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Vulnerability of wilderness areas to day-use visits

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Summary

Protected areas worldwide are impacted by human activities within their boundaries. Despite having the highest level of protection in the US, wilderness areas are still vulnerable to ecological impacts. We compiled population, population growth rate, median travel time, wilderness size, wilderness proximity, relative accessibility, trail density and an amenity index to generate a Day-Use Vulnerability Index (DUVI) for 722 wilderness areas in the continuous US (CONUS). Using DUVI, we found that the Mount Timpanogos wilderness area in Utah, the Glacier View wilderness area in Washington, the J.N. Ding Darling wilderness area in Florida, the Philip Burton wilderness area in California and the Birkhead Mountains wilderness area in North Carolina were most likely to have ecological impacts from high day-use. Our findings provide a system for evaluating daily use of wilderness areas that could be paired with visitor counts in the future to improve predictions. Growing human populations and recreation are worldwide issues, suggesting that this framework could also be of interest to stakeholders outside the CONUS.

Introduction

Human populations and settlements continue to grow worldwide while the number of places largely free from human disturbance continue to decline, threatening ecosystem services, biodiversity and natural ecological processes (Foley et al. 2005, Watson et al. 2016, Di Marco et al. 2019). Designated protected areas aim to preserve these ecological benefits, yet protected areas are not invulnerable to human disturbance (Hansen & Defries 2007, Jones et al. 2018, Belote & Wilson 2020). Therefore, it is important to monitor threats to protected areas in order to identify vulnerabilities and implement strategic management actions.

In the US, wilderness areas have a higher level of protection from human activity than any other protected areas (e.g., national parks, wildlife refuges), making them particularly important for preserving biodiversity and natural ecological processes (Dietz et al. 2015, Dietz et al. 2023). Yet, the ecological integrity of wilderness areas can be impacted by surrounding land use and by daily visitors (Martinuzzi et al. 2015, Marion et al. 2016, Aycrigg et al. 2022a). Recreation in wilderness areas presents a challenge because, despite a few wilderness areas being closed to the public, the ability to visit wilderness areas is a key mandate of The Wilderness Act (US Public Law 88-577; Stankey et al. 1985). The Wilderness Act also requires wilderness areas to be untrammelled, natural, undeveloped and have solitude or a primitive and unconfined type of recreation (Landres et al. 2008, Marion 2016). Recreation can have direct impacts on the natural and untrammelled state of wilderness areas through loss of vegetation and soil erosion, degradation of water quality, disturbance to wildlife and proliferation of garbage and human waste (Marion 2016, Marion et al. 2016, Eagleston & Marion 2017, Lindley et al. 2018). Adding further complications to this, wilderness visitation also has notable benefits because visitors gain appreciation for wilderness preservation (Watson et al. 2015, Racsh & Hahn 2018, Miller et al. 2022) and make significant economic contributions to local communities (Bowker et al. 2014, Holmes et al. 2016, Hjerpe 2018). Thus, monitoring vulnerability to overuse, wherein visitation significantly degrades the natural ecological processes being protected, is a key element in finding a balance between untrammelled wilderness and unconfined recreation (Stankey et al. 1985, Landres et al. 2008, Marion 2016).

Wilderness areas face unequal vulnerability to impacts from recreation because factors influencing overuse include nearby population growth and accessibility, which together increase the likelihood of visitation (Lindley et al. 2018, Rasch & Hahn 2018, Bowker et al. 2022). Between 2010 and 2014, 85.6% of visits to wilderness areas managed by the US Department of Agriculture (USDA) Forest Service were <12 h in duration, 75.9% were <6 h duration and 72.1% of visitors travelled <200 miles one-way (Bowker et al. 2022). This highlights the significance of day-use visitors in terms of both the proportional impacts associated with these visits and the value of understanding nearby populations as an indicator of wilderness area vulnerability to overuse.

Another factor influencing overuse is the appeal of the specific wilderness area, with some wilderness areas being more aesthetically pleasing because of landscape and vegetation characteristics or more popular due to their association with other popular natural attractions, such as national parks (Hanink & White 1999, Sonter et al. 2016). The appeal of a wilderness area may increase the number of visitors travelling further and spending multiple days, as well as influencing people to move closer to wilderness areas, thereby creating more potential day-use visitors (Radeloff et al. 2010, Holmes et al. 2016, Mockrin et al. 2018). The number of trails can also be an appeal of certain wilderness areas and has been shown to increase day-use visits (Bowker et al. 2022).

Previous studies have quantified wilderness visitation and examined the relationships with surrounding populations (e.g., Lindley et al. 2018, Rasch & Hahn 2018, Bowker et al. 2022), but these studies tend to focus on a subset of wilderness areas based on location or managing agency (e.g., Bureau of Land Management; Rice et al. 2021). In this study, we developed the Day-Use Vulnerability Index (DUVI) for 722 wilderness areas in the contiguous US (CONUS) using eight variables influencing day-use visitation and the potential for visitation to result in overuse. We present the wilderness areas most vulnerable to impacts from day-use visitation based on our index. We also compare the mean DUVI values with visitation estimates from the USDA Forest Service to validate our results.

Materials and methods

Study description

Given data availability, we chose to focus our study on wilderness areas in the CONUS. Furthermore, our focus on wilderness visitation limited our study to wilderness areas accessible to the public. We used the US roads network to determine the accessibility of each wilderness area and we estimated travel time from any given populated census block to the wilderness area boundary. Most wilderness visits are day-uses (75.9% are visits <6 h; Bowker et al. 2022). Therefore, we focused our analysis on human population changes within 2 h of wilderness areas (i.e., a 4-h round trip), as this reflects a reasonable amount of time for someone to travel to, recreate and return from a wilderness area in a single day.

In developing the DUVI, we evaluated variables likely to increase day-use visits or factors likely to increase the impacts of those visits, including human population in 2020 and population growth rate during 1990–2020, median travel time, wilderness size, wilderness proximity, relative accessibility, trail density and amenities (Table 1). We checked for correlation between our variables, ensuring none had a Pearson's r greater than 0.5.

Data

We gathered spatial data for 752 wilderness areas in the CONUS from Wilderness Connect (www.wilderness.net; accessed August 2022). Thirty wilderness areas were not accessible, being islands or >1 km from the road network, bringing the total number of wilderness areas included in our analysis to 722.

To build our road network buffer around each wilderness area, we downloaded 2020 road data for the CONUS (US Census Bureau 2020). We used the 'tigris' *R* package (https://CRAN.R-project.org/package=tigris) to automate downloads for all 3110 counties in the CONUS.

We obtained population data at the census block level for 1990 and 2020 from the University of Wisconsin–Madison SILVIS lab (Radeloff et al. 2022). Because census blocks change over time and due to differential privacy techniques implemented by the US Census Bureau, 1990 and 2020 census blocks cannot be compared directly; however, the error is minimized when census blocks are aggregated (D. Helmers, personal communication 2022).

We acquired line data for recreation trails across the CONUS from the US Geological Survey (USGS) National Geospatial Technical Operations Center (USGS 2023). These data were spatially intersected with the 722 wilderness areas included in our study.

To assess amenities, we used an index developed by McGranahan (1999) used in another recent study (Mockrin et al. 2022), which combines favourable summer climate, winter climate, availability of water and topographic variation to produce county-level amenity scores. We intersected wilderness areas in our study with the amenity index using the area-weighted average if a wilderness area fell into more than one county.

To validate our results, National Visitor Use Monitoring (NVUM) wilderness visitation estimates were downloaded for each USDA Forest Service region (https://apps.fs.usda.gov/nvum/results/R01-R02-R03-R04-R05-R06-R08-R09-R10.aspx/FY2019; accessed July 2023). We used estimates collected between 2015 and 2019, which were the most recent surveys with data for all regions (Table S1). Estimates for individual wilderness areas were not available.

Data analysis

First, we estimated travel time along the road network to any given census block from each wilderness area. We converted the road lines data for each county into a 1–km raster with attributes for the major road types (i.e., primary, secondary or local) used to estimate travel resistance along the surface. While speed limits vary by state and region, we calculated an average speed of 112.7 km/h for primary roads (interstate) and 104.6 km/h for secondary roads (highway) based on 2015 state-by-state data from the US Bureau of Transportation Statistics (www.bts.gov; accessed December 2020). We assumed an average speed on local roads of 56.3 km/h, which is half the speed of primary roads. Using these average speed limits, we produced a cost raster with resistance values of 1 for primary roads, 1.08 for secondary roads and 2 for local roads. These values were calculated by scaling the speed on secondary and local roads to the speed on primary roads (i.e., primary road travel is 1.08 times faster than secondary road travel and two times faster than local road travel).

Second, we buffered each wilderness boundary by 1 km to achieve intersections with the road network, with this also representing a reasonably short walking distance for a visitor to travel on foot from the road into wilderness. We used the buffered wilderness boundaries and the cost raster as inputs for the Distance Allocation tool in *ArcGIS Pro* (version 2.6.0; ESRI, Inc., Redlands, CA, USA). The Distance Allocation tool generated a cost-weighted distance raster (in metres) for each wilderness area, which we converted into hours by multiplying the raster value by the primary road rate of travel in metres per hour (Fig. 1).

Table 1. Description of variables used to calculate the Day-Use Vulnerability Index (DUVI) and hypothesized impact of each variable on wilderness areas.

Variable	Description	Hypothesized impact	Source(s)
Population (2020)	Number of people in 2020 living within 2 h of a given wilderness area	Wilderness areas with large populations within 2 h have more potential day-use visitors	Radeloff et al. (2022); US Census Bureau (2020); www.wilderness.net
Population growth rate (1990–2020)	Change in the number of people living within 2 h from 1990 to 2020 relative to 1990 for a given wilderness area	Wilderness areas with high population growth rates within 2 h may face challenges adapting to rapid increases in day-use visits	Radeloff et al. (2022); US Census Bureau (2020); www.wilderness.net
Median travel time	Median distance (in hours) of the population (2020) within 2 h of a given wilderness area	Wilderness areas with shorter median travel times may have more day-use visitors due to shorter travel times	Radeloff et al. (2022); US Census Bureau (2020); www.wilderness.net
Wilderness size	Area (in km^2) of a given wilderness area	Smaller wilderness areas may have more concentrated day-use visitors	www.wilderness.net
Wilderness proximity	Number of other wilderness areas within 2 h of a given wilderness area	Wilderness areas with fewer other wilderness areas within 2 h may have more concentrated day-use visitors because there are fewer other wilderness options nearby	US Census Bureau (2020); www.wilderness.net
Relative accessibility	The ratio of roads within 1 km of a given wilderness area's boundary to the size of the wilderness area	Wilderness areas with higher relative accessibility scores have more potential points of entry relative to their size, increasing potential for day-use visits because of greater accessibility	US Census Bureau (2020); www.wilderness.net
Trail density	The ratio of the total length of trails in a given wilderness area to the size of the wilderness area	Wilderness areas with higher trail density may be more appealing for day-use visits and have greater impacts relative to the wilderness area's size	USGS (2023); www.wilderness.net
Amenity index	Index of potential visitor appeal for a given wilderness area based on desirable climate and topography	Wilderness areas with a higher amenity index may be more appealing for day-use visits	McGranahan (1999); www.wilderness.net

Third, to define an area around each individual wilderness area where day-use visitors are most likely to originate, we selected pixels with a value ≤2 (i.e., within 2 h) and transformed those pixels into polygons representing 2-h buffers around each wilderness area. We intersected the population data from census blocks with the 2-h buffers to summarize population characteristics within 2 h of each wilderness area. This area was also used to determine wilderness proximity by intersecting each wilderness area with other wilderness areas within 2 h.

Lastly, for each variable related to day-use impacts (i.e., population in 2020, population growth rate during 1990–2020, median travel time, wilderness size, wilderness proximity, relative accessibility, trail density and amenity index) we binned the raw values into deciles such that wilderness areas were ranked 1–10 for each variable (e.g., a raw value >90th percentile for each variable was given a decile value of 10, <10th percentile was given a decile value of 1). The decile values were summed across the eight variables to determine wilderness areas with the highest overall impacts. To create the DUVI (1–10), we rescaled the summed values for the minimum value to equal 1 and maximum value to equal 10. Wilderness areas with a lower DUVI are less vulnerable to the aggregate of day-use impacts (see Table 1) compared to wilderness areas with a higher DUVI, which are more vulnerable.

Validation

To compare the DUVI with NVUM visitor count estimates, we selected wilderness areas in our study managed by the Forest Service (n = 423) and computed the mean DUVI for each Forest Service region (Table S1). We then compared the values with visitor count estimates using linear regression. There are some notable caveats to this validation, such as uncertainty in the NVUM count estimates, inclusion of all visitors (not just day-use) in the NVUM estimates, the aggregation of DUVI values to regional levels and the addition of variables in the DUVI meant to represent vulnerability to overuse (e.g., wilderness size) and not just an increase in visitor numbers. Despite these concerns, the NVUM represents the best available data for comparison with our results.

Results

Approximately 72% of the land area of the CONUS is within 2 h of any of the 722 wilderness areas we examined (Fig. 1). In 1990, 74.4% of the population (183.8 million people) in the CONUS was living within 2 h of any of the 722 wilderness areas, increasing to 75.6% (246.5 million people) in 2020. The population growth rate between 1990 and 2020 (i.e., relative to 1990) was higher within 2 h of any of the 722 wilderness areas (34.1%) than outside 2 h (26.0%).

Wilderness areas with the highest vulnerability (i.e., decile value of 10) differed by variable (Fig. 2). For instance, the amenity index was higher on average (5.5 vs 3.7) for wilderness areas in the western CONUS (i.e., west of 100° longitude; Fig. 2), whereas wilderness areas in the east were smaller on average (111 vs 362 km^2).

The combination and scaling of decile values across variables yielded the DUVI (Fig. 3). There were 30 wilderness areas with a DUVI of ≥8, representing the top 20% of the index (Table 2). The most vulnerable was the Mount Timpanogos wilderness in Utah, which had high decile values (≥7) across all eight variables. The Glacier View wilderness in Washington, the J.N. Ding Darling wilderness in Florida and the Philip Burton wilderness area in California were tied as the next most vulnerable, with a DUVI of 9.8 (Table 2). The Birkhead Mountains wilderness area in North Carolina was also in the top five (9.6). The full list of wilderness areas, raw values for each variable and DUVI values can be found in Table S2.

NVUM data indicated that the Rocky Mountain (R2), Pacific Northwest (R6) and Pacific Southwest (R5) regions had the

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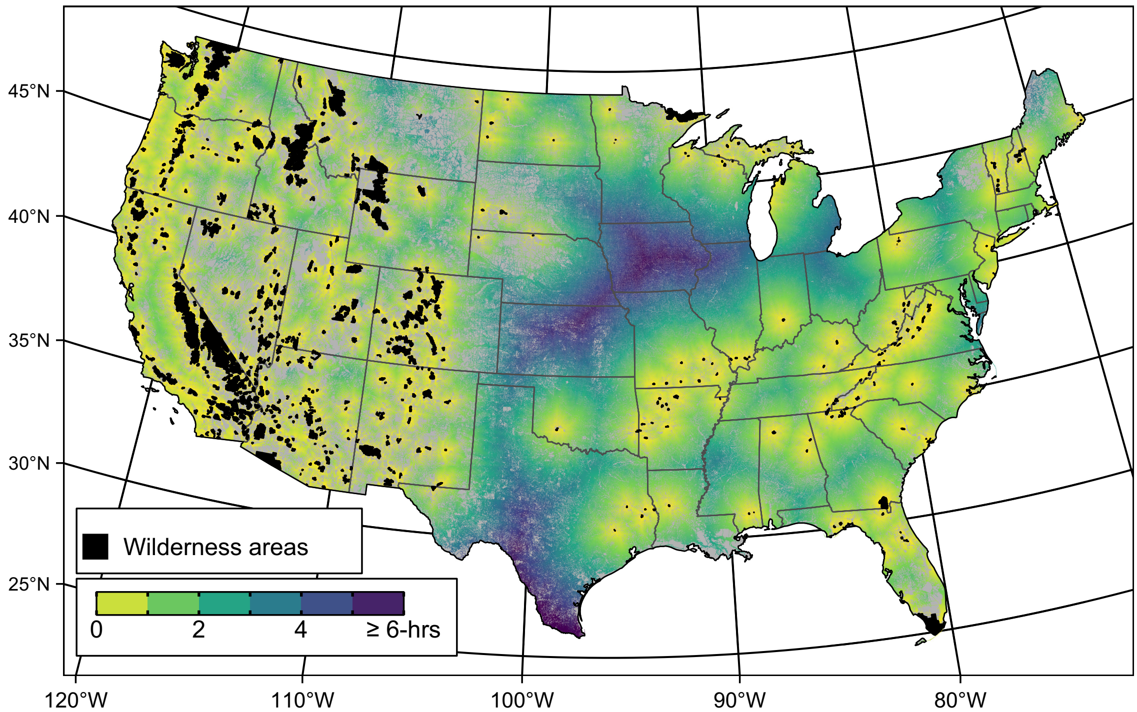

Figure 1. Distance (in hours) to any wilderness area within the contiguous US along roadways at a 1-km resolution. Grey areas on the map have no primary, secondary or local roads in the 2020 US Census Bureau data. The maximum distance to any wilderness area is 6.8 h.

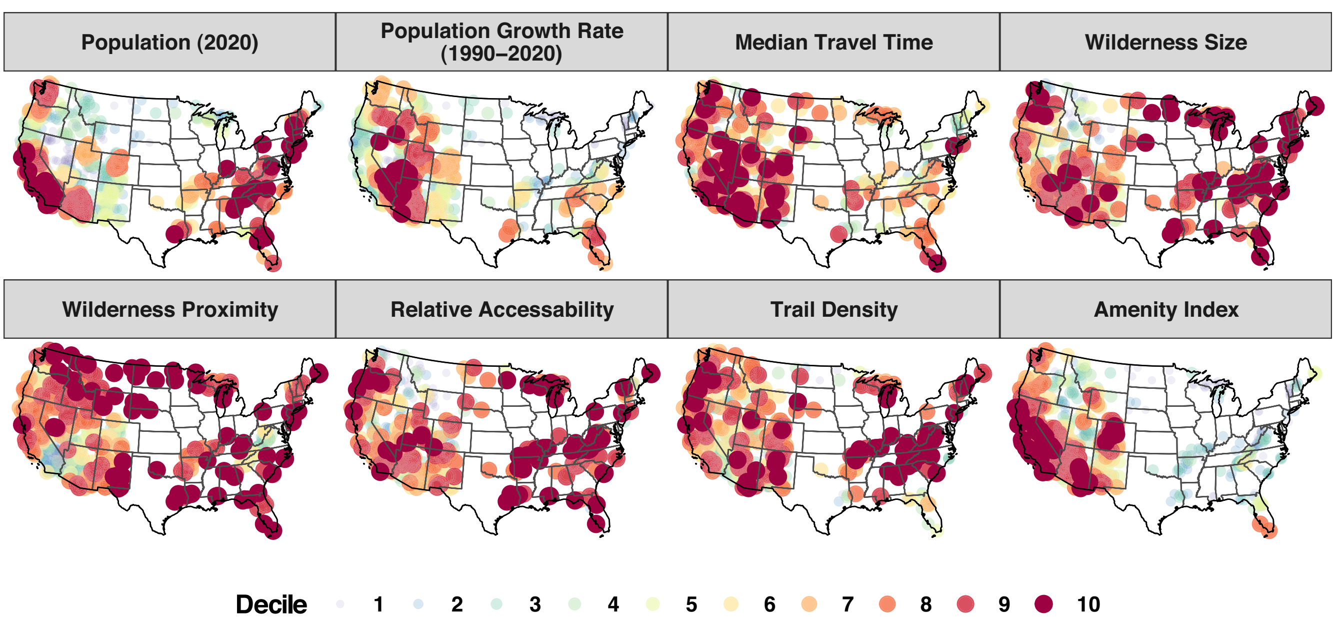

Figure 2. Relative impacts at 722 wilderness areas within the contiguous US for each of the eight variables related to day-use visitation (see Table 1). Raw values were binned into deciles (1–10), where decile values of 10 are wilderness areas in the top 10% for vulnerability for that variable.

highest numbers of visits to wilderness areas during 2015–2019, whereas the Eastern (R9) and Northern (R1) regions had the lowest (Table S1). We found a positive relationship ($R^2 = 0.19$) between the DUVI values and NVUM visitor count estimates. R2, R6 and R5 had lower average DUVI values than expected given the high visitor estimates, whereas R1, R9 and R8 (Southern region) had higher average DUVI values than expected (Fig. 4 & Table S1).

Discussion

We developed the DUVI to identify wilderness areas that might be threatened by human impacts. Validation with NVUM visitor count estimates indicated a positive relationship with the DUVI, suggesting subsequent modelling of visitor estimates is feasible with additional parameter tuning. We conducted this analysis at considerable scale and recognize that the DUVI rankings do not

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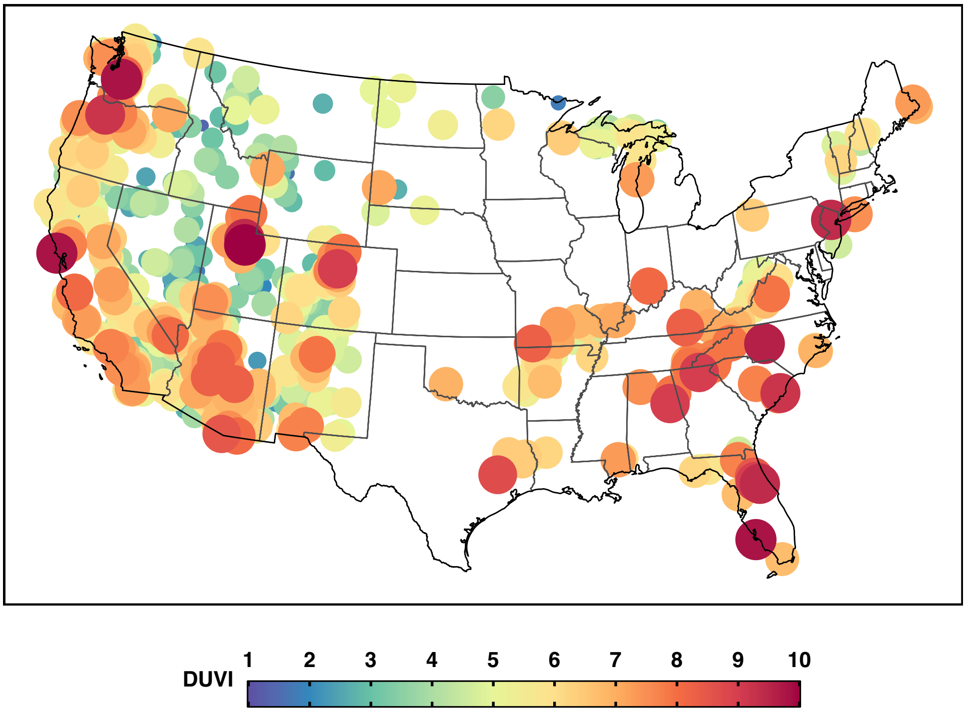

Figure 3. The Day-Use Vulnerability Index (DUVI) values showing potential vulnerability to impacts of day-use visitation for 722 wilderness areas in the contiguous US. Wilderness areas are represented with colour (blue to red) and circles in sizes relative to their index value.

capture all of the possible conditions and scenarios present in individual wilderness areas. However, the index provides a novel view of day-use vulnerability across the CONUS, which could lead to the identification of threatened wilderness areas followed by more in-depth assessments based on local knowledge.

Vulnerability

Population and visitation

The primary impact of more people being within 2 h of a wilderness area is the potential for higher visitation (Lindley et al. 2018, Rasch & Hahn 2018, Gosal et al. 2021), which in turn could result in environmental degradation, including reduction of vegetative cover, erosion of soils, disturbance to wildlife, degradation of water quality and buildup of trash and human waste (Monz et al. 2013, Marion 2016, Marion et al. 2016, Eagleston & Marion 2017). For the Mount Timpanogos wilderness area in Utah, which had the highest DUVI, Lindley et al. (2018) reported visitation had increased by 18% between 2013 and 2017, with 82% of visitors residing in adjacent counties. More broadly, Bowker et al. (2022) showed that wilderness visitation to national forests had increased by >27%, which is considerably faster than US population growth (c. 8%). They also found wilderness visitation across the western US had increased, whereas visitation had decreased in the eastern US. Using population projections and historical visitor use, Rasch and Hahn (2018) estimated that the greatest increase in day-use visits to wilderness areas in national forests through 2060 would be in the south-western US.

In addition to environmental degradation, increasing visitor numbers can affect other wilderness characteristics, such as primitive and unconfined recreation or solitude. These characteristics are mandated in The Wilderness Act (US Public Law 88-577) but can be challenging to achieve with the increase in numbers of visitors (Landres et al. 2008, Cole 2011). At wilderness areas near large urban areas there are more 'accidental' visitors (i.e., people who are not necessarily aware that they are entering a wilderness area). These types of visitors may or may not be interested in solitude, but they also tend to be less bothered by or cognizant of crowding (D'Antonio & Monz 2016, Lindley et al. 2018).

We focused on day-use visits and potential visitors living within 2 h. However, there are other visitor types, including those recreating within wilderness areas for multiple days (i.e., multi-day visits) and day-use visitors living farther than 2 h away but staying overnight in towns or cities near to a wilderness area. While comprising a smaller proportion of visitors (c. 14.4%; Bowker et al. 2022), multi-day recreation is more likely to impact lesser-travelled areas, causing greater ecological impacts on vegetation and soils (Monz et al. 2013, Salesa & Cerdà 2020). In this respect, we caution that some wilderness areas with a low DUVI still face threats from visitors. For instance, the Boundary Waters Canoe Area wilderness in Minnesota has a low DUVI (1.8), partly due to the small population within 2 h (306 965 people; see Table 2 for comparison). However, environmental degradation and high visitation within this wilderness area are evident (Eagleston & Marion 2017, Hjerpe 2018) and have resulted in this wilderness area being the first to institute a permit system (Holmes et al. 2022). According to a survey by Hjerpe (2018), >92% of visits to the Boundary Waters Canoe Area wilderness were multi-day trips. Additionally, >97% of visitors were self-described as not residing in the region (Hjerpe 2018). This highlights a limitation of our study for capturing visitors travelling from beyond 2 h.

Amenity migration

Migration towards wilderness areas and other public lands is expected to increase day-use visitation into the future. Radeloff et al. (2010) demonstrated higher rates of housing growth between 1940 and 2000 within 50 km of wilderness areas than within 50 km of national parks, national forests or the CONUS average. Mockrin et al. (2018) showed that cities with nearby public land in the western, southern and midwestern US were more likely to see high housing growth rates between 2000 and 2010, while Hjerpe et al. (2020) found that between 1980 and 2010 counties with wilderness

Table 2. Wilderness areas and locations within the contiguous US with the highest Day-Use Vulnerability Index (DUVI; ≥8) and the associated values for each of the eight variables used to calculate the index. The full dataset can be found in Table S2.

Wilderness area	State	Population (2020)[a]	Population growth rate (1990–2020)[a,b]	Median travel time[a]	Wilderness size[c]	Wilderness proximity[a]	Accessibility[d,e]	Trail density[c,f]	Amenity index[g,h]	DUVI
Mount Timpanogos	Utah	7	9	10	8	7	9	9	8	10.0
Glacier View	Washington	9	7	9	10	5	9	9	8	9.8
J.N. Ding Darling	Florida	7	8	9	10	10	10	4	8	9.8
Philip Burton	California	10	4	9	4	10	9	10	10	9.8
Birkhead Mountains	North Carolina	10	7	8	10	10	9	10	1	9.6
Great Swamp	New Jersey	10	2	10	10	10	10	10	2	9.4
Lake Woodruff	Florida	10	9	7	10	9	8	6	5	9.4
Mount Olympus	Utah	7	9	10	7	8	8	10	5	9.4
Table Rock	Oregon	8	6	9	9	5	10	10	6	9.2
Wambaw Creek	South Carolina	7	6	7	10	10	10	10	3	9.2
Blood Mountain	Georgia	10	8	8	9	5	9	10	3	9.0
Cheaha	Alabama	10	7	5	9	10	9	10	2	9.0
James Peak	Colorado	8	7	10	7	4	8	8	10	9.0
Juniper Prairie	Florida	10	8	8	7	9	8	7	5	9.0
Little Lake Creek	Texas	10	8	9	10	10	10	2	2	8.7
Lone Peak	Utah	7	9	10	5	8	6	9	7	8.7
Little Lake George	Florida	10	9	8	10	9	7	2	5	8.5
Pajarita	Arizona	5	6	8	9	9	6	9	8	8.5
Beaver Creek	Kentucky	8	4	5	10	10	10	10	2	8.3
Billies Bay	Florida	10	8	7	10	9	10	1	4	8.3
Hells Canyon	Arizona	9	9	10	8	2	3	9	9	8.3
Piney Creek	Missouri	6	5	9	9	8	10	9	3	8.3
Sierra Ancha	Arizona	9	9	5	6	4	7	9	10	8.3
Twin Peaks	Utah	7	9	10	8	8	6	5	6	8.3
Woodchute	Arizona	8	9	4	9	2	9	9	9	8.3
Charles C. Deam	Indiana	10	3	7	7	10	9	10	2	8.1
Clearwater	Washington	9	6	9	7	5	6	9	7	8.1
Hain	California	10	4	4	7	9	6	9	9	8.1
Miller Peak	Arizona	5	6	7	6	7	7	10	10	8.1
Wee Thump Joshua Tree	Nevada	6	10	9	9	1	10	4	9	8.1

[a]Measured within 2 h.
[b]Change in 1990–2020 population divided by 1990 population.
[c]Measured within the wilderness area.
[d]Roads divided by wilderness size.
[e]Measured within 1 km.
[f]Trails divided by wilderness size.
[g]See McGranahan (1999).
[h]Measured at the county level.

areas and other protected lands had higher population growth rates. Similarly, we observed that population growth rates (1990–2020) were 8.1% higher within 2 h of any of the 722 wilderness areas in our study than the rest of the CONUS. The amenity index (McGranahan 1999) tended to be higher on average (5.5 vs 3.7) for wilderness areas in the western US (i.e., west of 100° longitude; Fig. 2). In comparing the DUVI to NVUM visitor count estimates, the Rocky Mountain (R2), Pacific Northwest (R6) and Pacific Southwest (R5) regions each had lower DUVI values than expected based on visitor counts (Fig. 4 & Table S1). These three regions, along with the Southwestern (R3) region, also had the highest average amenity index values (5.2–6.2). This suggests that the relationship between amenities and visitation counts, such as are available through NVUM, should be explored further.

There is a growing body of literature devoted to the socioeconomic, cultural and environmental impacts of amenity migration (e.g., Gosnell & Abrams 2011, Abrams et al. 2012, Hjerpe et al. 2022). Socially constructed values regarding proximity to nature, recreational opportunities and escaping crowded urban areas have encouraged people to move closer to wilderness areas (Gosnell & Abrams 2011, Mockrin et al. 2018). Within these wilderness-adjacent communities there can be contradicting management goals. For instance, the desirability of natural amenities encourages local policies that protect qualities such as forest cover, clean water and unobstructed views, while at the same time disrupting natural processes such as wildfires through fire suppression and aversion to prescribed fire as a management tool (Radeloff et al. 2010, Abrams et al. 2012, Radeloff et al. 2018).

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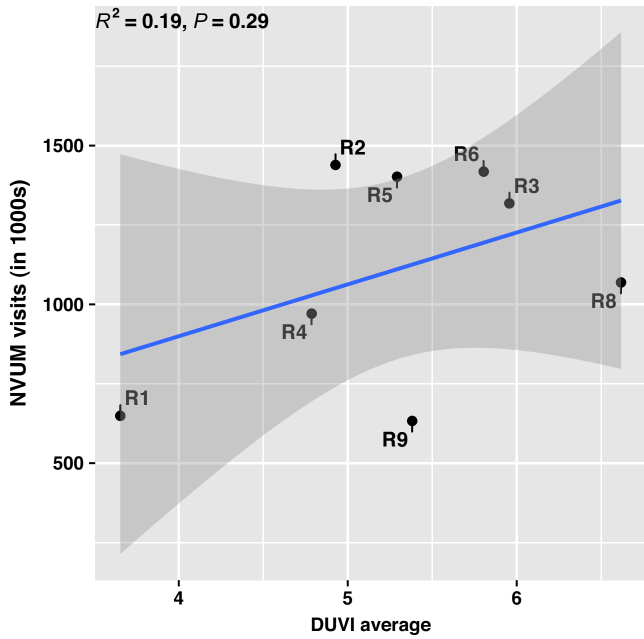

Figure 4. Comparison of National Visitor Use Monitoring (NVUM) estimated visitor counts and the Day-Use Vulnerability Index (DUVI) averaged for wilderness areas managed by the US Department of Agriculture Forest Service in each region. Forest Service regions in the contiguous US are: Northern (R1), Rocky Mountain (R2), Southwestern (R3), Intermountain (R4), Pacific Southwest (R5), Pacific Northwest (R6), Southern (R8) and Eastern (R9). The blue line indicates the line of regression, with a 95% confidence interval given in grey.

Wilderness size

There is considerable difference in the size of wilderness areas between the eastern and western US (Aycrigg et al. 2022b). This can have the effect of concentrating visitor use, resulting in degradation of aquatic habitats and impacts on wildlife such as avoidance and food dependence (Monz et al. 2013, Bleich 2016). In validating the DUVI against visitor count estimates, the Eastern (R9) and Southern (R8) regions each had higher DUVI values than expected based on visitor counts (Fig. 4 & Table S1). This suggests that many of the highest-ranked wilderness areas in these Forest Service regions are not as likely to experience impacts from high numbers of visitors. However, wilderness areas in these regions also had the smallest average size (129 km^2 for R9 and 37 km^2 for R8; Forest Service-managed wilderness areas only; Table S1). Although wilderness area visitation may be decreasing in the eastern US (Bowker et al. 2022), there could still be pronounced impacts from higher concentrations of visitors in smaller areas.

Fourteen of the wilderness areas that we found to be most vulnerable were in the eastern US (i.e., east of 100° longitude; Fig. 3 & Table 2). Among the variables we compiled, wilderness size, wilderness proximity, relative accessibility and trail density each had many wilderness areas in the eastern US in the highest decile (Fig. 2). These wilderness areas are vulnerable to environmental degradation because visitors are concentrated in smaller wilderness areas and have fewer wilderness options to visit while still having relatively high accessibility and recreational trail options. Our study did not evaluate the availability of state, county, local and other non-wilderness public land, which would affect the spatial distribution of people seeking outdoor recreation and could be an important consideration in future research.

Management implications

Our results can be a starting point to evaluate wilderness area vulnerability from day-use visits, but wilderness managers will need to consider many options to limit the impacts of increasing visitation. For instance, trailhead quota systems, which limit the number of visitors who can enter a wilderness area in a day, are a tool that can be used to limit environmental degradation (van Wagtendonk & Coho 1986). However, trailhead quota systems are less popular than other options such as education and are not always fully effective due to loopholes and the unequal spatial distribution of use within a permitted area (Lindley et al. 2018, Jenkins et al. 2021, Schneller et al. 2021). Wilderness permits also provide a useful tool for monitoring and regulating wilderness use in areas at risk of ecological degradation, and these data can be further used to understand trends in how many people take wilderness trips, how the demographic characteristics of visitors are evolving over time and how the demand for wilderness attributes is changing (Holmes et al. 2022). Restoration, resource modification and regulation are all available options, but these must be weighed against maintaining wilderness character (Stankey et al. 1985, Marion 2016, Lieberman et al. 2018). In addition, monitoring the effect of any management action is a key step in determining whether the action reduced impacts to an acceptable level, whether additional action is needed or whether a different approach is warranted (Stankey et al. 1985).

In essence, wilderness areas are composites of ecological, societal, cultural and political goals – and not always in that order (Bleich 2016). In studying trends in perceptions of wilderness, Rasch (2022) found that younger generations were less likely to view wilderness as untrammelled and more likely to support restoration and intervention. Other surveys have found that visitors expect wilderness areas to appear clean and natural, which may also lend support to management actions (Watson et al. 2015, Lindley et al. 2018). Just as wilderness-adjacent community policies can sometimes favour environmental action to preserve natural amenities (Abrams et al. 2012), increased recreation within wilderness areas can have positive impacts on perceptions of wilderness and support for conservation and management (Miller et al. 2022). The assessment and management of individual wilderness areas should employ a holistic approach that considers both local support for conservation and ecological threats from surrounding communities.

In the case of the Mount Timpanogos wilderness area, which ranked highest on our DUVI, surveys in 2013 indicated that people valued the natural characteristics of the area and recognize the impacts of overuse, even though the idea of a quota system was unpopular (Lindley et al. 2018). In 2023, the national forest instituted a quota parking permit system at popular trails for the busiest periods (https://www.fs.usda.gov/recarea/uwcnf/recarea/?recid=15110; accessed July 2023). While some wilderness visitors will likely not approve of any restrictions (Lindley et al. 2018), this type of system balances the need for limitation while still allowing visitors flexibility to choose less busy trails and to recreate during off-peak periods. For the wilderness areas we identified as most vulnerable to day-use impacts, there are probably additional opportunities to engage with visitors and nearby communities to develop mutually beneficial strategies allowing for recreation and limiting impacts.

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Conclusion

We developed the DUVI for 722 wilderness areas in the CONUS using eight variables influencing day-use visitation and the potential for visitation to result in overuse, highlighting individual wilderness areas that are most vulnerable (Table 2). A positive correlation between the DUVI and NVUM visitor counts demonstrated the potential for future development of models for estimating visitation. We focused on vulnerability to impacts from day-use visits in wilderness areas of the US, but protected places worldwide face many of the same impacts to wildlife and the environment from recreation (Salesa & Cerdà 2020, Salvatori et al. 2023). Population proximity has been shown to be an indicator of visitation in Brazil, Canada, Europe and Sub-Saharan Africa (Gosal et al. 2021, Hausmann et al. 2017, Nabout et al. 2022). Furthermore, populations have been growing faster near the edges of protected areas than other rural areas (Wittemyer et al. 2008). Visitor education, habitat restoration, resource modification, visitor quotas and wilderness permits are useful tools for managing the impacts of increasing populations near protected areas (Watson et al. 2015, Marion 2016, Lindley et al. 2018). Finally, it is worth noting that there are stark inequities between protected areas globally; strategies used to preserve wilderness character in the US might not apply in places facing different financial and cultural challenges (Jones et al. 2018). Engaged local communities are the best resource for incorporating actions most likely to succeed in a particular location with unique risks.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0376892923000279.

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