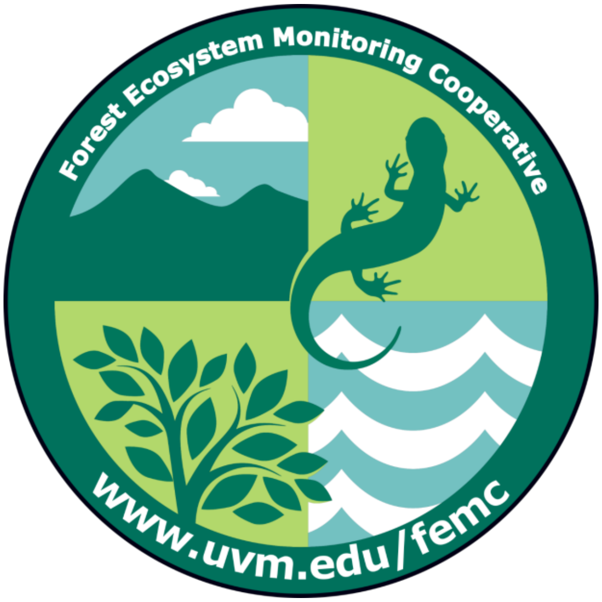

Recreation Impacts on Dimensions of Northeast Regional Forest Health

Technical overview of data analysis methods and products

FEMC Regional project 2023-2024: Recreation Impacts on Dimensions of Northeast Regional Forest Health

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Data Providers

STRAVA iNaturalist Open Street Map ForWarn NRCS f

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Executive Summary: Analyzing Recreation's Impact on Forest Health

Project Overview

This project investigated the impact of recreational hiking and biking on forest health. The analysis utilized several geospatial data sources, including ForWarn Sentinel data (ForWarn, 2022), Strava recreational use data (Strava, 2023), iNaturalist identification location information (iNaturalist, 2024), NLCD forest data (NLCD 2021), and USDA soil survey data (NRCS, 2023). The primary objectives were to determine whether forest-based recreational use correlates with forest tree canopy health and to provide managers with tools to help identify areas where soils are more susceptible to recreational use and where recreational activities may disturb wildlife.

Recreational activities, particularly hiking and biking, have experienced a notable surge in popularity, a trend exacerbated by the onset of the COVID-19 pandemic. This increased engagement presents a unique opportunity for individuals to establish meaningful connections with forested landscapes. While the uptick in recreational usage is positive for human well-being and nature appreciation, it concurrently raises concerns about potential impacts on forest health, specifically pertaining to soil quality, wildlife habitats, and tree and vegetation health.

Numerous studies have underscored the positive impacts of outdoor recreation on human well-being and mental health, emphasizing the importance of nature experiences in mitigating stress and promoting physical activity (Bowen et al., 2018; Bratman et al., 2019). However, land managers have expressed concern over the potential for the increased volume of recreational activity to harm forest health, and requested tools to support assessments of those potential impacts.

The Forest Ecosystem Monitoring Cooperative (FEMC) embarked on this project exploring the multifaceted interactions between recreation, soil vulnerability, wildlife disturbance, and overall forest health in 2022, and continued work on it through 2024. We employed geospatial analysis techniques to better understand how recreational activities affect forest health, and created geospatial products that could aid in more effective management of recreation in forest ecosystems. Although it is not detailed in this report, a separate component of this project focused on creating a decision tree tool to aid researchers and managers in selecting methods to monitor the impacts from recreation on forests; this can be found on the FEMC recreation project page.

The products of this work contribute to decisions being made by land managers, conservationists, and policymakers that aim to take a balanced approach weighing the benefits of both recreation and ecological protection and stewardship. We hope that by exploring the nuanced relationships between human activities and forest health, this project can inform sustainable management practices which ensure that recreation in forests can continue to exist with little or no detriment to forest health.

Key Findings

1. Recreation impact on forest canopy health: A simple t-test between forests with and without hiking and biking recreation showed a significant difference between the two, with lower positive Normalized Difference Vegetation Index (NDVI) deviance in forests with recreation. This indicates that across the entire region, forests with recreation may be slightly less healthy based on NDVI deviance as a proxy for canopy condition; however, the effect size was very small, suggesting that many other factors are of greater importance. Additionally, we found a significant but weak correlation between NDVI deviance and hiking use, suggesting that where hiking does occur, places with more hiking have worse canopy condition. However, again the effect size was weak—many other factors are likely more important. These findings also suggest that NDVI deviance may not be a sufficient measure of overall forest health, either due to other influential factors, coarse (30m) resolution of the data, or both.

2. Soil susceptibility: Existing geospatial data available from the NRCS (NRCS, 2023) indicated that certain forest soils were more susceptible to degradation due to recreation, allowing for targeted conservation efforts. Coupling these data with recreational use data (from Strava and iNaturalist users) (Fig. 1 shows relative hiking use based on Strava and iNaturalist data) allowed us to identify "hotspots" where heavy hiking and biking use is occurring on vulnerable soils. Examples include Kingdom Trails/Burke Mountain, VT, and Glacier Ridge/Overton Preserve, NY. Recreational hotspots on these suitable soils may exacerbate vegetation impacts. These hotspot areas and others, highlighted in the available geospatial layers, are ripe locations for further and more detailed assessment, and provide an example of the ways in which the geospatial products available from this project can indicate key locations for deeper and more detailed analyses.

3. Wildlife disturbance: We determined that the average undisturbed parcel of forested land was significantly reduced in size by disturbance from recreational activities. The wildlife buffer geospatial products available from this project may be utilized alongside other data to prioritize areas for wildlife management and conservation efforts.

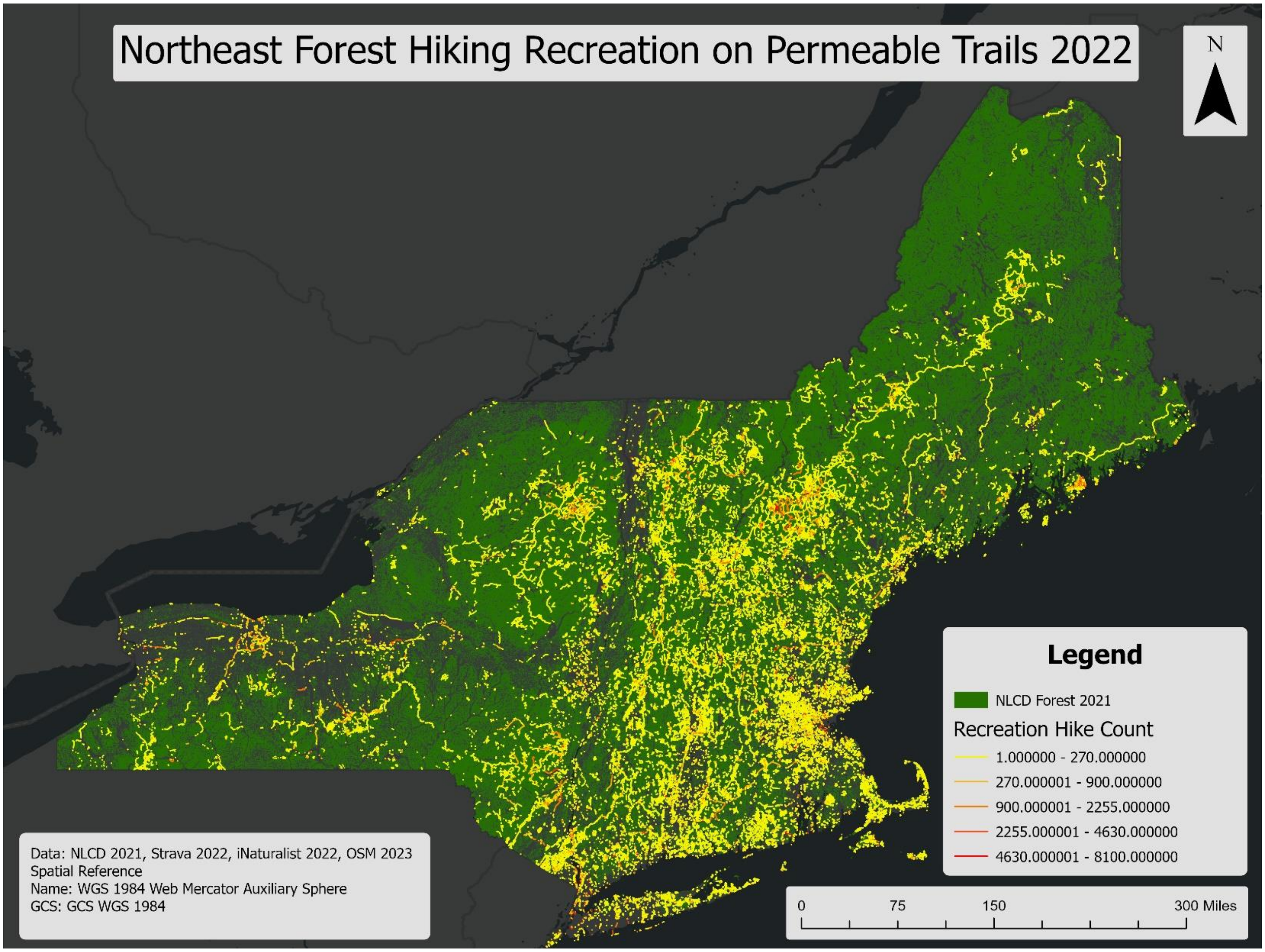

Figure 1. Northeast forest hiking on permeable trails based on Strava and iNaturalist data from 2022

Methods

1. ForWarn Sentinel data (ForWarn, 2022): We integrated ForWarn Sentinel data to monitor forest health indicators, such as vegetation stress and disturbance events, and examined whether these metrics could be linked to recreational activities. See Appendix for maps and further information.
2. NLCD Forest (U.S. Geological Survey, 2021) and USDA Soil Survey data (NRCS, 2023): We combined NLCD forest data and USDA soil survey data to create geospatial datasets identifying areas with soils susceptible to recreation and to assess how the locations of vulnerable soils intersected with documented recreational use.
3. Wildlife disturbance analysis: We mapped areas where wildlife was likely to be disturbed by outdoor activities and determined how often that disturbance occurs, as well as the average size of undisturbed forested parcels to explore the potential impact of recreation on wildlife. We provide layers for buffers at 400m, 150m, and 60m from trails.
4. Strava (Strava, 2023) and iNaturalist (iNaturalist, 2024) recreational use data: We leveraged Strava's recreational use data, which shows usage density on all trails across the project region, to assess the spatial distribution and intensity of hiking and biking activities—this added an additional dimension to our analysis. We also included iNaturalist observation points, related to the nearest trail, to account for trail users who may differ from those who typically use Strava.

Additional details regarding methods can be found in the report Appendices.

Recommendations for use

General recommendations for the use of the geospatial layers generated by this project are:

1. Land management: Use the Recreational Soil Suitability and NDVI Deviance layers to guide decisions on where to allocate resources for further assessment, or areas to consider for trail maintenance or closure. Areas with high recreational use on sensitive soils may require additional erosion control measures or rerouting.

2. Wildlife habitat conservation: Employ the Wildlife Habitat Patches layers to aid conservation prioritization decisions. Large, contiguous patches identified in these layers are essential for species requiring extensive territories. These data can also be used for planning wildlife corridors and mitigating fragmentation.

3. Trail development: Future trail development should consider the Recreational Soil Suitability Maps to avoid placing trails on highly erodible or compactable soils. These maps can also be used as a first step to guiding decommissioning or rerouting trails in areas where recreational use is likely to degrade soil health over time.

4. Public awareness and education: Sharing these maps with the public can help raise awareness about the impacts of recreation on forest ecosystems. Providing recreational users with information about how their activities contribute to forest health will encourage more sustainable behavior.

5. Collaboration and data sharing: The data generated in this project can be shared with local conservation organizations, municipalities, and state agencies, or other interested parties. Collaboration across these entities will ensure that the layers are effectively used to inform conservation and land management decisions.

6. State and regional level analyses: These layers can contribute to regional or state scale analyses of the overall impact of recreation on multiple dimensions of forest health.

Limitations

A significant challenge for this project was the lack of field-collected data that could have provided more precise insights into the impacts of recreational activities on soil, wildlife, and forest health. Without local-scale, high-resolution data we were unable to compare our geospatial products to field-based "ground truth" data to assess accuracy. Additionally, the geospatial products available may inaccurately or insufficiently represent smaller-scale variations or details that may be important for smaller-scale management decisions.

As a result, we recommend that these products be used as a starting point for more in-depth, local analyses and management decisions, but not as the sole source of information to guide these decisions. They can be used to aid prioritization efforts, identify potential areas of concern, or understand the overall impact of recreation on forests on a state or regional scale.

We also recognize the limitations inherent in using Strava and iNaturalist data to estimate trail usage. The results of this work incorporate any biases due to the user bases of those apps, and where people feel inclined to use those apps on the landscape.

Recommendations for future work

1. Data collection: Future studies should prioritize the collection of comprehensive field-based data that aligns with standardized methodologies. This will enable a more consistent and fine-grained assessment of recreational impacts on soil, wildlife, and canopy health. Standardized methods for monitoring recreation impacts can be selected using the methodology decision tree tool available on the FEMC recreation project page.

2. Collaboration: Collaboration among various stakeholders, including government agencies, conservation organizations, and research institutions, could help facilitate the collection of field-based data by establishing shared data standards and methodologies to ensure compatibility and consistency across locations.

3. Local engagement: Local communities and citizen scientists can play a crucial role in data collection efforts and the application of findings, as they often have valuable location-specific insights and a vested interest in understanding and mitigating the impacts of recreational activities in their regions.

4. Longitudinal studies: Conducting long-term studies that combine field data with remote sensing can provide insights into the evolving effects of recreational activities over time, helping inform sustainable management.

4. Improving analyses of impacts with ForWarn: Future efforts should integrate a variety of datasets such as field-based measurements and other remote sensing and geospatial products to establish a comprehensive suite of factors impacting canopy health. A more complete suite of factors that may influence canopy health could improve the preliminary ForWarn analysis presented here.

5. "Follow the Blue" trail optimization: The NH Trails for People and Wildlife project includes a "Follow the Blue" feature that uses habitat connectivity data to identify trails that, if decommissioned, would open the most significant wildlife habitat. These data can assist land managers in making data-driven decisions about establishing or closing trails, maximizing habitat restoration while minimizing recreational impact. Incorporating such analysis regionally can help optimize trail networks for both wildlife and human use.

6. Assess potential "lagged" temporal relationships: Annual correlations between NDVI deviance and recreation patterns may exhibit a lagged temporal relationship, meaning the vegetation response to recreational activity could manifest with a delay. This analysis, focusing on immediate correlations during the growing season, may not capture these delayed effects. For more accurate insights, future studies should consider lagging temporality, potentially employing Granger causality techniques, to determine whether changes in recreation use could predict shifts in NDVI over longer periods. This could provide a better understanding of cause-and-effect relationships.

Conclusion

This project provides a suite of geospatial products for managers and researchers to begin to assess the potential impacts of recreation on forest health—either at the regional or state scale—or as a guide to more in-depth local analyses. We used a multi-faceted approach that combined remote sensing data, geospatial analysis, and wildlife disturbance assessments, and performed a preliminary assessment of the relationship between forest canopy health (based on ForWarn Sentinel data) and recreational use. The products created during this project can inform decision-making and management strategies to ensure the sustainable use of forested landscapes, particularly by assisting land managers in identifying areas that are a priority for different management objectives. While the analysis utilized available data sources and remote sensing techniques, the lack of comprehensive field-based data presented a substantial limitation for validation of products and accuracy for smaller-scale applications. Recognizing the importance of such data, and addressing the challenges in collecting and standardizing it, is essential for future research aimed at assessing the impacts of recreational activities on soil, wildlife, and forest health more accurately. The other aspect of FEMC's recreation work (see more on FEMC's Recreation project page) has begun to address this limitation by creating a tool suggesting methods for different recreational impact monitoring and research needs.

Products and analyses

Recreation impact on forest canopy health

Introduction

Recreational use of forests can influence ecosystem dynamics, including canopy health. This study explores the relationship between hiking and biking activities and NDVI deviance from baseline canopy health using Strava (Strava, 2023) and iNaturalist data (iNaturalist, 2024) integrated with ForWarn's forest health products (ForWarn, 2022). Additionally, soil suitability metrics were assessed to determine whether recreation on sensitive soils exacerbates impacts on forest canopy health (NRCS 2023). However, the resolution limitations of ForWarn data likely affected our ability to detect small-scale recreational impacts, and we acknowledge any statistical relationships identified are confounded by other factors like forest management and natural disturbances.

Methods

Recreational use data for hiking and biking were collected from Strava and iNaturalist. NDVI deviance, used as a proxy for forest canopy health, was derived from ForWarn's satellite-based forest health assessments (see Appendix). Due to the relatively coarse resolution of ForWarn products (30 meters), detecting localized impacts from recreational activities was challenging, and we likely missed subtle vegetation changes at the sub-pixel level (Langner et al., 2021). A Welch Two Sample t-test was conducted to compare NDVI deviance in areas of recreation and general forested areas, while linear regression models assessed relationships between recreational counts, soil suitability, and NDVI deviance.

Results

Recreation impact on forest canopy health

A Welch Two Sample t-test revealed a statistically significant difference in NDVI deviance between areas of recreational use and broader forested regions ($t = -2.3991$, $df = 90{,}558$, $p = 0.01644$). Areas with recreational use exhibited lower positive NDVI deviance, which reflects slightly reduced improvements in canopy health compared to broader forested regions. This finding suggests that recreational activities may have a minor impact on forest canopy health, though the effect size was small, indicating that recreation is not a primary driver of canopy health changes. Additionally, the limitations of ForWarn data, including its coarse resolution, may obscure fine-scale disturbances, reducing the sensitivity of the analysis to localized impacts of recreational use (Langner et al., 2021).

Hiking recreation and NDVI deviance

A linear regression model showed a statistically significant relationship between hiking recreation counts and NDVI deviance (estimate = -0.00003498, $p = 3.09\text{e-}05$), indicating that of the areas with any recreation, those with more hiking had somewhat lower canopy health. The R-squared value (0.0002497) indicates that hiking explains only a tiny fraction of the variation in NDVI deviance, emphasizing the minor role recreation plays relative to other forest health drivers (Kuss, 1986).

Biking Recreation and NDVI deviance

The analysis for biking recreation revealed no significant relationship between biking counts and NDVI deviance (estimate = -0.000009975, $p = 0.594$), with the R-squared value (0.000004099) further suggesting that biking activity does not significantly affect forest canopy health. The resolution limitations of ForWarn data may obscure small-scale recreational effects, especially for localized biking impacts.

Soil suitability and NDVI deviance (hiking)

No significant relationship was found between soil suitability for recreation combined with relative hiking use[1] and NDVI deviance (estimate = -0.000008811, $p = 0.763$), indicating that hiking on unsuitable soils does not meaningfully affect

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[1] For details on how these layers were combined, see the Appendix.

forest canopy health. This finding may again be influenced by the spatial resolution of the NDVI data, which may not adequately capture subtle interactions between soil health and hiking activity.

Soil suitability and NDVI deviance (biking)

While the relationship between soil suitability for recreation combined with relative biking use[2] and NDVI deviance was statistically significant (estimate = 0.00007221, p = 0.00759), the R-squared value (0.0001025) suggests it explains very little of the variation. This weak relationship, like the others, indicates that while soil conditions might have some role in biking impact on canopy health, other environmental factors, like the presence of invasive species, temperature and moisture conditions, and others likely drive many changes in forest canopy health.

Discussion

The statistically significant differences between recreation areas and broader forested regions suggest some level of interaction between recreation and forest canopy health. However, the small effect sizes and the challenges associated with ForWarn's coarse resolution limit the ability to detect fine-scale impacts from recreational activities (Langner et al., 2021). Small-scale disturbances, such as localized canopy thinning or trail erosion, may not be adequately captured, weakening the predictive power of the relationships. The overall findings suggest that recreational activities like hiking and biking are not the primary drivers of NDVI deviance, with other factors such as climate, forest management practices, and natural disturbances likely playing a more substantial role (Kuss, 1986; Marion et al., 2016). Furthermore, areas without recreation have overall somewhat lower canopy health than those with recreation, suggesting that recreation may have a positive impact on forest canopy health, or perhaps that people choose to recreate in areas with a healthier forest canopy.

Conclusion

Recreational activities have a limited impact on forest canopy health when measured using coarse NDVI data. Although statistically significant relationships were identified, the small effect sizes and resolution limitations of ForWarn data suggest that recreational use is a weak predictor of canopy health changes. Future research should utilize higher-resolution remote sensing tools to better capture the ecological impacts of recreational use and further investigate the complex interactions between recreation, soil health, and forest dynamics.

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[2] For details on how these layers were combined, see the Appendix.

Recreation hotspots and soil suitability

Recreational activities in forested areas have expanded rapidly, and platforms like Strava offer insights into hiking and biking patterns. However, the environmental impact of these activities, especially in relation to soil health, remains a critical concern. Intensive recreation can lead to soil compaction, erosion, and vegetation degradation (Marion et al., 2016; Kuss, 1986). This study integrates Strava recreation data and iNaturalist user observations (assigned to the nearest trail) with NRCS Web Soil Survey to analyze recreation hotspots, focusing specifically on trails with permeable surfaces derived from OpenStreetMap (OSM) and limited to forested areas using NLCD 2021 data. Our goal was s to identify regions where recreation may negatively impact soil health and forest ecosystems.

Methods

We used Kernel Density Estimation (KDE – see Appendix for additional details) to map recreational hotspots within forested areas, filtering OSM trail data to include only permeable surfaces, such as footways, bridleways, and paths. This data was integrated with Strava hiking and biking and iNaturalist counts for 2022. To assess soil health risks, we incorporated NRCS Web Soil Survey data (NRCS 2023), which classifies soils based on susceptibility to erosion and compaction. Applying these data to our region highlighted the recreational soil suitability across major geological regions of the Northeast, with key distinctions along the Adirondacks, Green Mountains, White Mountains, and Appalachian Highlands (Fig. 2). The red areas, which are concentrated in parts of the Adirondack Mountains and northern Maine, suggest that these mountainous regions may have more sensitive soils that are prone to erosion or degradation from recreational use. Conversely, blue areas in the Green Mountains and White Mountains indicate more suitable soils that can sustain higher recreational activity with less environmental impact. The spatial distribution of suitability across these mountain ranges underscores the need for tailored management practices to balance recreational use with conservation. The combination of these datasets allowed us to evaluate where intensive recreation occurs on soils less capable of sustaining such activities. In addition, we created two layers to measure the difference between recreational use and soil suitability for both hiking and biking, which helped identify hotspots where usage occurs disproportionately on more vulnerable soils.

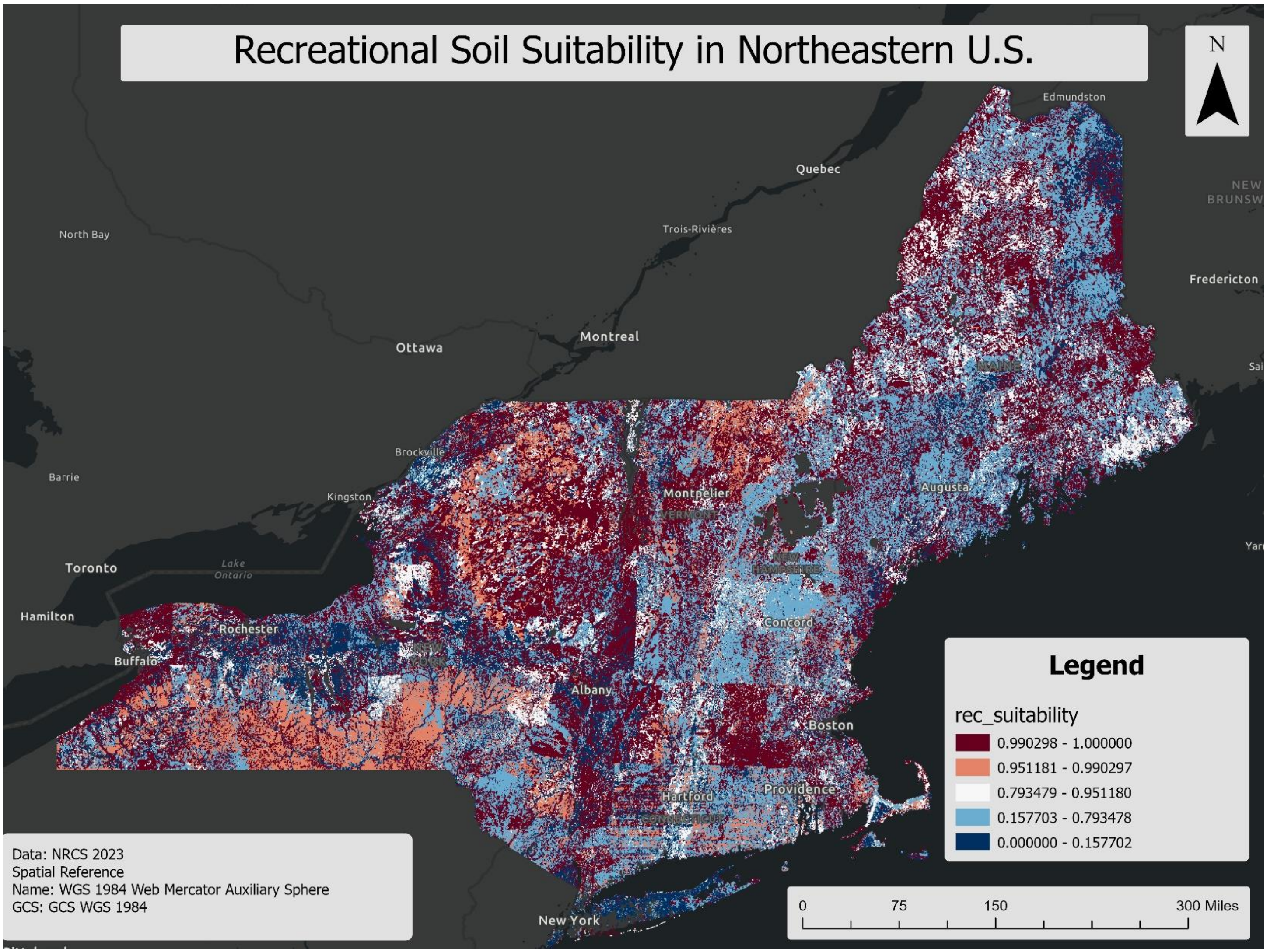

Figure 2. Recreational Soil Suitability in Northeastern U.S.

Results

Hiking hotspots on permeable surfaces

Recreation hotspots were identified in both expected and unexpected regions (Fig. 3). While Acadia National Park, the White Mountains, and the Adirondacks showed high levels of recreational use, unexpected hotspots emerged in places like Camden (ME), Minnewaska State Park (NY), and other areas in New York's Catskills. These regions demonstrate high recreational usage despite being far from major population centers. These findings highlight the regional importance of managing recreation across a range of landscapes, including those beyond traditional high-use parks.

Additionally, long trails (such as the Appalachian Trail, the Long Trail in Vermont, and others) show interesting and identifiable patterns, where certain areas are clearly more utilized than others. These differences across portions of the same trail can guide management, for example by indicating where additional signage may be needed (since the trail may not be as easy to identify as a more heavily-used trail), identifying areas that may require additional soil maintenance, and more.

As mentioned previously, the data on trail use is limited by the users of Strava and iNaturalist, and thus may be skewed toward demographics more likely to use those apps, or places where users are more likely to record activities or observations.

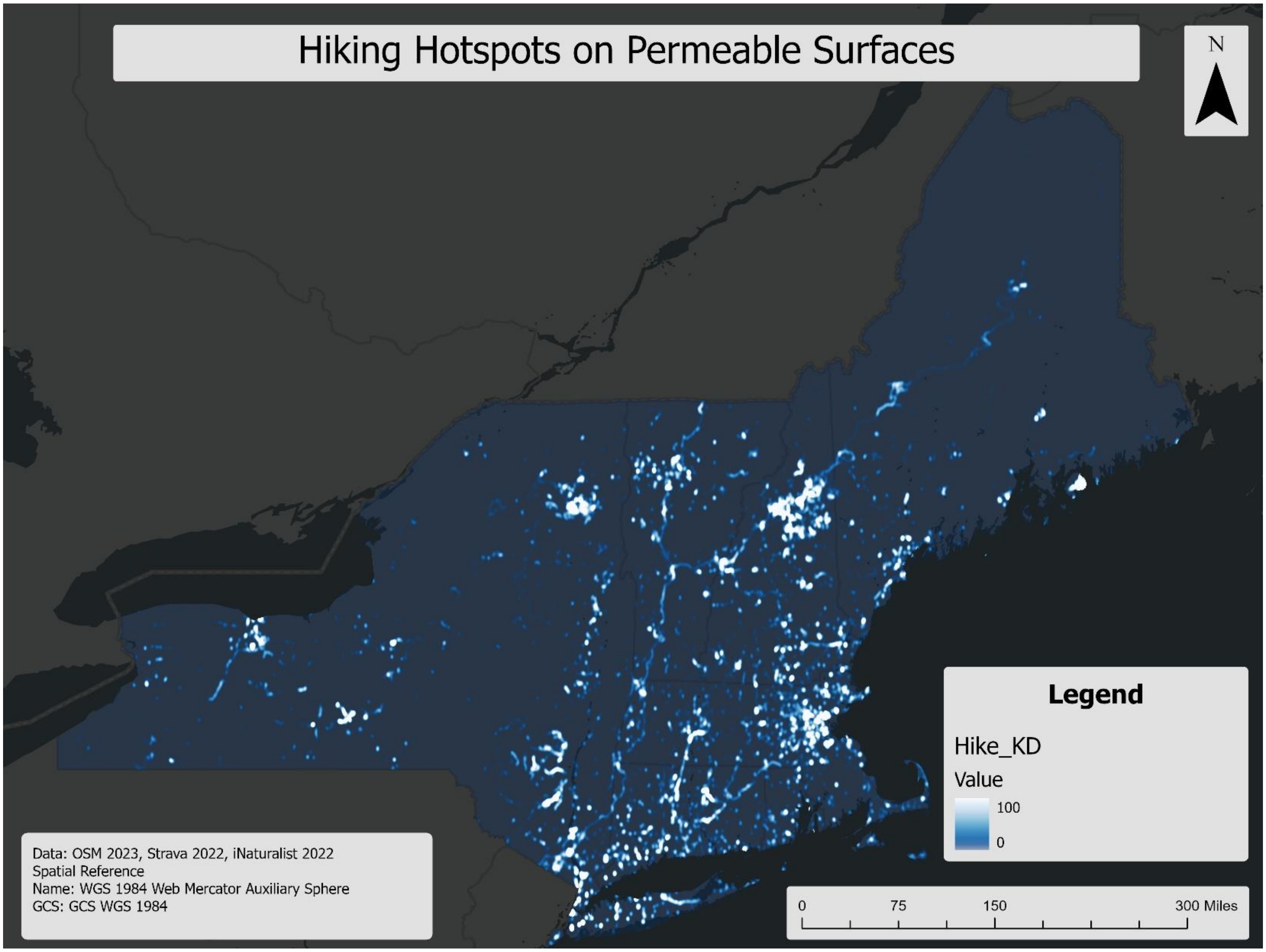

Figure 3. Hiking hotspots on permeable surfaces[3]

Population and hiking hotspots

The overlay of population density and hiking hotspots reveals areas like Bigelow (ME), Mt. Katahdin (ME), and the Adirondacks (NY), where recreational use is disproportionately high relative to local population densities (Fig. 4). This indicates that these regions attract significant visitation from outside local areas.

Mountain biking hotspots

The biking hotspots map (Fig. 5) shows concentrated use in both well-known and unexpected locations. Acadia National Park (ME) and the Carrabassett Valley (ME) are prominent, especially near Sugarloaf Mountain, where biking is popular. Additional hotspots include the Empire State Trail in New York and Kingdom Trails in Vermont. These patterns underscore the importance of both long-distance trails and regional biking destinations.

It is also apparent when comparing hiking (Fig. 3) and biking (Fig. 5) that there are differing spatial patterns; hiking activities spread across larger areas, while biking tends to occur in denser trail networks. The different uses of forest

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[3] Color symbology in map is by standard deviation; changing scale to min-max results in greater regional identification, but less definition able to be picked up in report maps.

space may be important to consider when assessing the ecological impacts of these different recreational activities and identifying potential mitigation strategies.

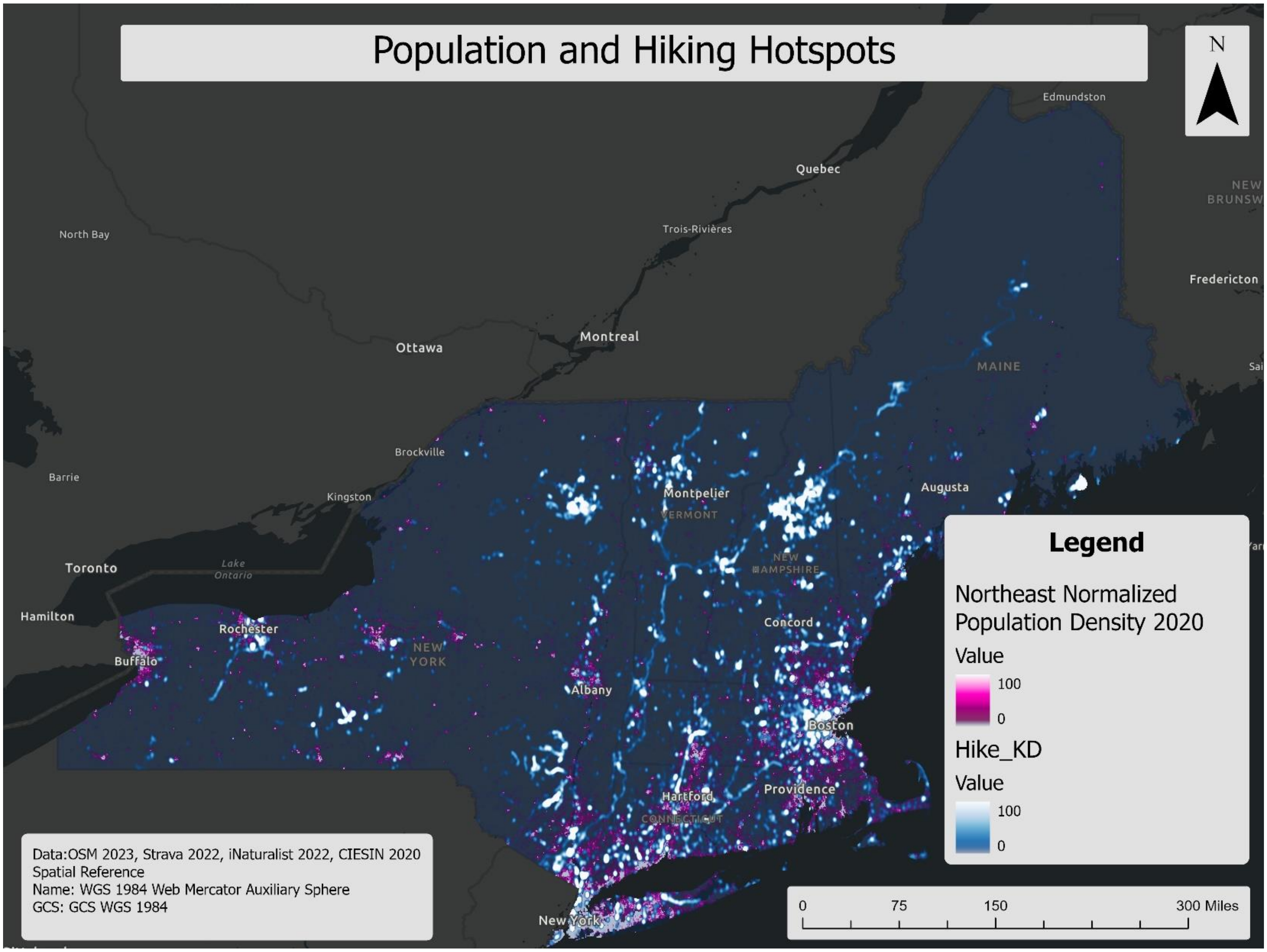


Figure 4. Population and hiking hotspots

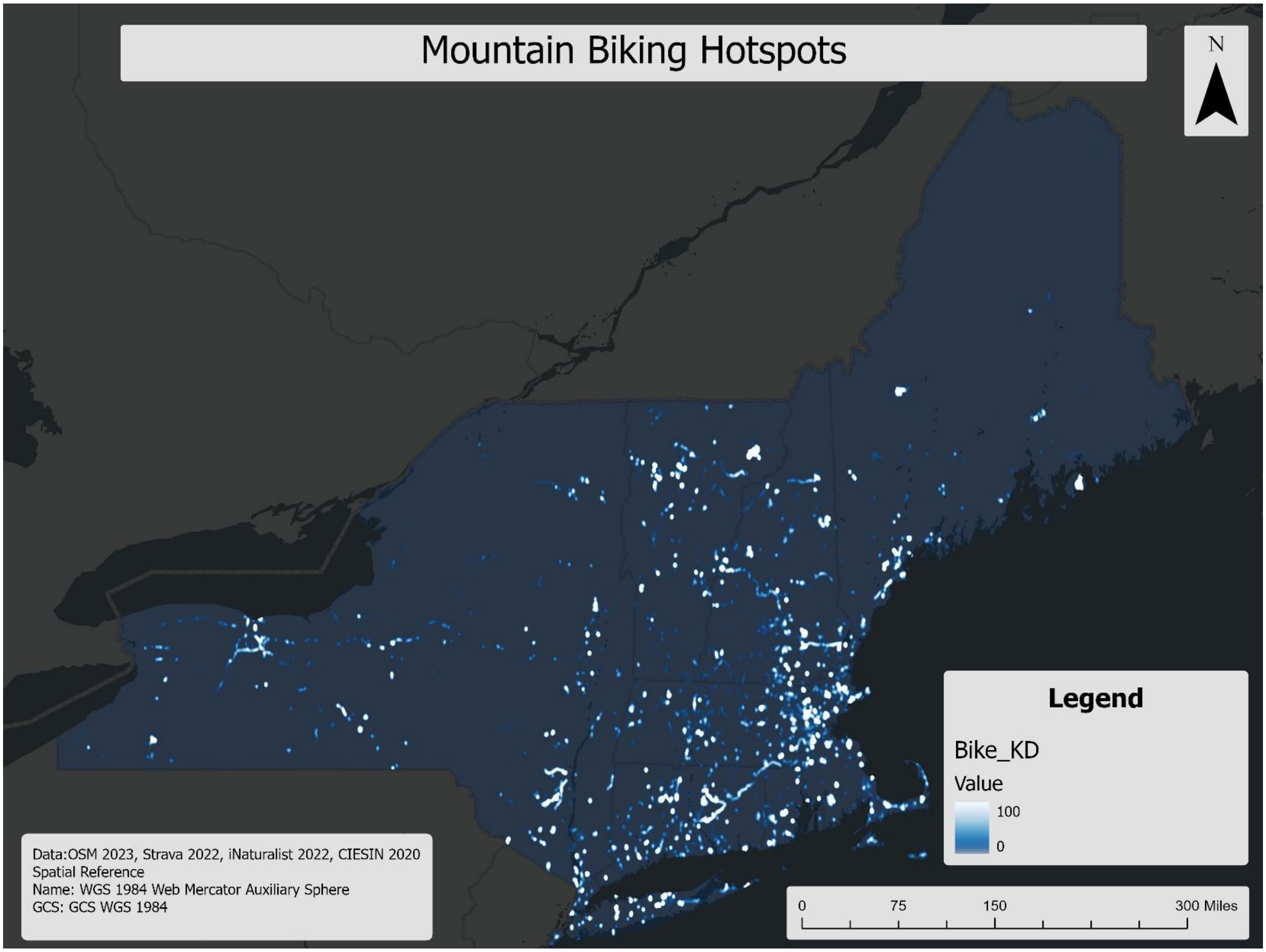


Figure 5. Mountain biking hotspots

Biking and hiking soil degradation difference maps

Figures 6 and 7 identify areas where recreation occurs on soils with low suitability. For biking (Fig. 6), we find concentrated high-use areas in places like Long Island (specifically Coram Hamlet), Charlemont, MA, and Kingdom Trails/Burke Mountain, VT. Hiking on poor soils (Fig. 7) occurs in places such as Central Park (NY), the reservoirs near Winchester, MA, and high-traffic areas in the White Mountains (NH) and Adirondacks (NY). These maps indicate the potential for soil degradation in these regions due to concentrated recreation on unsuitable soils, and may have utility in directing soil restoration or soil impact mitigation priorities.

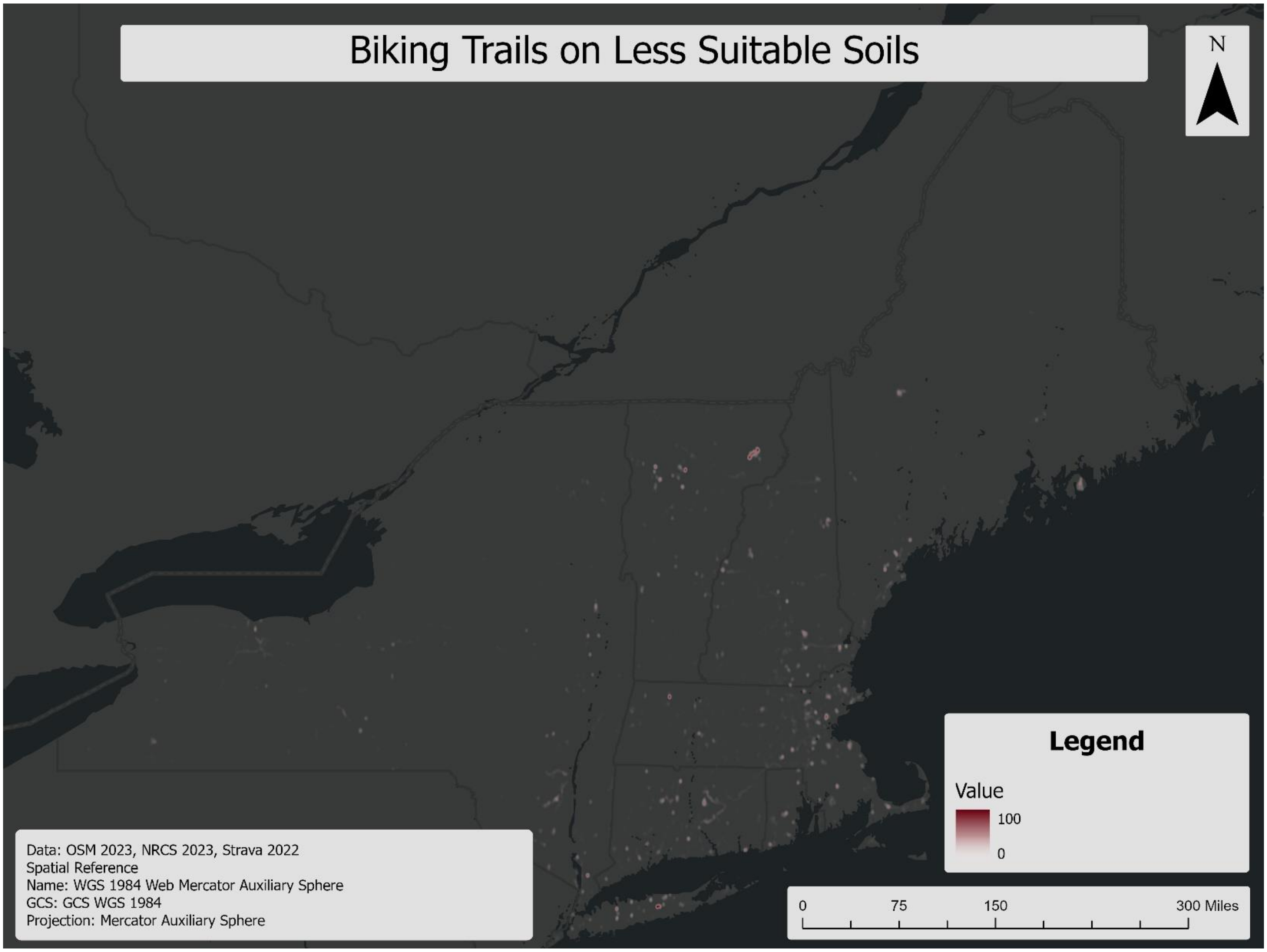
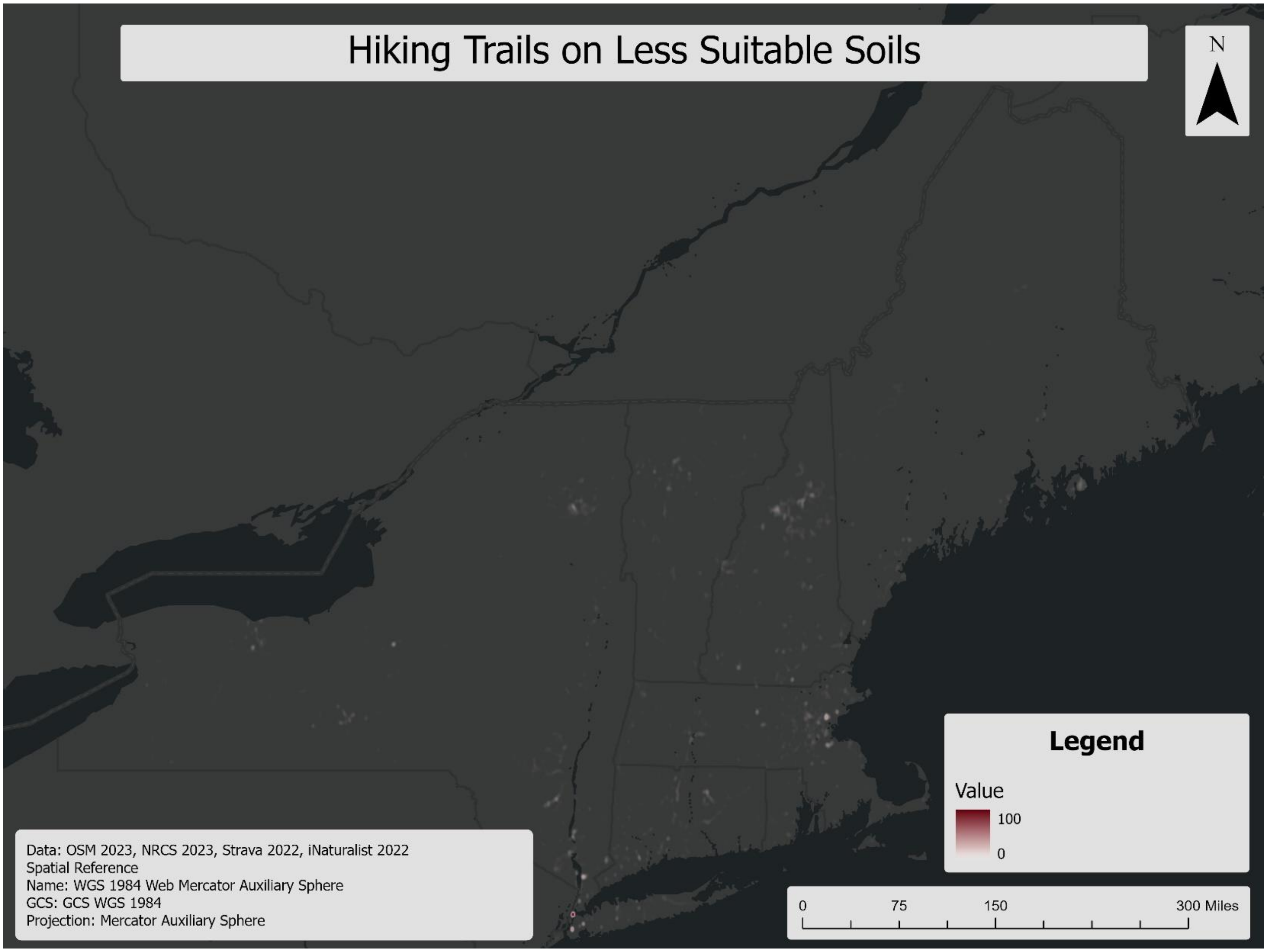


Figure 6. Hotspots of biking trails on unsuitable soils, including both heavily used and rarely used trails.

Discussion

The recreational use of permeable trail surfaces in forested areas, particularly when concentrated on unsuitable or vulnerable soils, presents challenges for forest health. When soils become compacted or eroded due to overuse, they lose their ability to support plant life, leading to vegetation loss and increased vulnerability to pests, disease, and climate-related stressors (Gossling et al., 2019; Fernandez-Juricic, 2000). Regions highlighted above are of particular concern due to their combination of high recreational use and vulnerable soils.

Targeted conservation efforts in these high-risk areas are essential to mitigate the long-term impacts of recreation on soil and forest health. Measures such as trail rerouting, restoration projects, and sustainable trail management practices should be prioritized in regions where soils are highly susceptible to degradation (Kuss, 1986; Marion et al., 2016).



Data: OSM 2023, NRCS 2023, Strava 2022, iNaturalist 2022
Spatial Reference
Name: WGS 1984 Web Mercator Auxiliary Sphere
GCS: GCS WGS 1984
Projection: Mercator Auxiliary Sphere

Figure 7. Hotspots of hiking trails on unsuitable soils, including both heavily used and rarely used trails

Conclusion

This study highlights the need for targeted interventions in areas where recreational use coincides with vulnerable soil conditions. By integrating Strava recreational data with NRCS soil suitability ratings, we provide a detailed assessment of regions at risk of soil degradation. Areas highlighted show regional importance and should be prioritized for restoration or trail management efforts to ensure long-term forest health. Adaptive trail reuse, ongoing soil monitoring, and conservation strategies are critical to balance recreational demand with sustainable environmental management.

Wildlife

We also developed several layers assessing the size of contiguous forest blocks across the region, taking into account different buffer widths from trails. Recognizing the critical role of wildlife in forest ecosystem health, our objective was to identify regions important for conservation and provide information to guide efforts to minimize recreational impact to wildlife. We adopted the New Hampshire Fish and Game Department's "Trails for People and Wildlife" guide for geospatial buffering, modifying it to fit our regional context (New Hampshire Fish and Game Department, 2019).

Methods

Using the NLCD 2021 forest layer and OSM trail data, we created three buffer layers representing different distances from trails: 60 ft, 150 ft, and 400 ft. These buffers were clipped with the NLCD forest data to assess changes in forest patch size when buffers are included. To better understand the impact of human activity on wildlife, we classified forest patches by size to provide raw data layers for future specialized analysis. These layers can be used by conservation planners for further connectivity analysis, integrating trail types into future analyses.

Patch size thresholds were based on general wildlife requirements. Small birds and mammals typically manage in patches between 10–100 acres, though smaller patches often experience edge effects that reduce habitat quality (Haddad et al., 2015). Forest-interior birds, such as the wood thrush, require 500–1,000 acres for successful breeding and population stability (Betts et al., 2008). Large mammals, including black bears and bobcats, need 5,000–10,000 acres to support foraging and dispersal (Beier & Noss, 1998).

Results

Forest patch size analysis

The forest patch size analysis across the three buffer layers (60 ft, 150 ft, and 400 ft) provides insight into how forest fragmentation changes based on proximity to trails. The total number of forest patches and their sizes were calculated for each buffer layer after excluding all patches smaller than 10 acres, ensuring the analysis focused on patches significant for wildlife habitat.

Table 1. Number of patches of each size for each assessed buffer width.

Metric	60 ft Buffer	150 ft Buffer	400 ft Buffer
Total Patches	133,328	126,858	117,124
Median Patch Size (acres)	38.05	38.31	47.41
Patches 10-100 acres	92,637	87,892	76,953
Patches 100-500 acres	26,438	25,346	27,603
Patches 500-1,000 acres	7,104	6,831	6,741
Patches 1,000+ acres	7,149	6,789	5,827
Large Patches (500+ acres)	14,253	13,620	12,568
Patches > 5,000 acres	1,045	997	707

The 400 ft buffer layer, which represents a larger buffer from trails, shows a lower total number of patches overall. However, the patches that remain are generally larger, with a median patch size of 47.41 acres, compared to around 38 acres for the 60 ft and 150 ft buffers. As expected, forest patches near trails (within the 60 ft buffer) include a higher number of smaller patches, with 92,637 patches in the 10-100 acre category.

As expected, the median patch size increases as buffer size increases; this is because smaller patches get eliminated as more of the patch "becomes" buffer. This trend highlights how forest fragmentation can differently affect different species, as some are more disturbed by trails (and thus a larger buffer size is appropriate) or require larger patches—or both—than other species.

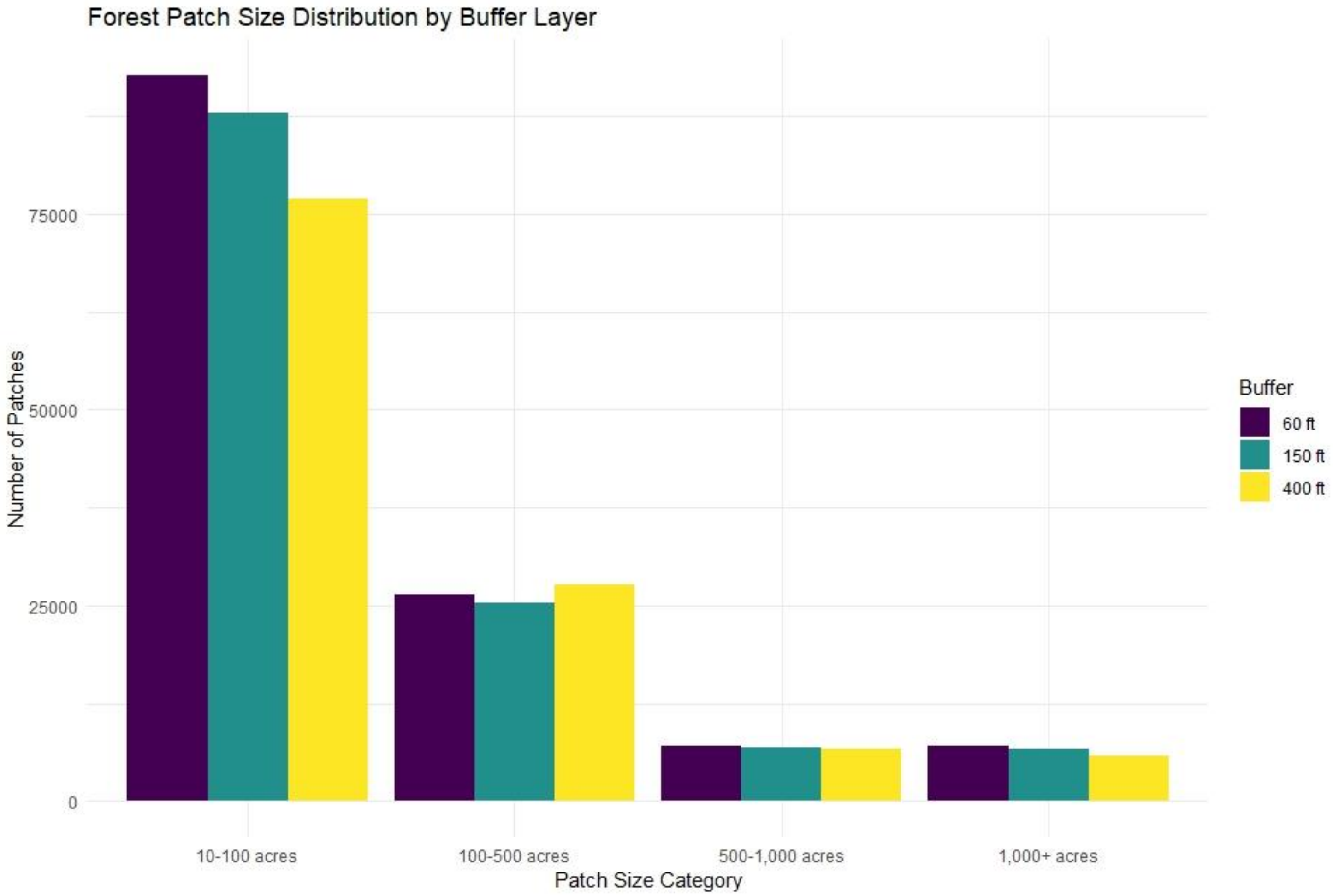


Figure 8. Forest patch size distribution by buffer layer

Spatial Patterns

In addition to patch size distribution, we mapped the spatial distribution of larger forest patches across the Northeast in Figure 10 below. These large patches serve as crucial habitats for species like black bears and bobcats, which rely on extensive, undisturbed territories (Beier & Noss, 1998). The map shows significant concentrations of large, contiguous patches in upstate New York, especially in the Adirondack Mountains, and in northern Maine, where public land ownership and low development pressure contribute to lower fragmentation. Darker green areas represent larger patches, primarily in upstate New York and northern Maine. In contrast, southern New England shows much more fragmentation, with fewer large patches. These fragmented areas likely face more pressure from development and the Wildland-Urban Interface (WUI), where human activity encroaches on natural habitats. Restoring connectivity between smaller patches in these regions could be key to improving habitat conditions for smaller, forest-interior species (Haddad et al., 2015).

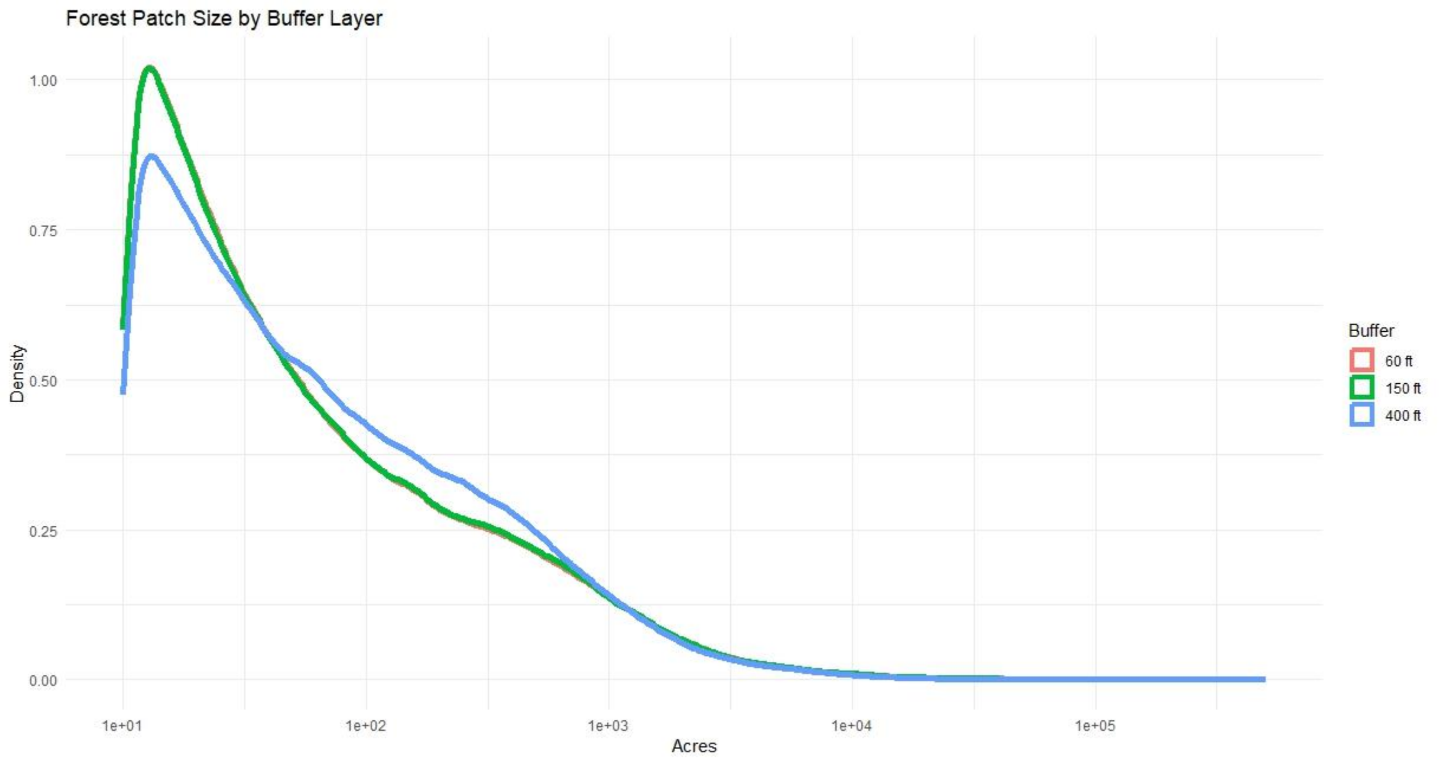


Figure 9. Forest patch size density plot. NOTE: 60ft and 150ft buffer data distributions are very similar; 60ft buffer line is "behind" 150ft buffer line.

Discussion

This analysis demonstrates that larger buffer distances from trails result in fewer but larger forest patches, which are crucial for species that require extensive, undisturbed habitats. Forest-interior species, such as the wood thrush, and large mammals, like bobcats, benefit from the remaining large patches (500+ acres), which are more prevalent in the 400 ft buffer (Betts et al., 2008). However, the number of patches larger than 5,000 acres, critical for large mammals, is significantly reduced, with only 707 such patches in the 400 ft buffer. This indicates a potential challenge in maintaining large, connected habitats for species requiring significant foraging and dispersal ranges (Beier & Noss, 1998).

The exclusion of smaller patches in the 400 ft buffer near the WUI highlights the need to focus conservation efforts on areas of fragmentation, particularly along forest edges where human development encroaches. Wildlife corridor restoration could help reconnect smaller patches in these fragmented regions (Cushman et al., 2006).

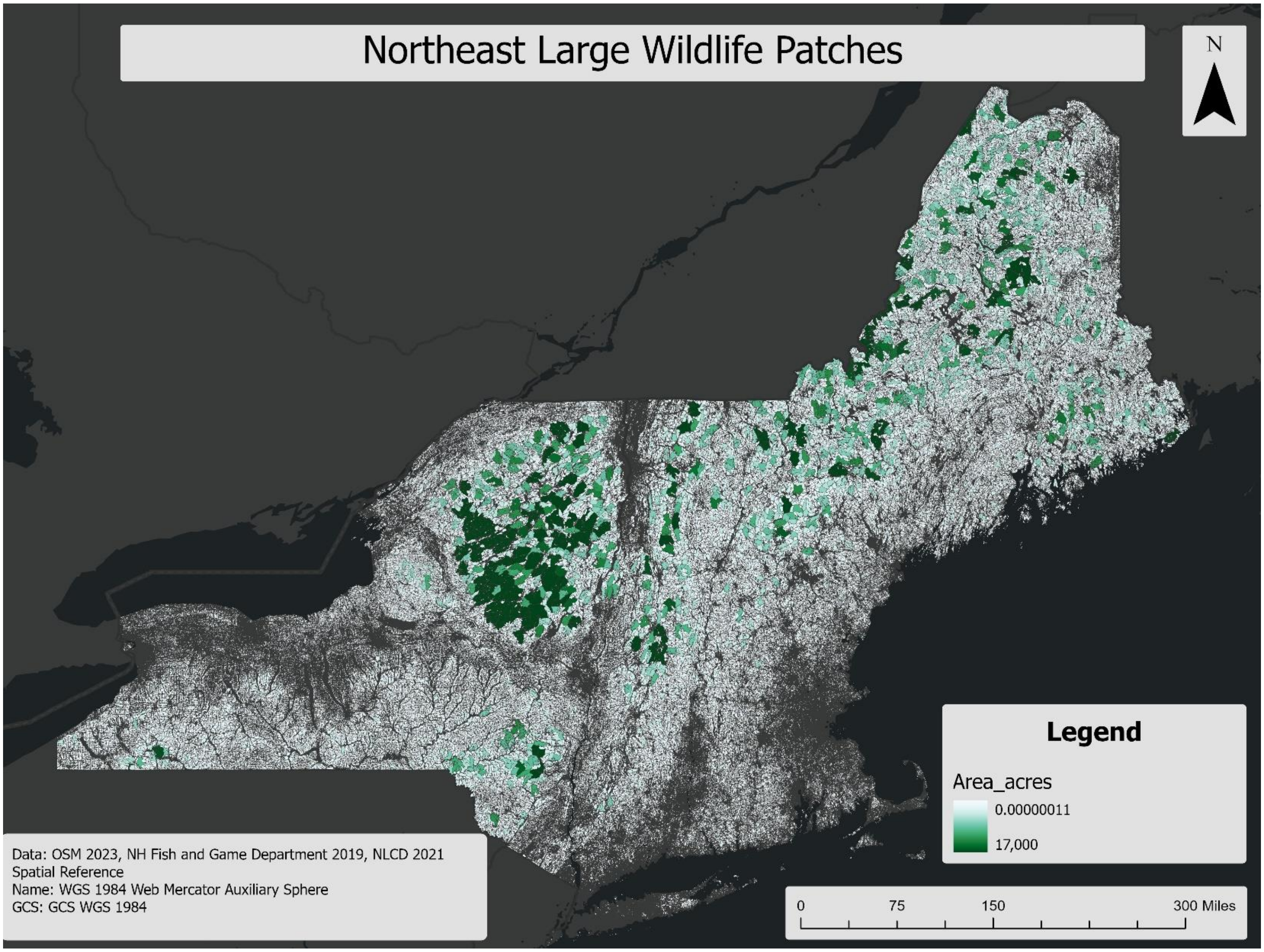


Figure 100. Northeast wildlife patches.

Conclusion

This preliminary analysis provides essential insights into forest patch dynamics in response to trail development and human recreation. The findings highlight the importance of maintaining large, contiguous forest reserves for wildlife, particularly in regions less impacted by fragmentation. Conservation strategies should also focus on restoring connectivity in fragmented landscapes, particularly in southern New England, where forest patches are smaller and more isolated. Future research should aim to integrate wildlife connectivity analysis and explore the long-term impacts of human activity on forest ecosystems, potentially employing advanced methods such as Granger causality to identify causal relationships between trail development and wildlife behavior (Beier & Noss, 1998).

Project implications and applications

The results of this project provide some insight into the relationship between recreational activities and forest health, and make available several geospatial products to support recreation management with forest health in mind. Below, we will expand on each major component of the analysis while also providing recommendations regarding how the resulting layers can be used by public and private stakeholders.

Recreation and forest canopy health

Our analysis of the relationship between recreational use (hiking and biking) and forest canopy health, measured through NDVI deviance, indicated that while there is a significant negative relationship between recreation areas and canopy health, the correlation is weak. We also found that increased hiking correlated with lower canopy health, though again the correlation was weak. The regional scale and the limitations of the ForWarn NDVI data likely explain why subtle effects of recreational use were not detected in finer detail. Additionally, various confounding factors such as forest management, natural disturbances, and climate conditions may have overshadowed the impacts of recreation. These findings align with previous literature (Kuss, 1986; Marion et al., 2016), which also found that human-induced impacts on canopy health often manifest at local scales and require higher-resolution data for more precise detection.

While the immediate impacts on forest canopy health may be limited, this study highlights the need for continuous monitoring using higher-resolution data and localized field assessments. Local assessments can account for more potentially influential variables and detect smaller-scale changes that may be washed out in regional data. One recommendation for stakeholders is to use this preliminary data to identify hotspots for further investigation and ground-truthing. More refined analyses using drone imagery or LiDAR could complement this approach, providing better spatial resolution and a more comprehensive understanding of the effects of recreational activities on canopy health.

Soil suitability and recreation hotspots

The integration of Strava recreational data along with iNaturalist observation locations (indicated iNaturalist user presence) and NRCS soil survey data allowed us to identify critical areas where recreational use overlaps with vulnerable soils. Our results indicate that certain regions, particularly the Adirondacks, Green Mountains, and White Mountains, are experiencing intense recreational use on soils with limited capacity to absorb that pressure. In these areas, trails may require additional maintenance or rerouting to avoid further degradation.

The recreation soil suitability maps (Fig. 2, along with Figs. 6 and 7) show clearly where high recreational use occurs on less suitable soils. These maps should be used by land managers to prioritize trail management and restoration efforts. The layers can also be integrated into existing decision-support systems to ensure that future trails are developed in areas with soils better suited to handle human traffic, minimizing long-term impacts on soil health and forest ecosystems.

Wildlife conservation and trail buffers

Although this project primarily focused on forest health in relation to recreational use, the wildlife analysis provided additional insights into how trail development fragments wildlife habitats. The creation of buffer layers around trails allowed us to analyze the size and distribution of undisturbed forest patches, and the resulting products can aid land managers making decisions about how and where to prioritize forest protection, trail use limitations, or other measures to minimize impacts to wildlife.

Larger forest patches, especially those exceeding 500 acres, are critical for forest-interior species like the wood thrush, as well as large mammals such as black bears and bobcats, which require patches of 5,000+ acres for foraging and dispersal (Betts et al., 2008; Beier & Noss, 1998). However, the number of such large patches was significantly reduced in the 400 ft buffer, indicating that recreational trails contribute to habitat fragmentation for these sensitive species.

The wildlife habitat patches map (Fig. 10) provides a visual guide to where these larger, undisturbed patches exist. Our products show a concentration of large, contiguous patches in regions like upstate New York and northern Maine, where public lands and low development pressure have helped maintain larger, less fragmented landscapes. These areas represent key habitats for species requiring large ranges. Conservation organizations and land managers can use these layers to focus on preserving or enhancing habitat connectivity in these and other areas. The wildlife patch layers could also inform future land acquisition or easement strategies, ensuring that critical wildlife habitats remain protected from further fragmentation.

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Appendices

NDVI magnitude of deviance from norm: A methodology for assessing forest health

The Normalized Difference Vegetation Index (NDVI) is widely utilized to assess vegetation health by monitoring changes in canopy greenness and density. By comparing 2021 NDVI values to a long-term median, such as the MEDIAN_ALL_YR product from ForWarn, we can identify deviations that signify areas of forest stress, recovery, or disturbance. NDVI deviations are particularly useful for detecting early indicators of forest canopy degradation, enabling forest managers to identify regions requiring intervention before damage becomes irreversible.

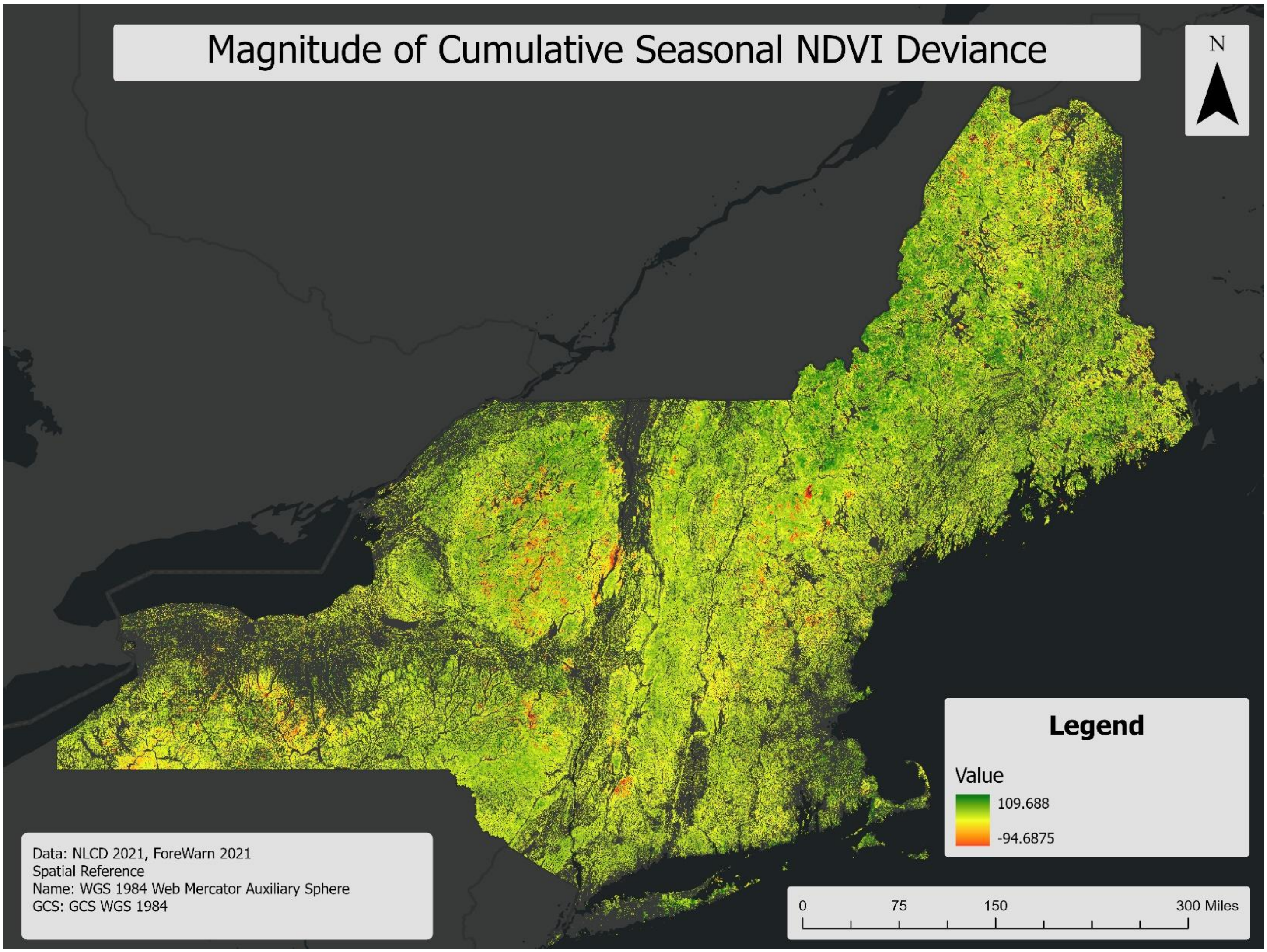

Figure 111. Magnitude of cumulative seasonal NDVI deviance

ForWarn provides MEDIAN_ALL_YR, a long-term NDVI baseline that allows deviations to be measured against historical norms. These deviations can be indicative of natural factors, such as drought or pest infestations, or anthropogenic impacts, including soil degradation or recreational overuse. Studies like Díaz-Delgado et al. have demonstrated that NDVI deviations can reveal long-term ecosystem changes caused by recurrent disturbances such as wildfires. Additionally, research by Fensholt et al. highlights how NDVI deviations over time can serve as a useful indicator of ecosystem health, particularly in relation to soil and vegetation degradation.

NDVI deviations provide insights into forest canopy health because they quantify the departure of current conditions from established norms. These deviations are valuable for detecting both acute disturbances (such as deforestation or storm damage) and chronic stressors (such as overuse from recreational activities or climate-related impacts). When forests experience prolonged stress, the canopy's ability to regenerate declines, leading to decreased biodiversity, soil erosion, and increased vulnerability to pests and disease (Hu et al., 2019). Monitoring NDVI deviations can therefore help track such trends, allowing for timely responses by land managers.

Methodology for calculating NDVI deviance

The calculation of NDVI deviance is a multi-step process that combines recent satellite data with historical NDVI baselines. Here's how the methodology works:

pctNDVIc Calculation:

$$\mathrm{pctNDVIc}(x,y) = \left(\frac{\mathrm{NDVI}_{2021}(x,y) - \mathrm{NDVI}_{\mathrm{MEDIAN\_ALL\_YR}}(x,y)}{\mathrm{NDVI}_{\mathrm{MEDIAN\_ALL\_YR}}(x,y)} \right) \times 100$$

This equation represents the percentage deviation between current NDVI and the historical median at a given point (x,y)(x,y).

Cumulative Deviance:

$$\text{Cumulative Deviance}_{\text{avg}}(x,y) = \frac{1}{n} \sum_{i=1}^{n} \mathrm{pctNDVIc}_i(x,y)$$

This formula averages the percentage deviations across all time points, helping to smooth out short-term fluctuations.

Magnitude of Deviance:

$$\text{Magnitude of Seasonal Deviance}(x,y) = \frac{\sum_{i=1}^{n} \mathrm{pctNDVIc}_i(x,y)}{\text{Cumulative Deviance}_{\text{avg}}(x,y)}$$

This final formula helps assess the overall severity of NDVI deviations, identifying significant areas of concern for forest management. For the magnitude of deviance calculation, the NDVI data was collected over a series of 24-day windows, spanning from May 8th to October 5th of 2021. This period represents the active growing season in the region, and each raster corresponds to a 24-day maximum NDVI composite. The cumulative and magnitude of deviance values were computed by analyzing the deviations in NDVI during these intervals across this growing season.

Applications for monitoring forest health

NDVI deviance can be a powerful indicator of forest canopy health when combined with other data sources, such as soil metrics, climate data, and recreational use. For example, incorporating Strava recreation data can reveal how recreational overuse impacts canopy health by leading to soil compaction and erosion. Moreover, studies like Yengoh et al. demonstrate that long-term NDVI trends are particularly useful for assessing land degradation and changes in vegetation productivity.

In practice, forest managers can use these NDVI deviance maps to pinpoint areas where interventions such as reforestation or trail rerouting might be necessary. For example, regions with large deviations from the MEDIAN_ALL_YR baseline can be identified as critical areas for conservation action, while areas showing minimal deviation may be considered stable and healthy.

Conclusion

By utilizing NDVI deviations from the ForWarn MEDIAN_ALL_YR baseline, forest managers and conservationists can monitor forest health effectively. NDVI provides valuable insight into how vegetation is responding to both natural and anthropogenic factors. Long-term NDVI monitoring, as demonstrated by studies like Fensholt et al. (2012) and Hu et al. (2019), is essential for understanding broader ecosystem changes and ensuring the sustainability of forested regions.

Calculation of soil recreational use impact

The calculation of soil recreational use impact combined recreational use intensity with soil suitability to assess areas where recreational activities might disproportionately affect soil health. To derive this measure, the recreational use data for hiking and biking, represented by use counts from Strava, was prepared as a spatial layer indicating use density along each trail segment. The soil suitability values from the NRCS Web Soil Survey were classified on a 0-1 scale, where 0 represented soils not suitable for recreational use, 0.5 represented soils somewhat limited for recreational use, and 1 represented soils not limited for recreational use.

The recreational use density layer was spatially overlaid with the soil suitability layer, aligning both datasets to the same spatial reference system. Each trail or segment in the dataset was assigned a corresponding soil suitability value based on its location. For each trail segment, the number of recreational uses was multiplied by the soil suitability value to calculate a weighted recreational use score, as given by the formula:

$$Weighted\ Recreational\ Use\ Score = Recreational\ Use\ Count \times Soil\ Suitability$$

This calculation provided an impact score that considered both the frequency of recreational activities and the soil's ability to sustain such use. The resulting weighted scores allowed for identifying areas with high recreational pressure on soils that are less suitable.

These scores were used to create kernel density rasters that identified recreational hotspots, taking soil sensitivity into account. This approach helped to highlight areas where management intervention may be required. The methodology ensured that recreational use was evaluated not just by activity level, but also in the context of soil vulnerability, providing a more nuanced understanding of potential environmental impacts.

Hotspot and kernel density estimation (KDE)

Kernel Density Estimation (KDE) formula that incorporates both the density and population can be described as follows:

$$\mathrm{KDE} = \frac{1}{nh^2} \sum_{i=1}^{n} P_i \cdot K\left(\frac{d(x, x_i)}{h}\right)$$

Where:

- *N = Total number of features (trail segments)*
- *h= Bandwidth (search radius)*
- *Pi = Population field value for the iii-th feature (number of recreational uses in 2022)*
- *K = Kernel function, typically a Gaussian function*
- *d(x,xi) = Distance between the point xxx and the iii-th feature*
- *nh^2= Normalizing factor to ensure the density is properly scaled*

This formula adjusts the density calculation by weighting each feature by its associated recreational use value, which in your case is the number of recreational uses recorded in 2022. The result is a more accurate representation of the intensity of use across the region.

KDE as a tool for hotspot detection

While KDE is traditionally a density estimation technique, it is often employed for hotspot analysis in various fields. KDE was used in Taiwan to map soil pollution hotspots. By applying KDE to spatial data, researchers were able to identify regions with heavy metal contamination, revealing strong spatial correlations with industrial activity (Yang et al., 2020). KDE has also been applied to crash data to identify traffic accident hotspots in urban environments. In studies like the one conducted by Li et al. (2020), KDE was used to analyze crash data in Hennepin County, Minnesota, demonstrating its effectiveness in spatial analysis of critical areas. These applications demonstrate that KDE, while not technically a hotspot detection tool, can effectively highlight areas of high intensity or use, making it applicable in a wide range of spatial analyses.

Why KDE works for recreational studies

In the context of recreational trail use, KDE offers a detailed visualization of trail utilization patterns. By smoothing the data over space, KDE identifies regions with the highest concentration of users, which can be interpreted as recreational hotspots. This method helps pinpoint trails that may be under significant stress due to heavy usage, aiding in trail management and conservation efforts. KDE is particularly useful in this scenario because it provides a continuous surface rather than discrete points, giving a more nuanced view of spatial usage patterns.

Conclusion

KDE has proven effective in a range of spatial analyses, from environmental pollution mapping to traffic accident studies. In the case of recreational trail analysis, KDE provides a clear view of high-use areas, helping land managers prioritize regions for trail maintenance, rerouting, or habitat conservation. Future applications of KDE, in combination with other geostatistical methods, can further enhance our understanding of spatial patterns in recreational use.

Using iNaturalist data to Complement Recreational Trail Analysis

In an effort to diversify the sample of trail users and provide a broader understanding of trail use across the region, we integrated iNaturalist observation data with OpenStreetMap (OSM) line features. This addition aimed to capture a wider spectrum of users, addressing the assumption that Strava data represents a specific subset of recreationists, potentially biased toward fitness-oriented individuals. By including iNaturalist data, which represents a broader range of outdoor enthusiasts—such as wildlife observers and casual hikers—we sought to obtain a more diverse population for analyzing trail use.

Methodology for using iNaturalist data

iNaturalist observation points were linked to the nearest OSM trail features using a Euclidean distance approach. This allowed us to assign each observation point to the closest recorded trail. The primary assumption in this method is that while we cannot know the exact path the observer took to arrive at the location, we assume they accessed it via the nearest trail, a reasonable approach in natural areas with established trail networks.

The iNaturalist observation points were collected and georeferenced. Each point represents an individual observation of species or natural elements by users of the iNaturalist platform. For each observation point, we calculated the Euclidean distance to all OSM line features representing trails. The observation point was then assigned to the nearest trail based on this distance. This method assumes that the closest trail is the one most likely used by the observer to access the area. Once assigned to the nearest trail, the tally of iNaturalist trail uses was incremented. The result was a layer that included Strava data for fitness users and iNaturalist data for general outdoor enthusiasts, adding a new dimension to trail use analysis. The aim was to capture a more comprehensive picture of recreational patterns across different user groups.

Assumption and equation for tallying iNaturalist use

The assumption underlying this approach is that iNaturalist users likely accessed the nearest trail in the network, even though their exact route cannot be known. This assumption is reasonable in areas with extensive trail systems where most access points are well-defined. However, we acknowledge that this may introduce a small margin of error, particularly in densely forested or remote areas where unofficial paths may exist.

The process of adding each iNaturalist use to the closest trail segment is described by the following equation:

$$T_{\mathrm{OSM}}(x,y) = T_{\mathrm{OSM}}(x,y) + \sum_{i=1}^{n} 1_{d(x_i,y_i)=\mathrm{min}d(x,y)}$$

Where:

- $T_{\mathrm{OSM}}(x,y)$ is the tally of trail uses for the OSM line feature at location (x,y).
- x_i, y_i represents the location of the iNaturalist observation point.
- $d(x,y)$ is the Euclidean distance between the iNaturalist point and the OSM trail feature.
- $\mathrm{min}d(x,y)$ indicates that the point is assigned to the trail with the shortest distance.

This method results in a cumulative tally of both Strava and iNaturalist users for each trail, offering a more diverse understanding of trail usage.

Why iNaturalist data were included

The decision to integrate iNaturalist data into the trail analysis stemmed from the recognition that Strava users likely represent a specific demographic—typically focused on fitness, such as runners and cyclists. To capture a broader range of outdoor activities, iNaturalist was included because its users are often engaged in wildlife observation, photography, and nature-based tourism. This allowed us to diversify the trail use dataset, providing insights into how different populations utilize the trail network.

By combining Strava's active users with iNaturalist's more general outdoor enthusiasts, we were able to paint a more comprehensive picture of trail use, highlighting areas that may be more popular with casual hikers or nature observers. This helps land managers better understand how different user groups interact with trails and informs more holistic land management and conservation efforts.

NRCS soils metadata summary

The URB/REC - Paths and Trails soil interpretation focuses on guiding users in evaluating soil suitability for recreational development, specifically for paths and trails. The interpretation considers various soil properties and qualities that impact trafficability and erodibility, essential for the performance of paths and trails after development. However, it is important to note that these ratings are based on the present condition of soils and do not account for factors such as land use, location, accessibility, scenic quality, or water access.

Soils are classified into interpretive rating classes—limited, somewhat limited, or not limited—based on factors like water erosion, organic matter content, flooding, stoniness, depth to permafrost, and other criteria. Each soil property is assessed against restrictive limits to determine its impact on the interpretive rating. For instance, limitations related to water erosion consider factors such as the erosion factor and slope, while limitations related to flooding consider the frequency and duration of flooding events.

Additionally, soil properties like organic matter content, stoniness, and others are evaluated for their impact on recreational use. The interpretation provides specific criteria and limits for each property to classify soils into the appropriate rating class.

The soil interpretation emphasizes factors influencing the ease of developing paths and trails, including the ability of the soil surface to absorb rainfall, remain firm under foot traffic, and resist dustiness. While these criteria are applicable nationally, the document acknowledges the need for onsite evaluation, especially in sparsely populated regions with lower-intensity soil surveys.

Table 2. Soil components that inform the NRCS URB/REC - Paths and Trails suitability layer

Factor	Limiting	Somewhat Limiting	Not Limiting	Not Rated
Slope: Trail establishment and ability to support multiple recreation uses	Slope is ≥ 25%	Slope is > 15% and < 25%	Slope is ≤ 15%	Slope is Null
Water Erosion from Slope	Slope is ≥ 8%		Slope is < 8%	Slope is Null
Water Erosion by Erosion Factor	Erosion factor (first non-organic layer) is ≥ 0.35		Erosion factor (first non-organic layer) is < 0.35 or Null	
Ponding Duration	Ponding duration is very brief, brief, long, or very long		Ponding duration is Null, or is not very brief, brief, long, or very long	
Ponding Frequency	Ponding frequency is none		Ponding frequency is Null or not none	
Flooding Frequency	Flooding frequency is Null	Flooding frequency (maximum duration) is frequent or very frequent	Flooding frequency (maximum duration) is none, very rare, rare, or occasional	
Depth to Saturated Zone	Minimum high water table depth is ≤ 30cm	Minimum high water table depth > 30 to < 60cm	Minimum high water table depth is ≥ 60cm or Null	
Organic Matter: Soil strength and reclamation ability	Surface layer organic matter thickness is > 25cm, and unified thickest layer (25 - 180cm) is "pt" or highly organic		Surface layer organic matter thickness is ≤ 25cm, and unified thickest layer (25 - 180cm) is not "pt" or highly organic	Unified class is Null
Clay: Water absorption, soil compaction, excessive mud	Surface layer clay percentage is > 40%	Surface layer clay percentage is > 40% and in Oxisols order, suborders OXI, ARID, TOR, UST, or XER suborders, or TOR,	Surface layer clay percentage is ≤ 40%, or taxonomic classes are Null	Surface layer clay percentage is Null

		UST, or XER great groups		
Clay: Blowing sand, ability to revegetate, and ability to support multiple recreation uses	Surface layer clay percentage is < 15cm		Surface layer clay percentage is ≥ 15cm or is Null	
Sand: Blowing sand, ability to revegetate, and ability to support multiple recreation uses	Sand (0.075 - 4.75mm) percentage is ≤ 70	Sand (0.075 - 4.75mm) percentage is > 70 and < 90	Sand (0.075 - 4.75mm) percentage is ≥ 90, or percentage is Null	
Sand: Impact of dust on human health and aesthetics	Sand percent weighted average (0 - 50cm depth or above restriction, no organic layer) is ≥ 70%	Sand percent weighted average (0 - 50cm depth or above restriction, no organic layer) is > 20% and < 70%	Sand percent weighted average (0 - 50cm depth or above restriction, no organic layer) is ≤ 20%	
Gypson: Impact of dust on human health and aesthetics	Gypsum percent weighted average (0 - 50cm depth or above restriction, no organic layer) is ≥ 15%	Gypsum percent weighted average (0 - 50cm depth or above restriction, no organic layer) is > 2% and < 15%	Gypsum percent weighted average (0 - 50cm depth or above restriction, no organic layer) is ≤ 2%	
Dryness Index: Impact of dust on human health and aesthetics; (mean annual air temp)/(mean annual precip)*100	Dryness Index ≥ 5	Dryness Index > 0.3 and < 5	Dryness Index ≤ 0.3	
Stoniness: Trafficability	Surface fragments (2 - 75mm) percent are > 65%		Surface fragments (2 - 75mm) percent are ≤ 65%	Surface fragments (2 - 75mm) percent is Null
Stoniness: Nuisance and trail establishment or maintenance	Surface fragments (> 75mm) percent by weight is > 75%, or surface fragments (≥ 250mm) coverage is > 3%	Surface fragments (> 75mm) percent by weight is ≤ 75%, or surface fragments (≥ 250mm) coverage is ≥ 0.1% and ≤ 3%	Surface fragments (> 75mm) percent by weight is < 25%, or surface fragments (≥ 250mm) coverage is < 0.1%	Surface fragments (> 75mm) percent or surface fragments (≥ 250mm) coverage is Null