustainable design and maintenance.
- 3. New material on two methods for rating trail sustainability based topography.





Management Challenge:
How can managers make visitation more sustainable?

Trail Sustainability

- **Definition:** A "sustainable" trail can accommodate the intended type and amount of use over time without unacceptable levels of degradation or maintenance.
- Generally, a primary resource protection objective is to minimize "aggregate" trail impact and soil or vegetation loss.
- Trail degradation most frequently occurs due to poor trail design, except trail widening and informal (visitor-created) trail proliferation, which are more directly related to visitation.

Paper link

Trail Impacts...

Occur more frequently & severely on non-sustainable trails

Soil Impacts

Trampling and loss of vegetative cover

↓

Pulverization and loss of organic litter

↓

Soil compaction and increased runoff

↓

Soil erosion and muddiness

Paper link

Trail Impact Significance

Loss of soil is perhaps the most ecologically and managerially significant form of trail impact. A more permanent impact that suggests impairment.

Paper link

Soil Deposition Into Streams

Endangering rare federally listed freshwater mussels at

Big South Fork River & Recreation Area, TN/KY

Paper link

Tread Widening

A trail twice as wide as necessary doubles the areal extent of intensive trampling-related impact…

AT: 18 in wide = 400 acres of tread, 36 in = 800 acres

- Use-related visitor trampling is the primary agent of trail widening
- Solutions involve *modifying* visitor behaviors.

Paper link

Muddiness

- **Causes:** incised treads in flat terrain or trailside berms in sloping terrain
- Treads capture and hold or transport water (i.e., treads are not hydrologically invisible)
- Promotes trail widening behavior
- Decreases utility of the trail and visitor satisfaction

Paper link

Non-native Vegetation

- Visitors both introduce and disperse non-native plants to trail corridors. Most species are disturbance-associated and remain in trail corridors, but some are invasive.
- Managers are increasingly concerned about the locations and lengths of formal and informal trail networks within PA's.

Microstegium vimineum
(Japanese stiltgrass)

Sustainable Trail Management

Management Toolbox of Best Management Practices:

- Recognize and assess the sustainability of “legacy” trails
- Design/construct sustainable trails and relocations
- Create durable treads and drainage features

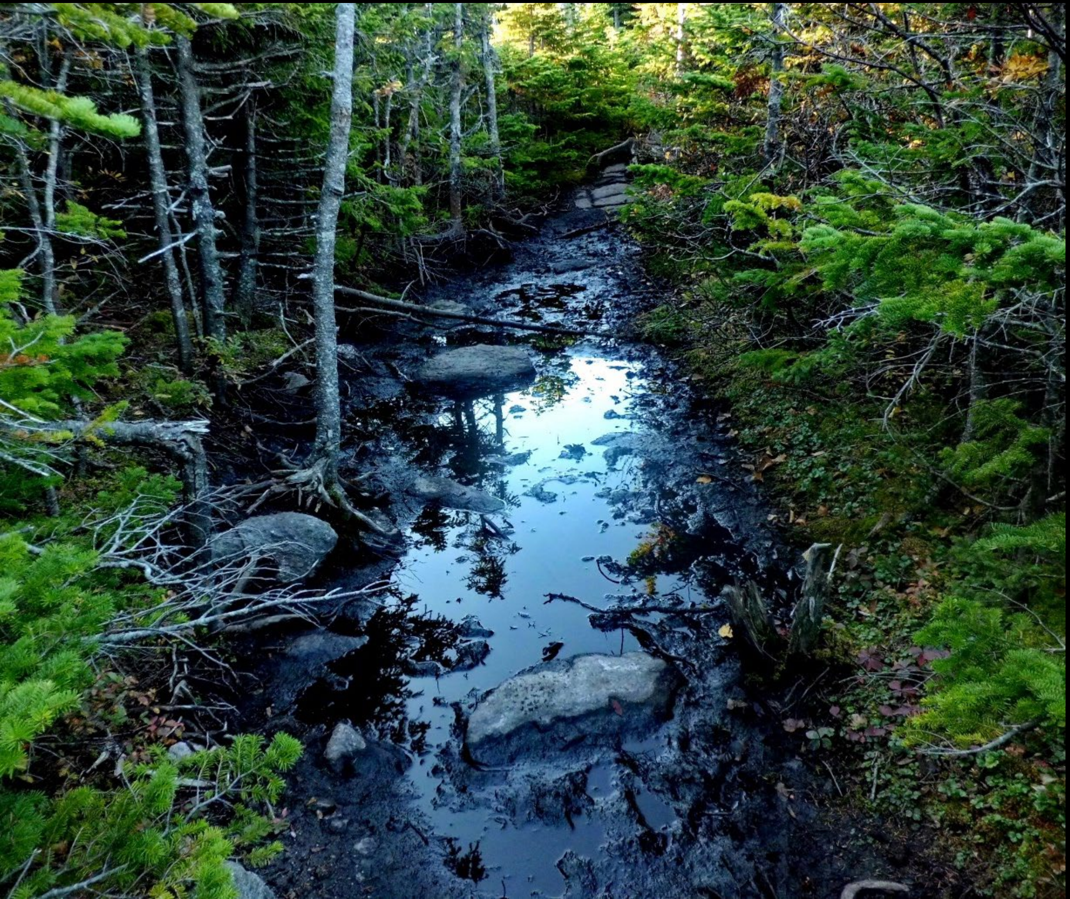
The Limitations of Legacy Trails

- **The Problem: Most trail networks are an amalgamation of historic "legacy" trails created without the benefit of modern sustainable trail design knowledge:**
  - **Native American or pioneer & early settlement routes**
  - **Old logging, mining, and ranching roads**
  - **Firefighting roads**
  - **Roads to homesteads**
  - **Visitor-created *Informal* trails and early *Formal* recreational trails**

Chief Limitations of Legacy Trails

Flat Grades ⟷ Steep Grades

AT



Chief Limitations of Legacy Trails

Fall-line Trails

AT

Chief Limitations of Legacy Trails

Proliferation of non-sustainable visitor-created Informal Trails

Paper link

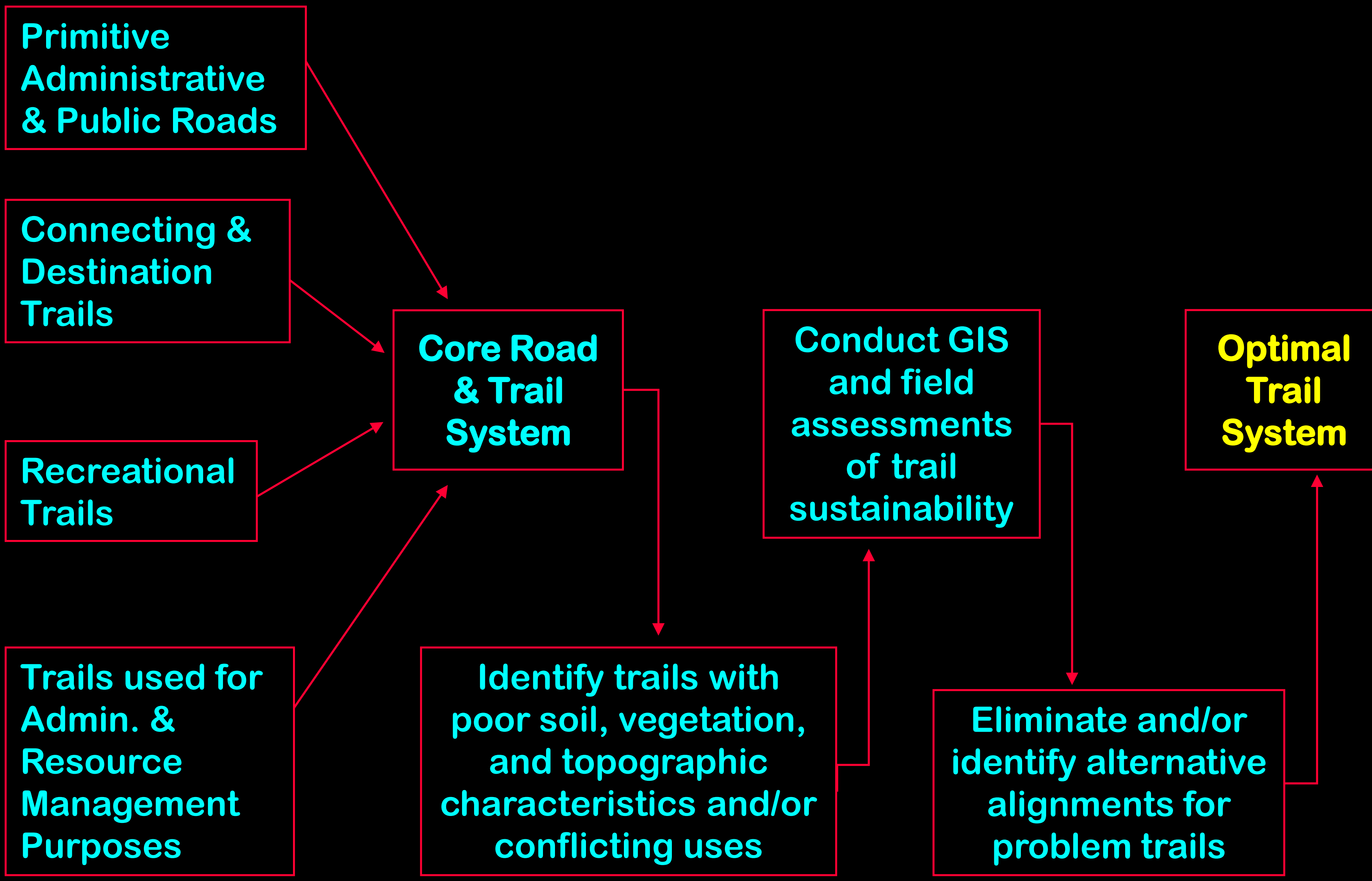
Solution: Trail System Assessment

Existing Inventory of Trails: Inventory and evaluate the need/purpose and sustainability of what you have based on trail system objectives.

- Are all existing trails necessary?
- Are they in the right places and are they fully sustainable (are relocations needed)?
- Are any new segments needed to fulfill administrative or recreation purposes?
- Are the desired types of uses suitable and sustainable?

Paper link

Trail System Assessment Model



Sustainable Trail Management

Management Toolbox of Best Management Practices:

- Recognize and assess the sustainability of "legacy" trails
- Design/construct sustainable trails and relocations
- Create durable treads and drainage features

Recreation Ecology

Definition: Scientific field of study that evaluates visitor impacts to protected areas and their relationships to influential factors. *This includes Trail Science studies.*

Paper link

Applications:

- Measure and monitor recreation impacts,
- Statistical modeling to ID factors that can be manipulated to avoid or reduce impacts,
- Develop sustainable trail and campsite management practices.

Literature Review of Factors Influencing Trail Impacts

Attributes	Research Findings	Citations
Trail Grade	Soil loss (+)	Eagleston & Marion, 2020; Dissmeyer & Foster, 1984; Farrell & Marion, 2002; Goeft & Alder, 2001; Marion & Wimpey, 2017; Meadema et al., 2020; Nepal, 2003; Olafsdottir & Runnstrom, 2013; Olive & Marion, 2009; Selkimaki & Mola-Yudego, 2011; Storck, 2011; Svajda, 2016; Wallin & Hardin, 1996; Wilson & Seney, 1994
	Trail width (+ for steep fall-line trails)	Marion, 1994; Meadema et al., 2020; Selkimaki & Mola-Yudego, 2011
	Trail muddiness (-)	Marion, 1994; Meadema et al., 2020; Nepal, 2003
Trail Slope Alignment (TSA)^2	Soil loss (- for steep grades)	Aust et al., 2004; Eagleston & Marion, 2020; Marion, 2009; Marion & Wimpey, 2017; Meadema et al., 2020; Olive & Storck, 2011
	Trail width (-)	Marion, 1994; Meadema et al., 2020; Wimpey & Marion, 2010; Svajda, 2016
Landform Grade	Soil loss (+)	Meadema et al., 2020; Nepal, 2003
	Muddiness (-)	Hawes et al., 2013; Meadema et al., 2020; Nepal, 2003
	Trail width (+ for steep fall-line trails; - otherwise)	Deluca et al., 1998; Eagleston & Marion, 2020; Marion, 1994; Meadema et al., 2020; Wimpey & Marion, 2010; Sutherland et al., 2001
Substrate Gravel/Rock	Soil loss (-)	Aust et al., 2004; Bodoque et al., 2017; Marion & Wimpey, 2017; Meadema et al., 2020; Olive & Marion, 2009; Selkimaki & Mola-Yudego, 2011
	Muddiness (-)	Aust et al., 2004; Meadema et al., 2020
Tread Drainage Features	Soil loss (-)	Aust et al., 2004; Marion, 1994; Marion & Wimpey, 2017; Meadema et al., 2020; Olive & Marion, 2009; Rodway-Dyer & Ellis, 2018
	Muddiness (-)	Meadema et al., 2020
Rugosity	Trail width (+)	Deluca et al., 1998; Marion, 1994; Meadema et al., 2020; Sutherland et al., 2001; Tomczyk & Ewertowski, 2013b; Wimpey & Marion, 2010)
	Soil loss (+)	Deluca et al., 1998; Sutherland et al., 2001; Tomczyk & Ewertowski, 2013b
Trail Borders	Trail width (-)	Doucette & Kimball, 1990; Wimpey & Marion, 2010

Multiple Regression Modeling

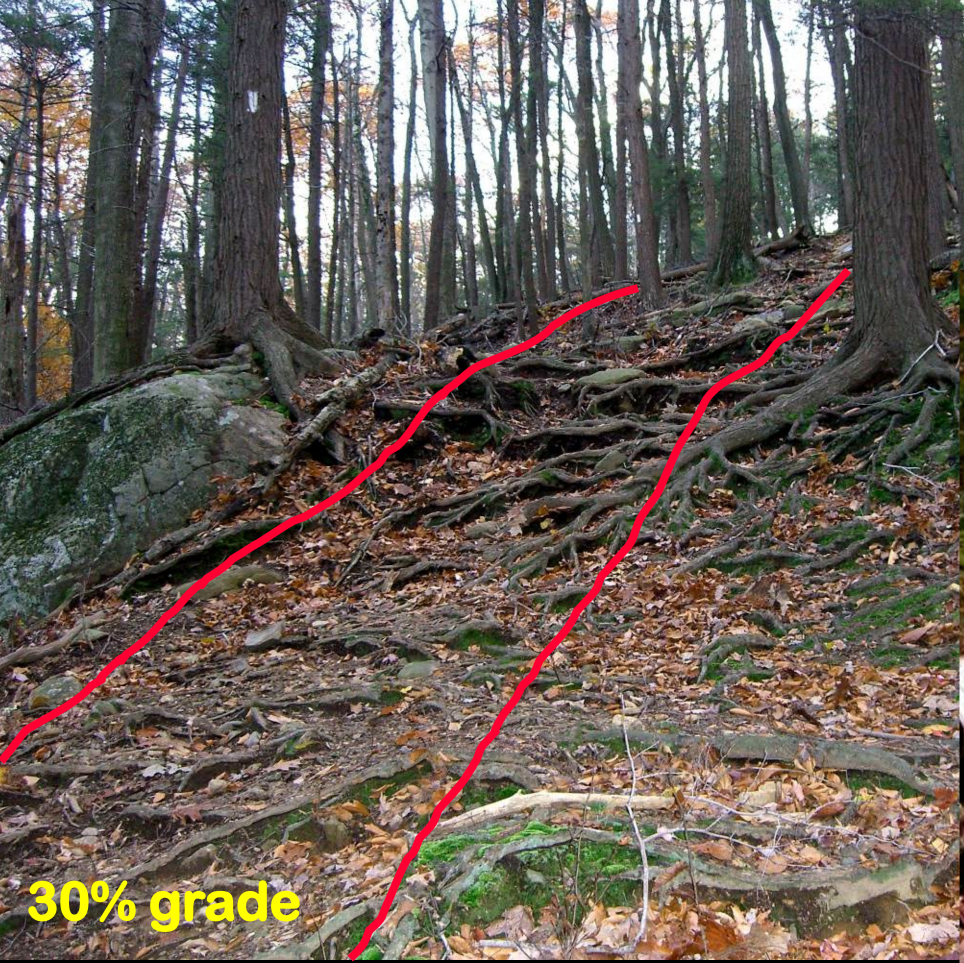
Trail Soil Loss – Most Influential Factors

Variables	Protected Natural Area		
	Hoosier NF	Big South Fork	Acadia NP
Trail Grade (%)	45.4 (.000)	17.2 (.000)	5.9 (.006)
Trail Slope Alignment (deg)	-2.1 (.039)	-9.9 (.000)	-1.6 (.004)
Tread Drainage (m)	6.1 (.074)	14.8 (.022)	--

Note: A diverse array of use-related, environmental, and managerial indicators were evaluated for influence. Only factors found to be significant are included. The amount of rock in tread substrates was borderline non-significant – we attribute its omission to inaccurate field assessment practices.

Paper link

Trail Grade

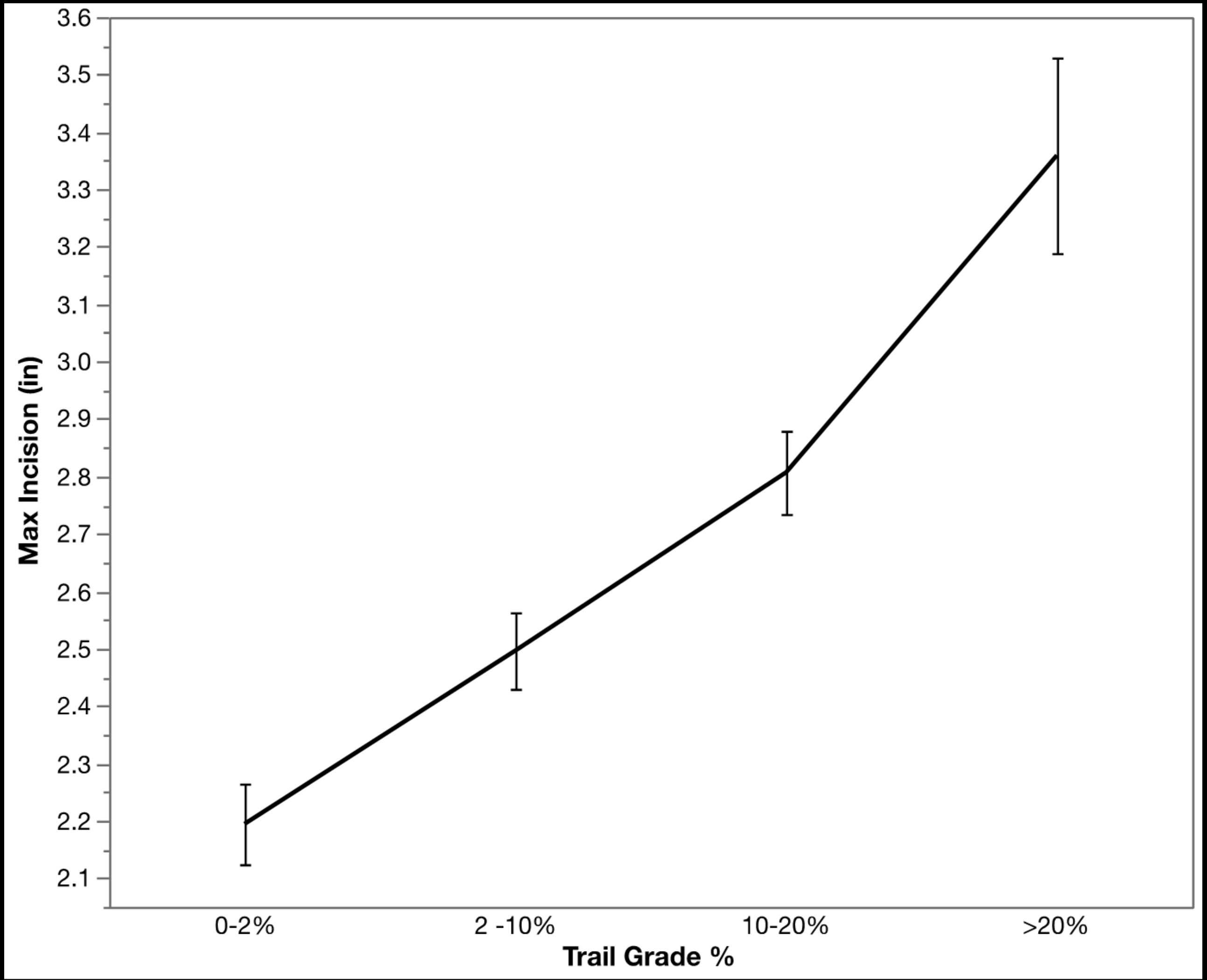


AT: NY

AT: NH

Trail Sustainability: A.T. data

Soil loss increases w/increasing trail grade



Paper link

Trail Grade

Trail Grade	Remarks	Drainage Spacing [1]
0-2	Avoid – difficult to drain	Not possible
3-6%	Ideal for general uses	500 ft
7-10%	OK in places if maintained	300 ft
11-15%	OK for short segments if well-maintained or in rocky soils	100
>15%	Avoid unless steps are constructed	<50

1 – USFS guidance: we've found no reliable research on this topic. Depends on many factors, including soil type, amount & type of use, rainfall, slope alignment angle, and tread drainage efficacy.

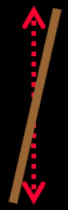
Trail Slope Alignment (TSA)

Alignment Angle to the Prevailing Landform Slope

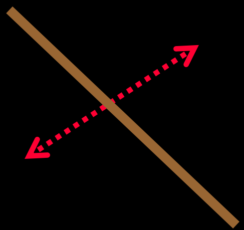
Irrespective of Trail Grade

Range: 0º (fall-line) – 90º (side-hill)

Low Alignment Angle (fall-line)



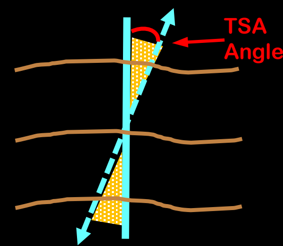
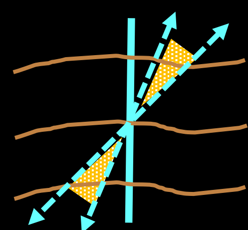
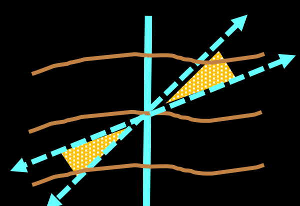
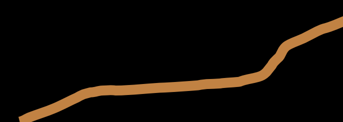
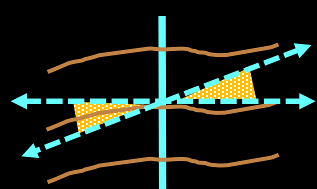
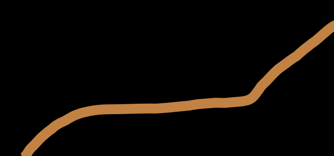
High Alignment Angle (side-hill)



Fall-Aligned Trails

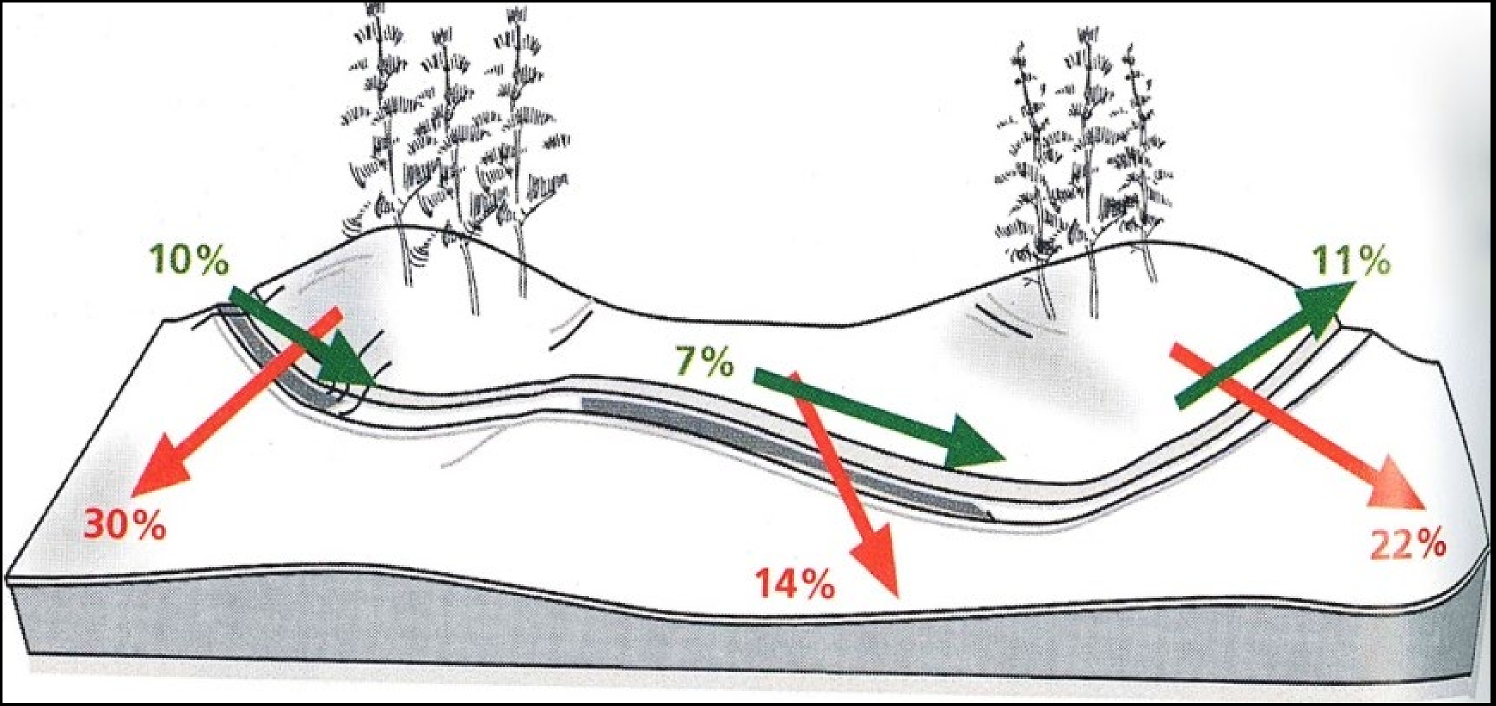
AT: NY

AT: CT

Trail Slope Alignment (TSA)		Degradation Potential	Trail Profile
Fall-aligned Trails			
0-22^{o}		**Very High** – tread drainage rarely possible; erosion, widening, & muddiness probable	
23-45^{o}		**High** – tread drainage is often difficult; erosion, widening, & muddiness are likely	
Side-hill Trails			
46-68^{o}		**Low** – tread drainage is possible; low potential for problems	
69-90^{o}		**Very Low** – tread drainage is easy; very low potential for problems	

Paper link

TSA or Slope Ratio?

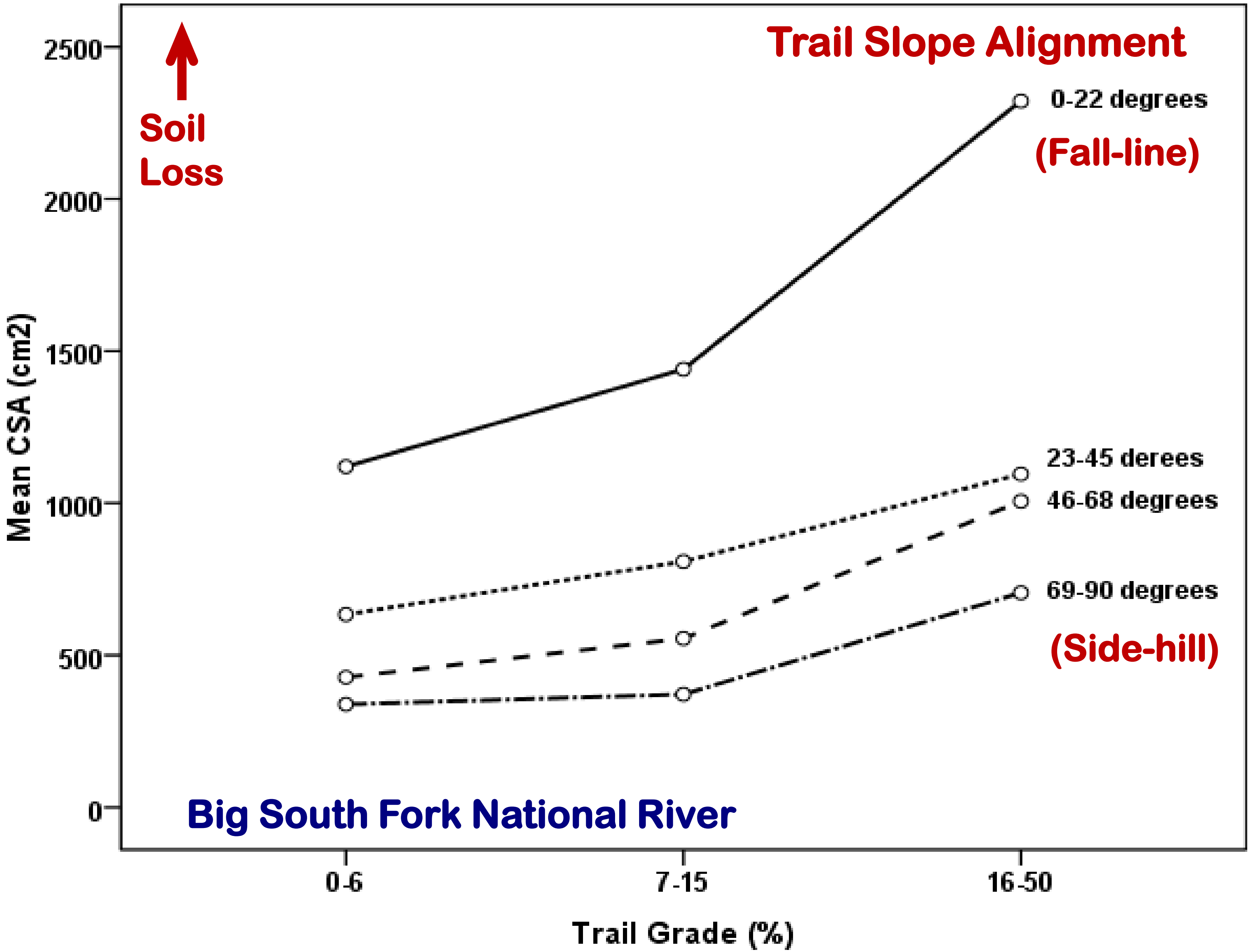


Slope Ratio = Trail Grade / Landform Grade

Range: 0 (side-hill) to 1 (fall-line)

Slope Ratio

- TSA is equivalent to Slope Ratio (SR), which is more widely used by trail practitioners (IMBA 2004).
- Fall line trails are nearly as steep as their surrounding terrain and have high SR values close to 1, whereas side-hill trails have low SR values closer to 0.
- The IMBA "Half Rule" states that trail grades should be less than half (50%) of the landform (side-slope) grade, this effectively prevents trail alignments close to the fall-line.
- This guidance was not based on any research. E.g., why 50% and not 40% or 60%?



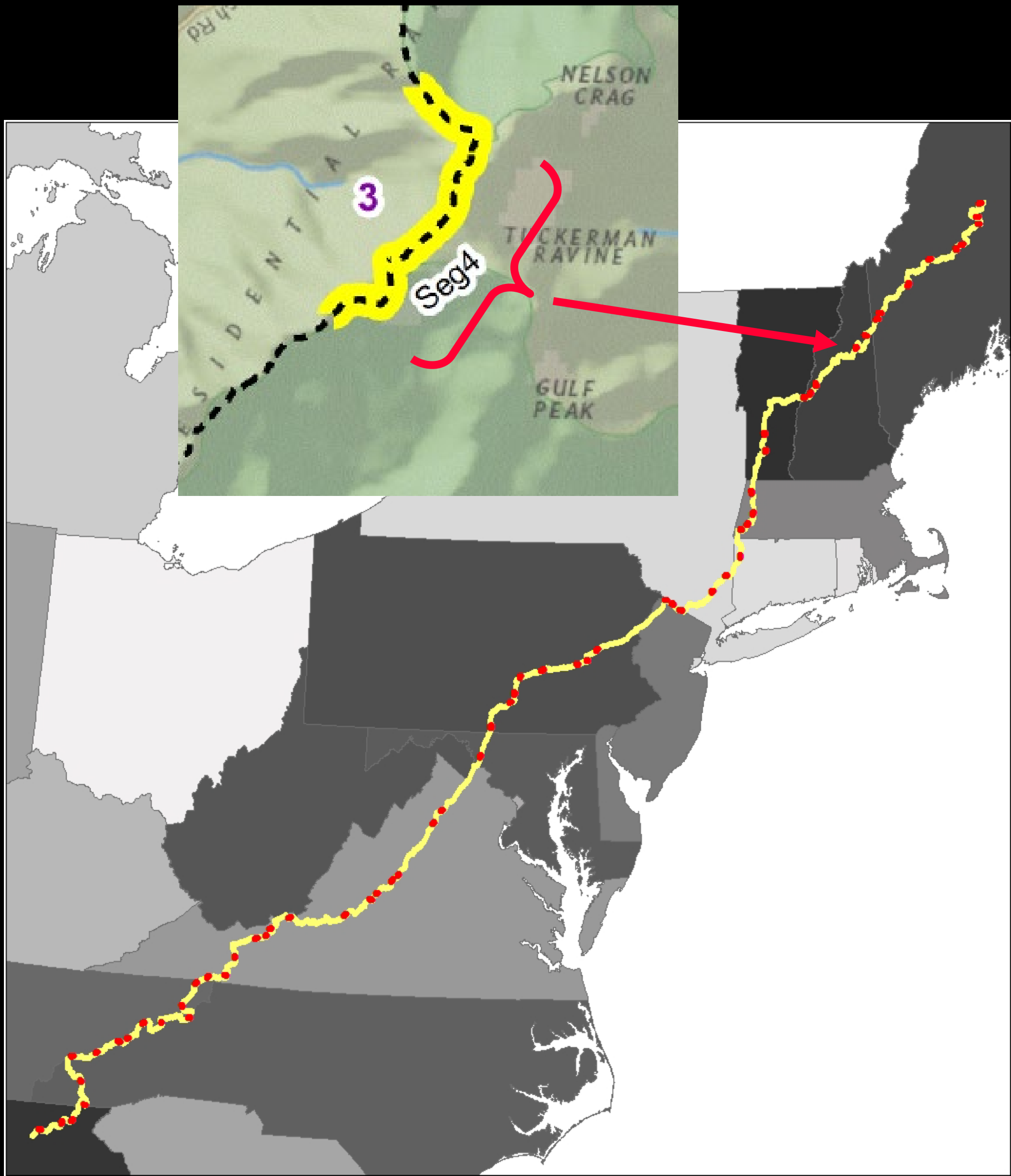
Trail Slope Alignment
Soil
Loss
0-22 degrees
(Fall-line)
23-45 derees
46-68 degrees
69-90 degrees
(Side-hill)
Big South Fork National River
Mean CSA (cm2)
2500
2000
1500
1000
500
0
0-6
7-15
16-50
Trail Grade (%)

Appalachian Trail Recreation Ecology Study

- Funded by NPS ATPO, administered by ATC.
- Assessed the AT tread, informal trails, recreation sites, shelters, and campsites.
- Provided a geographically representative 9% sample of A.T. baseline data to support sustainability analyses and VUM decision-making.
- Largest recreation ecology dataset ever developed.

Research Design

- Applied the Generalized Random Tesselation Stratified (GRTS) sample design.
- The GRTS algorithms achieve a spatial balance between the sampled AT trail segments.
- 63 5k segments - a 9% representative sample of the entire AT.

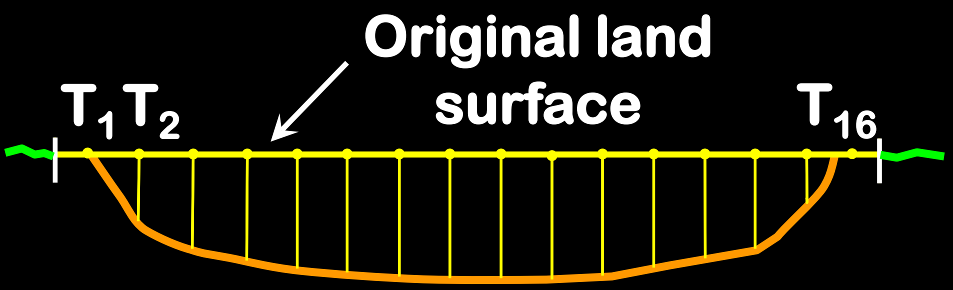


Research Design

GRTS sampling was also applied within the 63 5k segments to determine the locations of 50 trail transects where tread measures are made (N= 3150 transects). A Trimble GPS unit was used to navigate to each sample point.

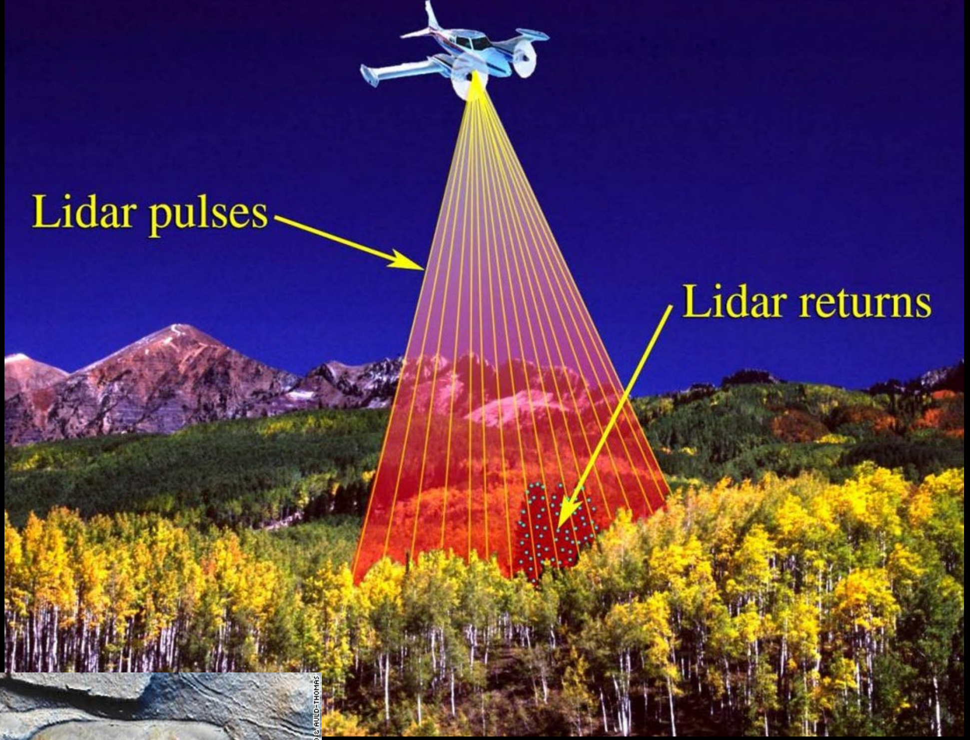
Soil Loss Measures

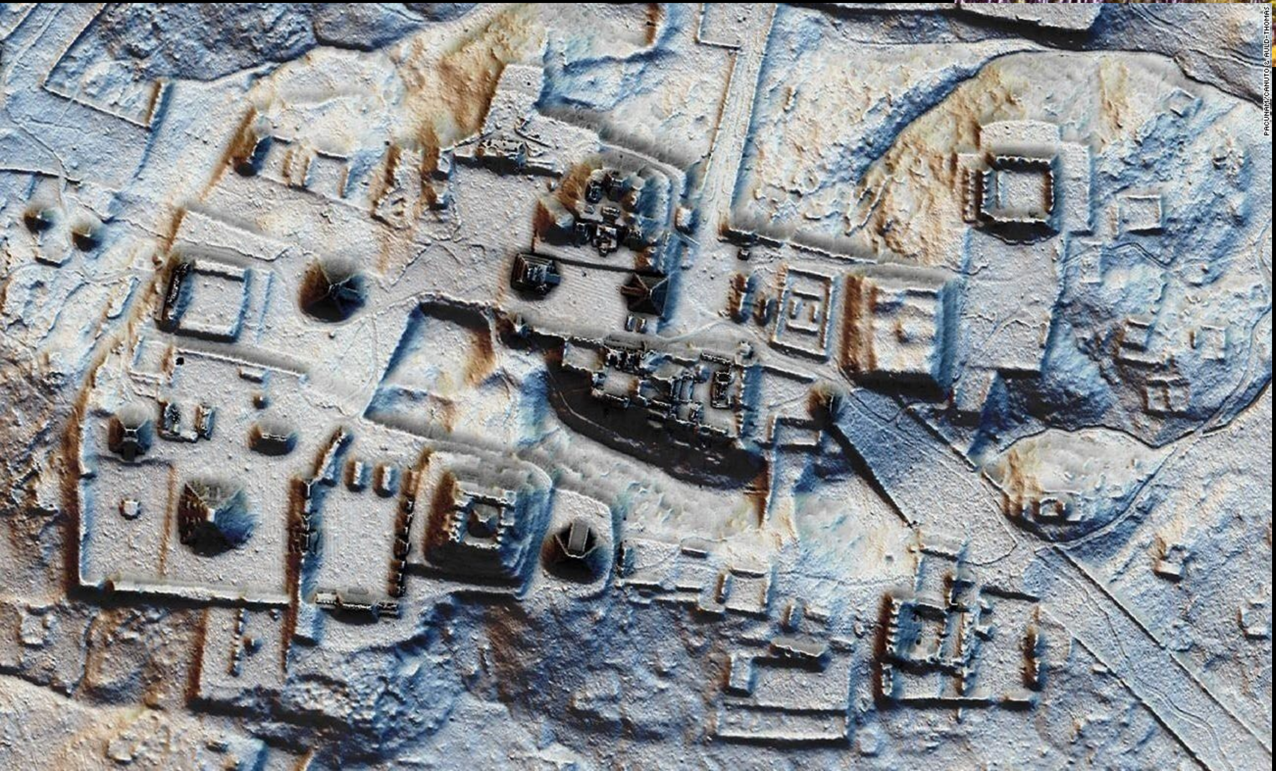
Maximum incision
Mean tread depth
Cross-sectional area (CSA)



- **Maximum Incision:** Median = 2 in, 16.2% of the AT has <1 in but 18.5% has > 4 in incision.
- **CSA:** Median = 32.2 in^2 Estimated soil loss for the AT is 2,585,660 ft^3 or 7,980 standard 12 yd^3 dump trucks.

GIS analyses of trail sustainability with LiDAR Digital Surface Models





A Mayan city detected thru a rainforest !


LiDAR data can reveal trails and roads under forest canopies.

Trail sustainability ratings were developed and applied based on trail grade and slope alignment angle.

INDICATORS (n=2957)		TRAIL SLOPE ALIGNMENT ANGLE				
		0-22° (fall-line)	23-45°	46-68°	69-90° (side-hill)	Totals
TRAIL GRADE	0-2%	4.8%	2.5%	3.9%	8.1%	19.3%
	3-10%	10.5%	5.7%	10.0%	13.0%	39.2%
	11-20%	9.5%	4.8%	9.1%	6.9%	30.1%
	>20%	5.0%	2.5%	2.9%	1.0%	11.4%
	Totals	29.8%	15.5%	25.8%	28.9%	100.0%

TRAIL SUSTAINABILITY RATINGS			
Good	Neutral	Poor	Very Poor

Paper link

Sustainability of the A.T. Tread

AT Section	Trail Sustainability Ratings			
	Good	Neutral	Poor	Very Poor
North AT	25	14	30	32
Middle AT	32	29	27	12
South AT	41	15	29	15

(Percentages of the AT Section in each category)

Trail Sustainability Ratings

Study Area	Good	Neutral	Poor	Very Poor
Big South Fork	46%	22%	25%	7%
Hoosier Natl Forest	26%	57%	13%	4%
Acadia NP	26%	22%	34%	18%
Appalachian Trail	29%	18%	32%	21%

(Portions of trail system in each category)

Trail Sustainability Ratings

New Trail Sustainability Ratings from Slope Ratio Analyses

Tallgrass Prairies National Preserve

Trail Triangle tables calculated from 10 ft trail segments using GIS w/LiDAR data

Trail Grade (%)	Landform Grade (%)				
	0 - 2	2.1 - 5	5.1 - 10	10.1 - 15	15+
0-2	5	4	4	4	4
2.1 - 5		4	3	1	1
5.1 - 10			5	3	1
10.1 - 15				5	5
15+					6

Paper link

Sustainability Ratings	Sustainability Rating Descriptions and Rationales
1	**High Sustainability.** Side-hill trail alignments with a 2-5% trail grade in >15% landform grades. Optimal trail grades with steep side-slopes that promote narrow easily drained treads.
2	**Moderate Sustainability.** As above – less optimal trail or landform grades.
3	**Low Sustainability.** As above – less optimal trail or landform grades. Trail alignments closer to the fall-line that inhibit tread drainage; less-steep side-slopes allow some tread widening.
4	**Unsustainable.** Flat side-hill trails in landform grades >2% that can retain water/muddiness and fall-line trails with 2-5% landform grades that inhibit drainage and allow tread widening.
5	**Moderately Unsustainable.** Fall-line trails with 5-15% trail and landform grades that inhibit drainage and allow tread widening, and steep trail grades in steep terrain (10-15%).
6	**Highly Unsustainable.** Fall-line trails with >15% trail and landform grades that can quickly erode and widen.

Trail Sustainability Photos

Trail Sustainability Photos

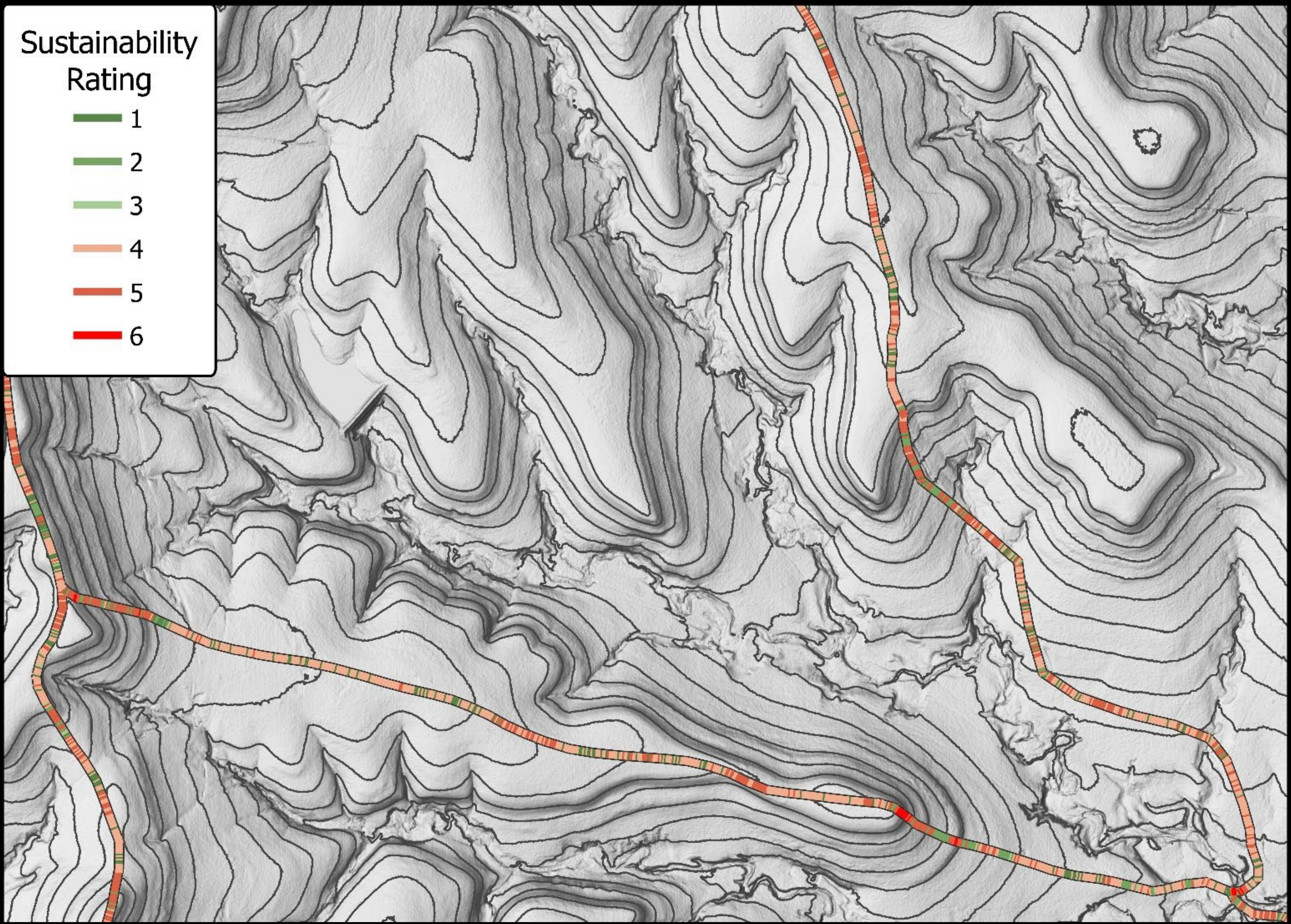
Flat terrain

Flat tread on contour

Fall-line, can't drain

Perfection!

Trail Sustainability Ratings Mapped



Trail Sustainability Based on Slope Ratio

Tallgrass Prairies National Preserve

Proportion of trails system in each sustainability cell and rating

Trail Grade Categories (%)	Landform Grade Categories (%)											
	0 - 2		2.1 - 5		5.1 - 10		10.1 - 15		15+		All	
	Sum (mi)	*% of Total*	*Sum (mi)*	*% of Total*	*Sum (mi)*	*% of Total*	*Sum (mi)*	*% of Total*	*Sum (mi)*	*% of Total*	*Sum (mi)*	*% of Total*
0-2	6.3	19.8	7.1	22.5	2.7	8.5	0.4	1.3	0.1	0.3	16.3	51.3
2.1 - 5			5.9	18.3	3.2	10.2	0.5	1.5	0.1	0.4	9.9	31.1
5.1 - 10					2.8	8.9	0.9	2.8	0.2	0.7	4.1	12.9
10.1 - 15							0.7	2.4	0.3	1.1	1.1	3.5
15+									0.4	1.3	0.4	1.3
All	6.3	19.8	13.0	40.8	8.8	27.7	2.5	7.9	1.2	3.7	31.8	100
Color Coding	Sustainable:		Low		3 (13.0%)		2 (2.2%)		1 (0.4%)		*High*	
	Unsustainable:		Low		4 (52%)		5 (32.2%)		6 (1.3%)		*High*	

Paper link

Tread Widening

Median = 22 in, just over half of the AT (59%) is <2 ft wide while 15% is > 3 ft wide.

- **Trampling is the primary agent of trail widening (rather than water)**
- ***Where*** **visitors walk is a function of their** ***behavior*** **…**

What influences trail widening behavior?

Statistically Evaluated

- Trail alignment
- Trail grade
- Rugosity
- Muddiness
- Borders
- Artificial tread
- Amount of use

Most Influential Factors

Independent Variable	Regression Coefficient	Significance
Use Level	16.0	0.001
Rugosity	14.6	0.001
Borders	-15.3	0.031
Trail Grade	0.5	0.043
Landform Grade	-0.4	0.001

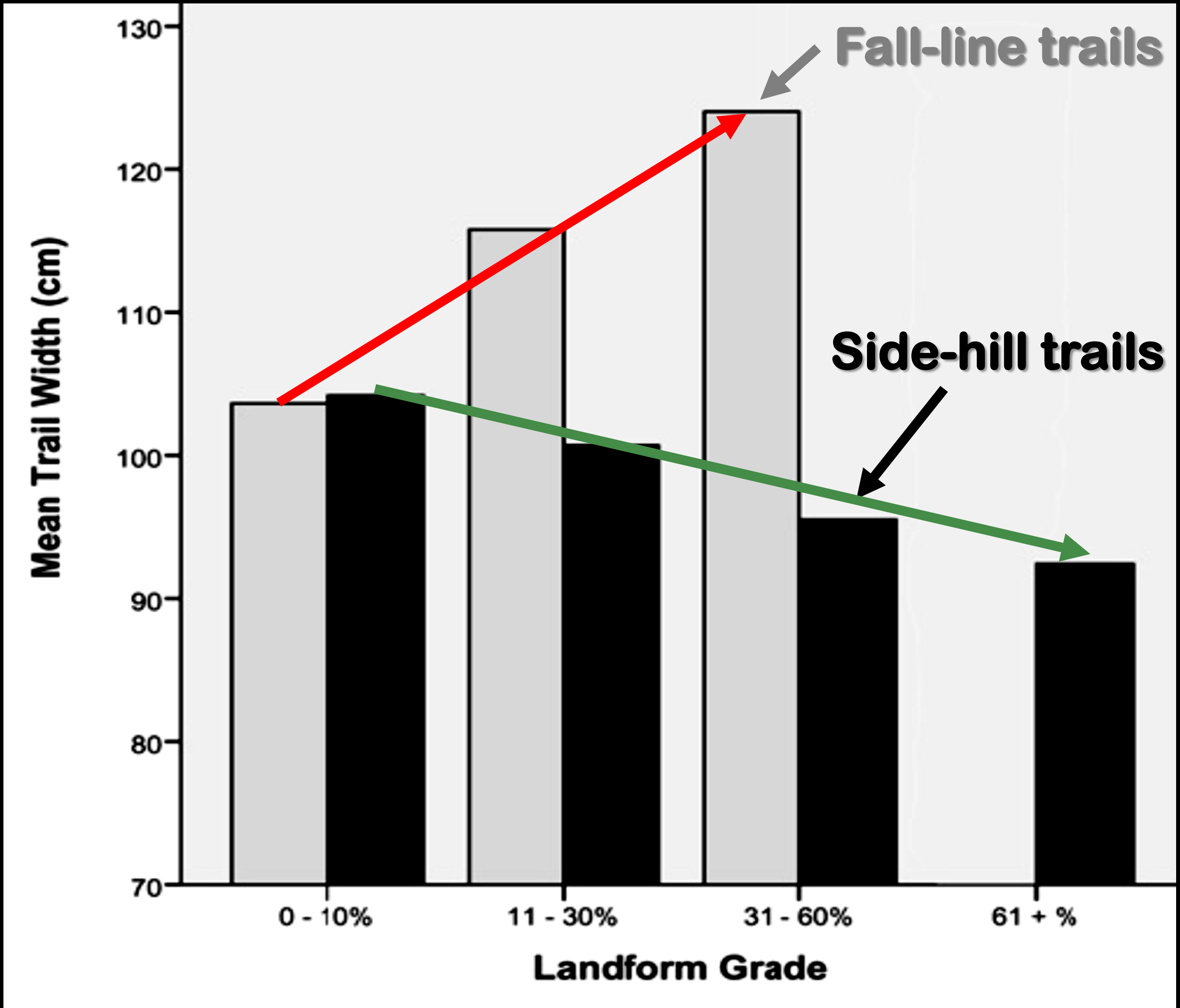
Paper link

Tread Widening Behaviors

- Passing other trail users
- Side-by-side travel
- Avoidance of tread problems (e.g., muddiness, erosion, roughness)
- Inability to remain on the intended tread due to poorly marked trails or ambiguous tread borders
- Roaming associated with picking the easiest route when traversing steep grades

Paper link

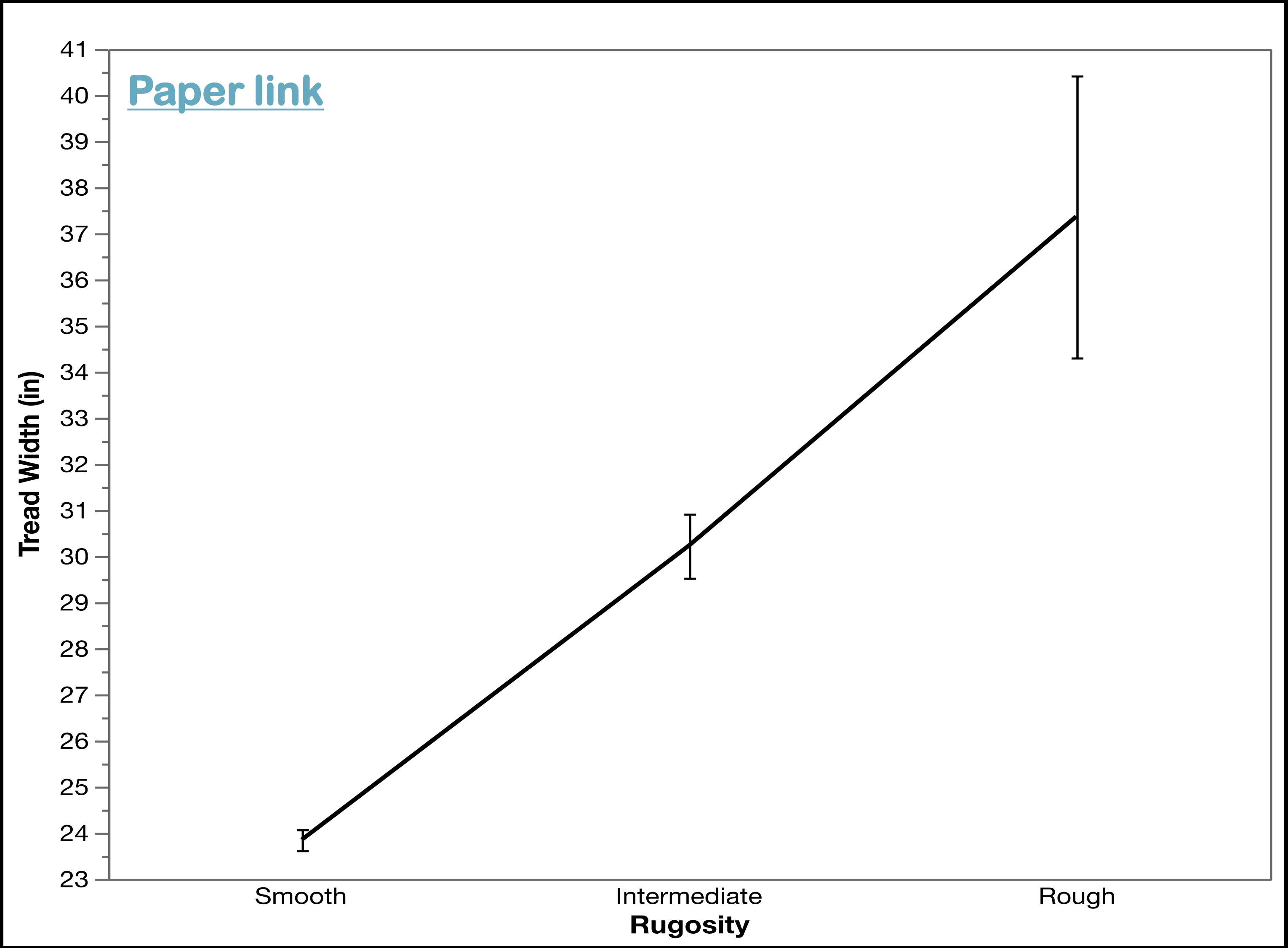
Influence of Landform Grade & Alignment on Trail Width



Paper link

Tread Width by Tread Rugosity

Tread rocks, roots, & uneven terrain increases tread width



Sustainable Trail Management

Management Toolbox of Best Management Practices:

- Recognize and assess the sustainability of "legacy" trails
- Design/construct sustainable trails and relocations
- Create durable treads and drainage features

Sustainable Horse Trails

Big South Fork

Yosemite NP

Sustainable Motorized Trails

Maintain Trails to Reduce Impacts

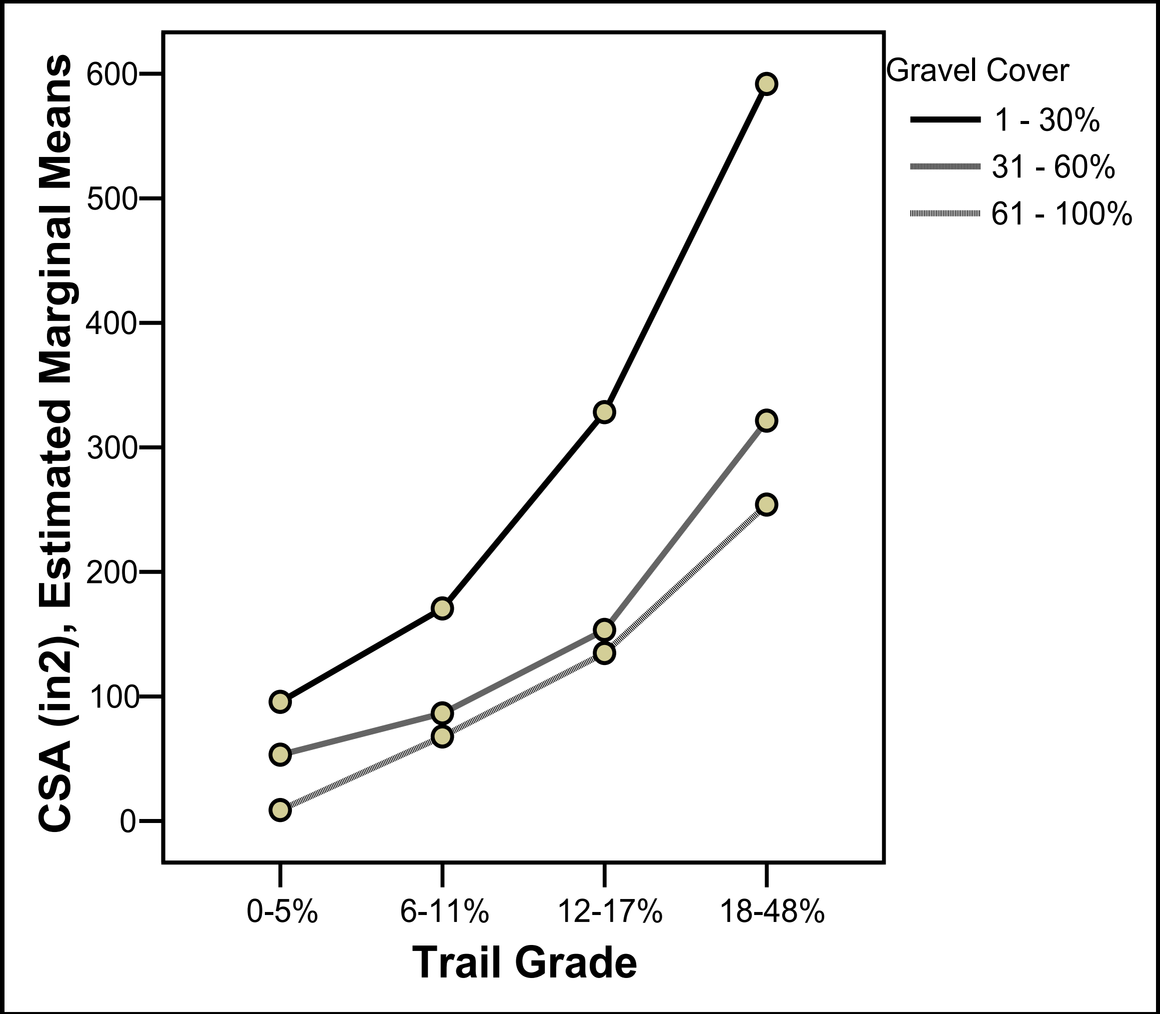
Graveling

Big South Fork

Trail Sustainability: Big South Fork

Based on relational modeling of trail soil loss:

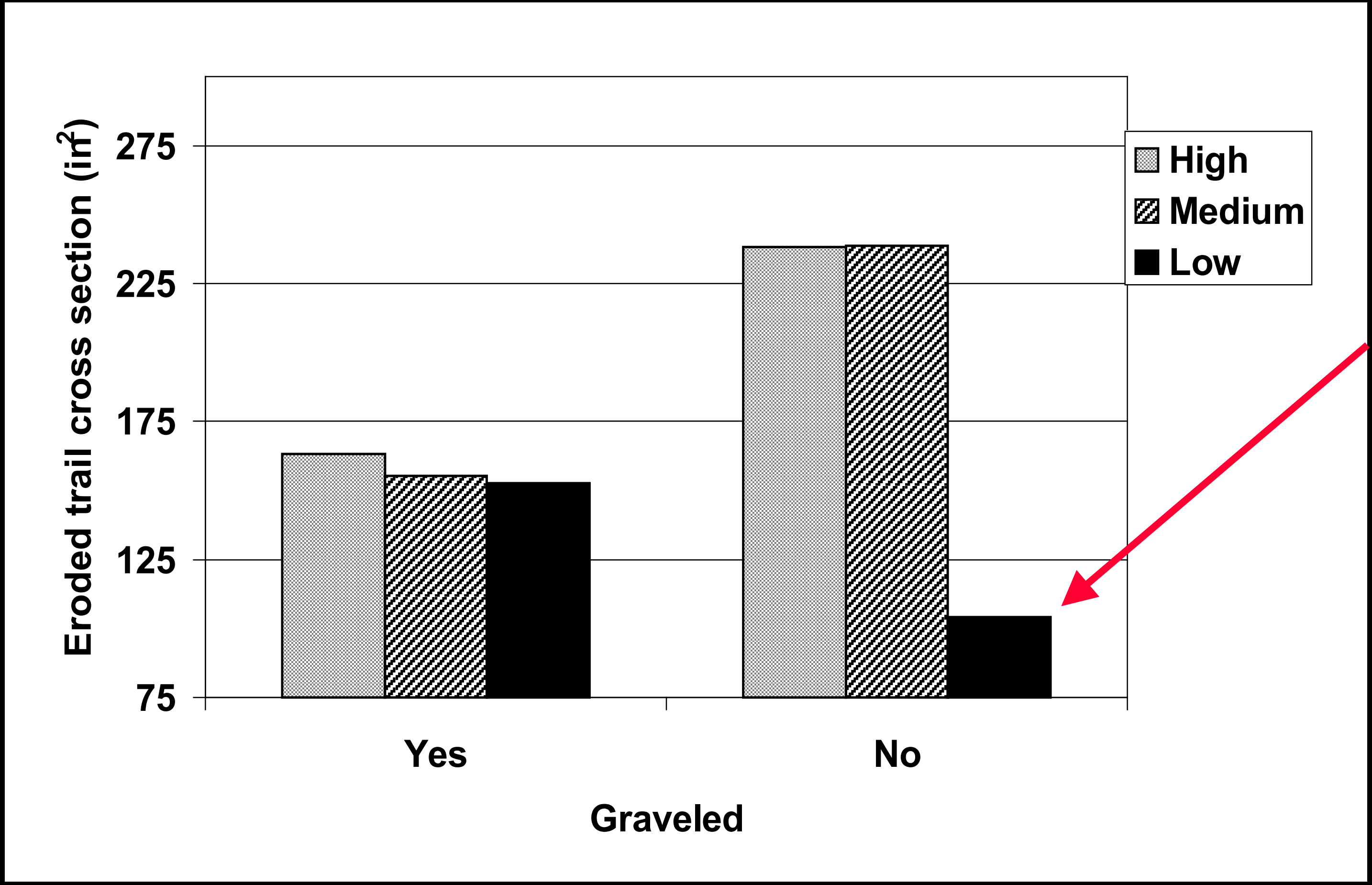
Soil loss increases with grade but graveling is an effective practice



Paper link

Trail Sustainability: Hoosier NF

Moderate and high use non-graveled trails are significantly more eroded than graveled trails.



Only low use horse trails can sustain traffic w/out graveling.

Paper link

Construct Durable Treads

Geotextiles

Construct Durable Treads

Stonework and redwood steps in Olympic NP

Armor Steep Grades

AT

Superb "natural" rockwork…

Construct Durable Treads

Acadia NP

Rock surfacing

Grand Canyon NP

Durable Treads in the Tropics

Gravel, concrete block,
& cement surfacing

Costa Rica & Belize

Construct Durable Treads

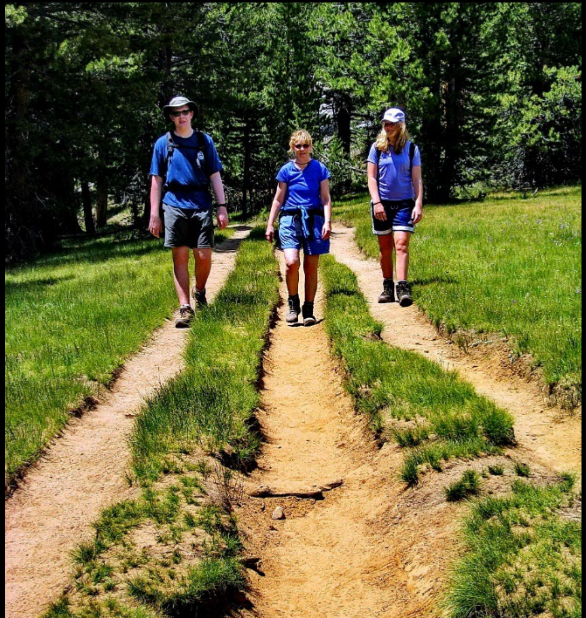
Wood Surfacing
(also plastic wood)

Yellowstone NP

Everglades NP

Resolving multiple trailing problems.

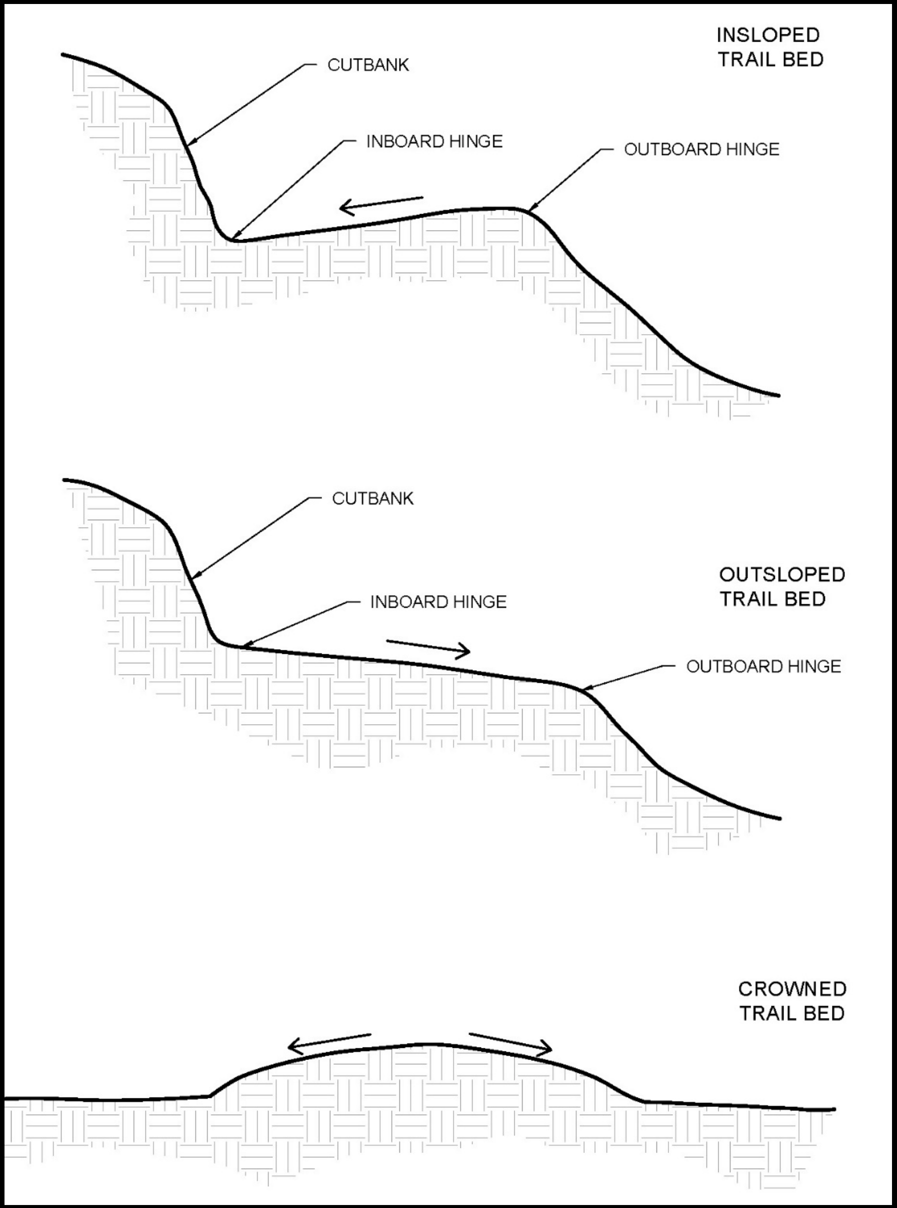
PCT, Yosemite NP



No Research On...


Tread compaction

Full vs partial bench construction

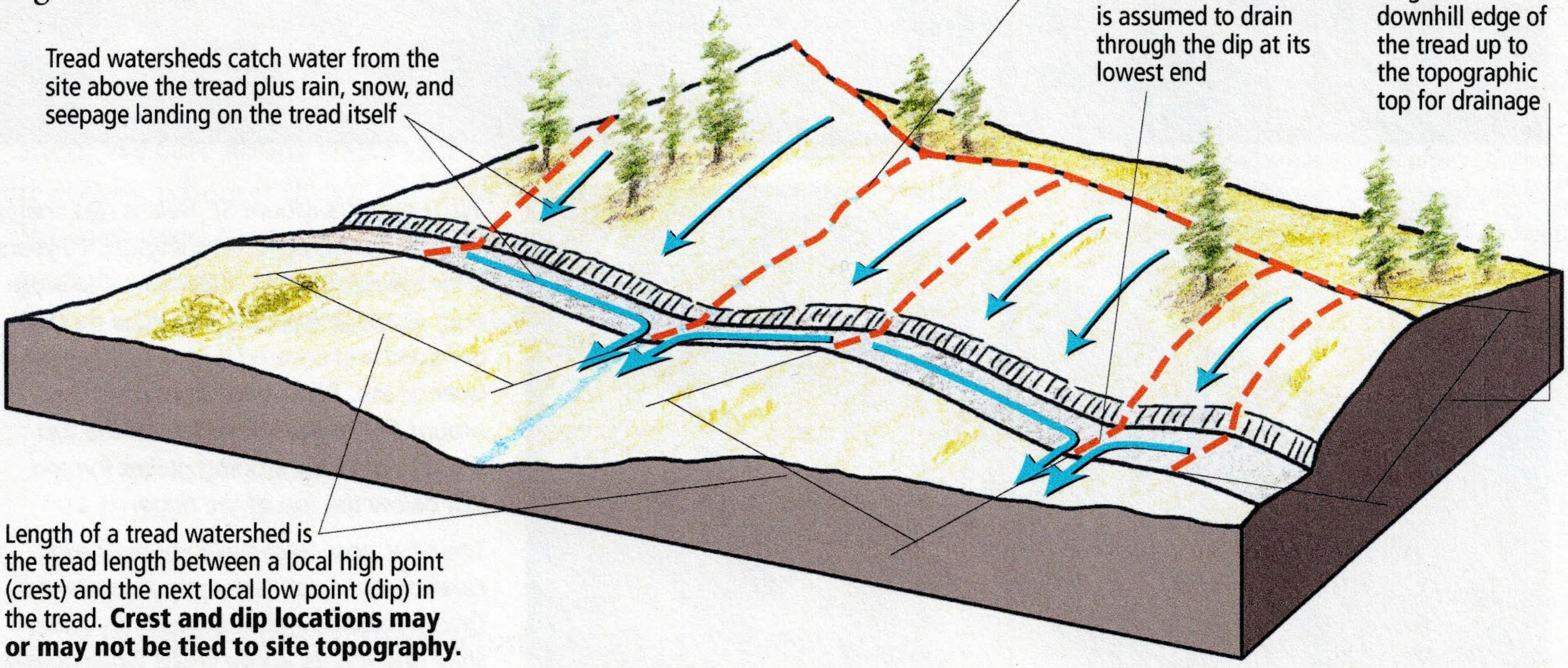


Tread sloping

Tread Drainage

Tread Watershed

A watershed is the land area that drains into a given water body or channel. A *tread watershed,* however, is a bit different. A tread watershed is the trail tread between a local high point (crest) and the next local low point (dip), plus the land area that drains onto this tread segment:

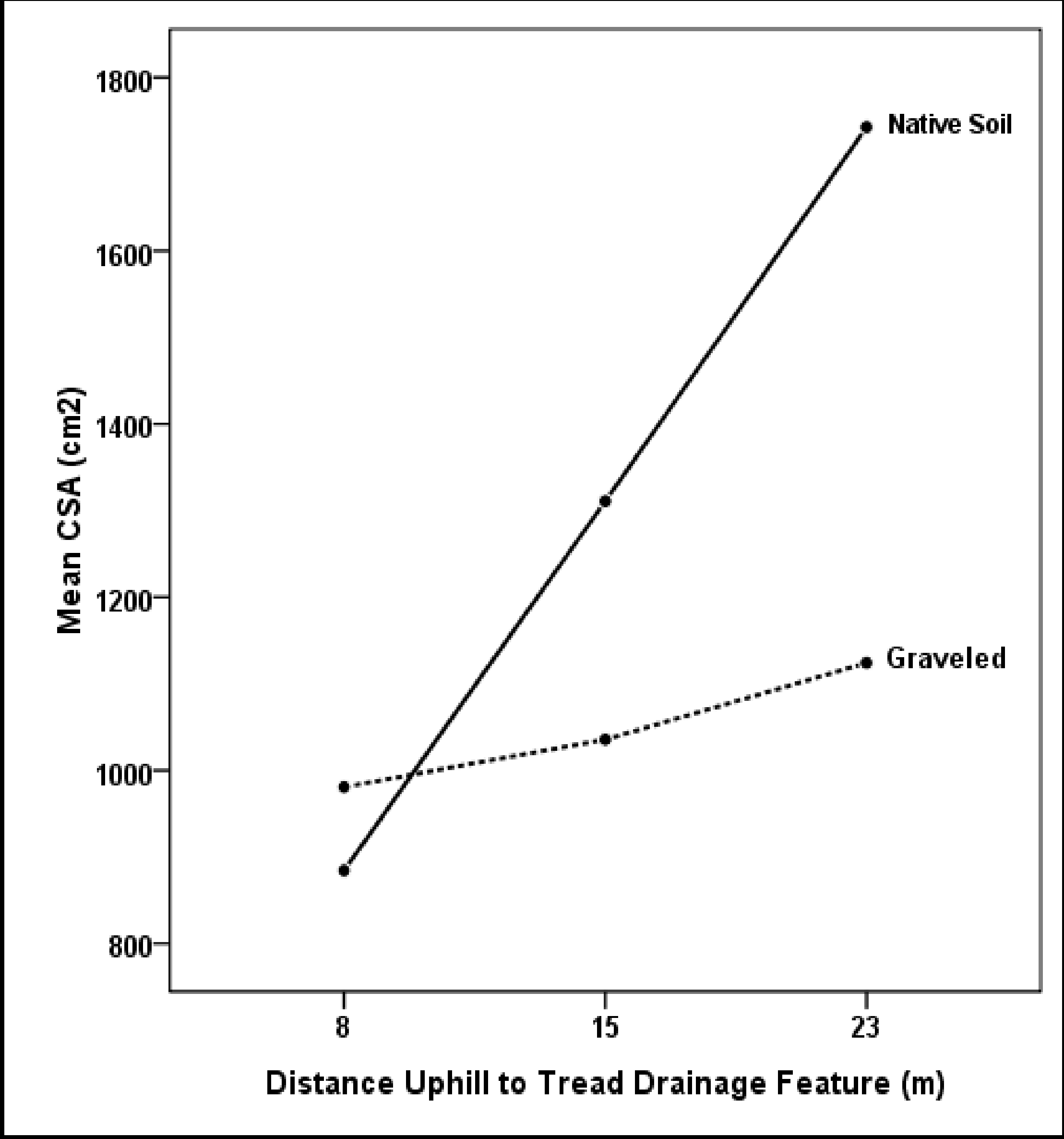


From: Troy Scott Parker's excellent book "Natural Surface Trails by Design"

Tread Drainage

Implications: Trails must have an adequate density of effective tread drainage features.

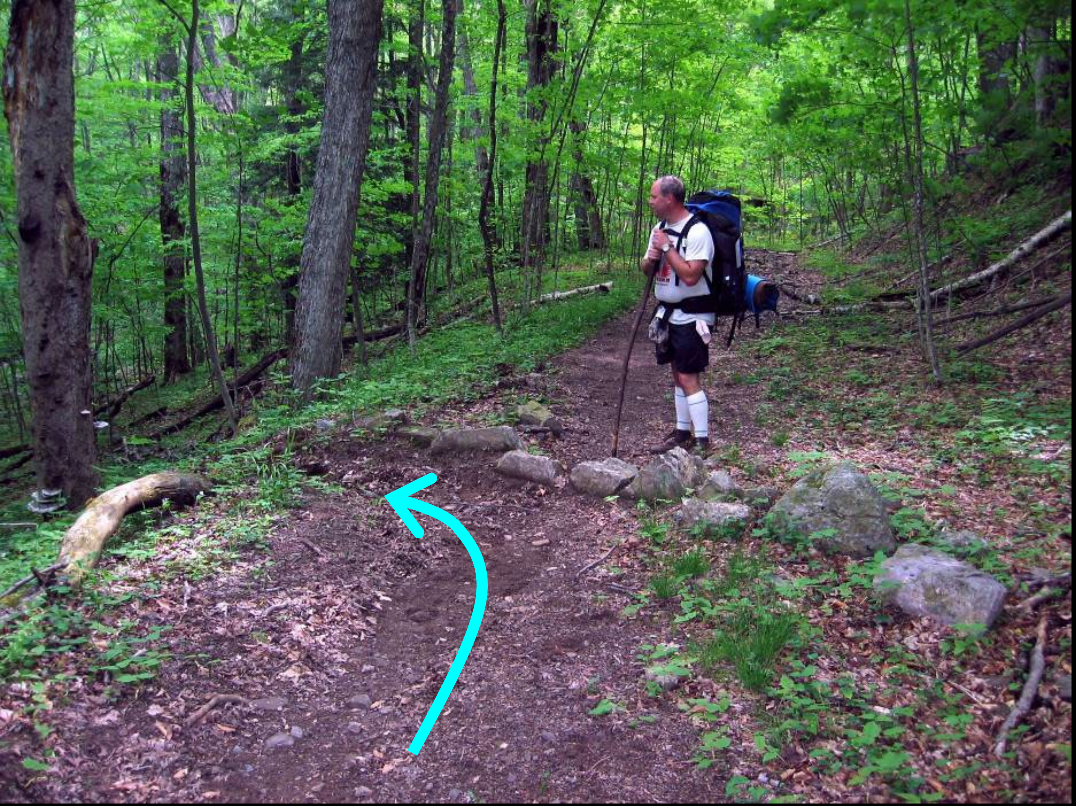
Note: Can't rely on tread outsloping as this generally fails due to substrate compaction, displacement, & erosion.



Hoosier NF

Paper link

Tread Drainage



- Note poor angles on both installed rock water bars; angle shown on right photo uses the flowing force of water to drop sediment further off-trail.
- Relevant guiding studies have not yet been conducted.

Tread Drainage

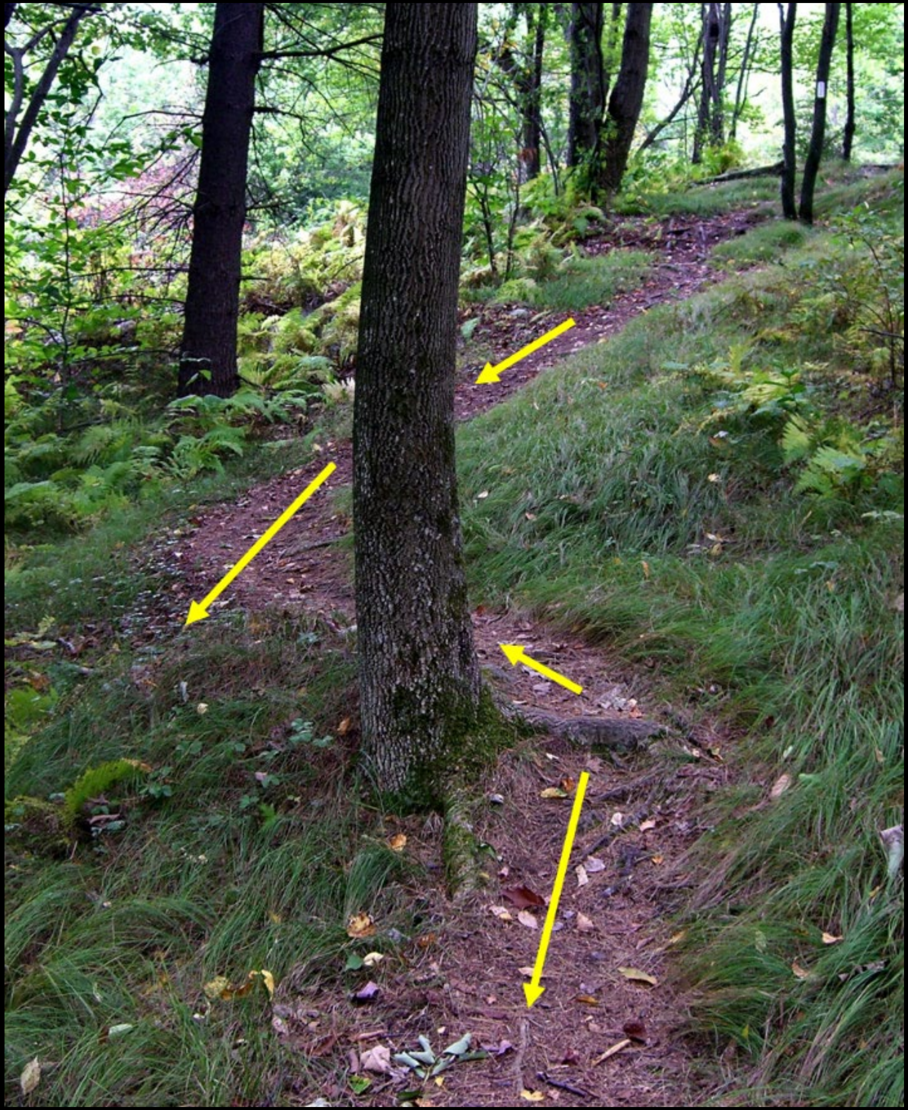
Tread Grade Reversal

Tread grade-reversals (rolling grade dips) *should be* designed into ALL new trails. They can be added to existing trail alignments but require substantial work.

Advantages:

- **Sustainable drainage with no maintenance**
- **More effective than water bars, drainage dips, or tread out-sloping over time**

Tread Drainage



Tread Drainage

I've maintained this neighborhood fall-line trail segment for 34 yrs (can't be rerouted). I have effectively resolved soil loss by maintaining long drainage ditches and by fertilizing the grass/moss every 6-8 yrs!

Mechanized Trail Construction




Talk Summary:
The Most Sustainable Trails are…

Constructed full-bench sidehill alignments with steeper side-slopes, angular rock/gravel substrates, and an adequate density of tread grade reversals for drainage.