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Research article

Recreational use in dispersed public lands measured using social media data and on-site counts

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ABSTRACT

Outdoor recreation is one of many important benefits provided by public lands. Data on recreational use are critical for informing management of recreation resources, however, managers often lack actionable information on visitor use for large protected areas that lack controlled access points. The purpose of this study is to explore the potential for social media data (e.g., geotagged images shared on Flickr and trip reports shared on a hiking forum) to provide land managers with useful measures of recreational use to dispersed areas, and to provide lessons learned from comparing several more traditional counting methods. First, we measure daily and monthly visitation rates to individual trails within the Mount Baker-Snoqualmie National Forest (MBSNF) in western Washington. At 15 trailheads, we compare counts of hikers from infrared sensors, timelapse cameras, and manual on-site counts, to counts based on the number of shared geotagged images and trip reports from those locations. Second, we measure visitation rates to each National Forest System (NFS) unit across the US and compare annual measurements derived from the number of geotagged images to estimates from the US Forest Service National Visitor Use Monitoring Program. At both the NFS unit and the individual-trail scales, we found strong correlations between traditional measures of recreational use and measures based on user-generated content shared on the internet. For national forests in every region of the country, correlations between official Forest Service statistics and geotagged images ranged between 55% and 95%. For individual trails within the MBSNF, monthly visitor counts from on-site measurements were strongly correlated with counts from geotagged images (79%) and trip reports (91%). The convenient, cost-efficient and timely nature of collecting and analyzing user-generated data could allow land managers to monitor use over different seasons of the year and at sites and scales never previously monitored, contributing to a more comprehensive understanding of recreational use patterns and values.

1. Introduction

Outdoor recreation is one of many important benefits provided by public lands. Nearly 900 million visits to federally-managed lands in the United States support over 800,000 jobs and contribute $49 billion in economic activity annually (FICOR, 2012; White et al., 2016). The outdoor recreation economy as a whole accounts for $887 billion in annual consumer spending and 7.6 million jobs in the United States (OIA, 2017). As the population grows and makes increasing demands on conservation areas, managers and policy-makers find themselves facing challenging decisions about where and how to manage recreation opportunities and associated infrastructure (Cerveny and Ryan, 2008). Data on recreational use are critical for informing such decisions and evaluating their outcomes, especially when there are competing demands for limited budget and staff resources. Managers of large dispersed areas without controlled access points, which characterizes many public lands and protected areas worldwide, often lack actionable information on the amount and character of recreation use.

Recreation managers from the U.S. Forest Service (USFS) and other management agencies need visitor use data in order to evaluate the benefits and costs to the public of proposed policies and management alternatives such as transportation and facility planning, staffing and budget levels, prioritizing maintenance, outfitter and guide use allocations, and many others (Cerveny et al., 2011; Manning, 2010).

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Recreation use numbers are also frequently used in applications for grant opportunities. Since 2000, the USFS has relied on the National Visitor Use Monitoring (NVUM) Program to count and characterize recreation use through a systematic random sample of recreation sites within each unit of the National Forest System (NFS). For each NFS unit, traffic counts and visitor interviews are done at multiple locations over the course of a year, every five years. Typically less than 1% of the population of site-days (recreation locations and days with expected recreation use) are sampled using a combination of temporary and permanent traffic counters, recreation reservations or permits, and counts provided by concessionaires (e.g., ski areas and campgrounds). NVUM data also describe certain characteristics of recreational use, including activity participation, visitor demographics, visit duration, measures of satisfaction, and trip spending generated from the visit (USFS, 2016). The NVUM Program sampling protocol was designed to produce statistically reliable estimates of recreational use across the entire NFS, for each Forest Service region, and for individual national forests and grasslands; it was not designed to generate estimates of recreation use at the recreation site or landscape level or for specific seasons of the year.

A range of well-studied techniques for counting visits at the site level do exist, but the cost and time required to collect such data restricts their application to a limited number of sites and short timeframes. Thus managers are often challenged to monitor recreation use at remote, dispersed, and openly accessible areas that characterize the vast majority of public lands (Leggett, 2015). Two broad methods for measuring use at a recreation site involve either devoting staff to conduct on-site counts or deploying automated devices to count people or vehicles. Existing methods have advantages and disadvantages. Staff-based methods for counting visits may be the most accurate but they are also the most labor intensive and expensive. Infrared beam counters are a common automated tool for counting pedestrians, and have been shown to be 94% correlated with on-site observations (Cessford and Muhar, 2003), yet they still require regular maintenance and are not suitable for all locations. Video monitoring is another option for passive data collection, with the advantage of distinguishing general activities as well as counting users, but the volumes of data may require technical expertise to manage and counts require staff-time to review the recorded images (Arnberger et al., 2005).

Recent technological developments and the widespread use of mobile phones and the internet have opened opportunities to address the challenges of counting visitors in dispersed areas and inferring their preferences for different types of recreation sites and experiences. In this application, we discuss social media data as user-generated geographic content that is shared in online public platforms for purposes other than facilitating research (Elwood et al., 2012). Some have referred to this as "ambient" geographic information (Stefanidis et al., 2013). User-generated geographic content has been used to answer questions about visitor preferences and behaviors in many research domains including conservation biology, ecosystem services, and landscape planning (Becken et al., 2017; Hausmann et al., 2017a, 2017b; Levin et al., 2015; Sonter et al., 2016; van Riper et al., 2012; van Zanten et al., 2016). Many applications of these data for measuring use across public parks or protected areas have dealt with aggregated use across an entire park unit (Heikinheimo et al., 2017; Levin et al., 2017; Sessions et al., 2016; Tenkanen et al., 2017). Some studies have measured use across a network of individual recreation sites such as trails, but have largely done so in urban areas or high-use areas in national parks where social media data are plentiful (Donahue et al., 2018; Hamstead et al., 2018; Korpilo et al., 2017; Walden-Schreiner et al., 2018; Wu et al., 2017). Using social media data, or any other means, to accurately measure use in dispersed areas and across a large set of recreation sites remains challenging.

We address this challenge by building on prior research that shows the density of geolocated images shared by Flickr users is correlated with on-site counts of visitors at recreation sites. Previous studies have evaluated this correlation at recreation destinations globally (Wood et al., 2013), lakes in the U.S. (Keeler et al., 2015), protected areas in Victoria, Australia (Levin et al., 2017), urban parks in the Twin Cities, Minnesota (Donahue et al., 2018) and New York City, New York (Hamstead et al., 2018), natural water treatment areas worldwide (Ghermandi, 2016), and at sites within a national park in Finland (Heikinheimo et al., 2017). In addition to correlations, a recent study showed that a statistical model using geotagged photographs from Flickr as a predictor can approximate seasonal trends in recreational use to national parks in the Western U.S. (Sessions et al., 2016). In the U.S., access to most national parks is controlled through a limited number of entry points (often staffed or with a permanent traffic counter), which makes on-site counts of recreation obtainable and provides the basis for reliably estimating seasonal visitation rates. Furthermore, U.S. national parks such as Yellowstone, Yosemite, and Glacier are premier tourism destinations where visitors may be having a once-in-a-lifetime experience, and are likely to share their experiences on social media for others to see. It is unclear whether information gathered from social media platforms can effectively measure recreation use in more dispersed, lower-profile destinations, such as those typical in U.S. national forests.

The purpose of this study is to explore the potential for user-generated social media data to provide land managers with useful measures of recreational use to dispersed and remote areas that have been costly and difficult to monitor, and to provide lessons learned from comparing several more traditional methods for counting visitors. We explore the utility of user-generated social media content at two scales. First, we measure visitation rates at individual trails – much finer scales than are typically tested for such remote areas – in the Mount Baker-Snoqualmie National Forest (MBSNF) in western Washington. For this fine-scale test, we compare traditional visitor-counting techniques to those based on the locations of geotagged photographs and user-contributed trip reports, both shared publicly via online platforms. Second, in order to understand how applicable and generalizable the results from MBSNF might be on a national scale, we directly compare measurements derived from geotagged photographs with official estimates from NVUM, the program charged with tracking use at every NFS unit.

2. Methods

2.1. Study area

The NFS covers 7,73,000 km^2 and includes 154 national forests and 20 national grasslands in 43 states and Puerto Rico. The individual NFS units are administered in nine Forest Service regions spanning the country. NFS lands are managed for multiple uses including recreation, commodity resource extraction, grazing, production of clean water and air, and protection of habitat and ecosystems. In general, national forest lands represent rural areas with limited development that are open to public use. Hiking is the most common recreation activity: about 46% of visits involve hiking/walking and it is the primary recreation activity in one in four visits (USFS, 2016). Most visits to national forests are fairly short: the median visit duration is 3.9 hours. About half of national forest visits come from individuals who make between one and five trips to that same national forest each year. However, those who live relatively close to national forests report visiting with greater frequency and, in some cases, report up to near daily visitation (USFS, 2016).

The MBSNF in Washington extends over 225 km along the western slopes of the Cascade Mountains from the Canadian border to the northern boundary of Mt. Rainier National Park (Fig. 1). The forest is divided into four ranger districts with nine wilderness areas, four ski areas, and over 6880 km^2 of temperate forest, riverine, and alpine landscapes. The MBSNF contains over 1642 km of hiking trails (over half in designated Wilderness areas, and over half open to equestrian use). The Forest also includes 209 km of crosscountry ski trails, 335 km

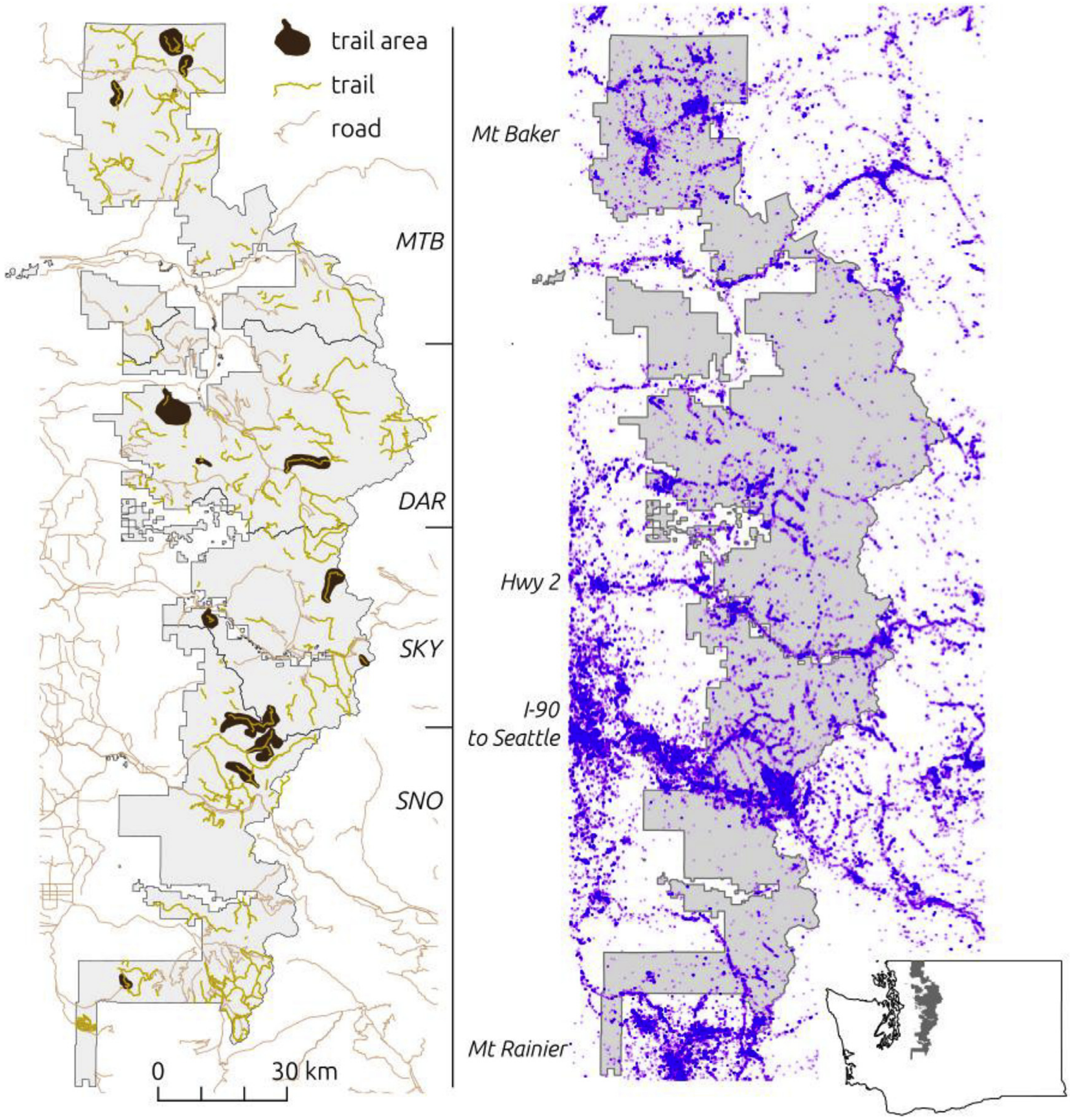

Fig. 1. MBSNF (boundary in gray) in western WA. *Left:* The 15 trail areas observed in this study are dispersed across 4 ranger districts (MTB: Mt. Baker, DAR: Darrington, SKY: Skykomish, SNO: Snoqualmie). *Right:* Geotagged Flickr photos (purple points) taken in and around the MBSNF. Sources: USFS and Flickr. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of snowmobile trails, 51 km of mountain bike trails, 113 km of motorbike trails, 40 km of off-road vehicle trails, and 19 km of barrier-free accessible trails (Paull, personal communication). The Seattle metropolitan area is nearby with over three million U.S. residents living within 113 km of the national forest. In 2015, the NVUM Program estimated there are 2.2 million visits annually to the MBSNF (NVUM, 2017).

2.2. Site selection

To compare various methods for measuring trail use, we selected 16 study trails for monitoring in the MBSNF. Trails were selected from a pool of 87 trailheads across four ranger districts within the MBSNF that were studied by the NVUM Program in 2015 (NVUM, 2017). In the Inventory Design phase of NVUM, each trailhead was classified by local Forest Service managers into one of five anticipated levels of recreation use for each calendar day of the year (closed, low, medium, high, or very high use). We translated those categories into daily scores of 0–4 and summed the scores across the calendar year to generate annual use scores for each trailhead, then assigned one of four annual use quartiles to each. We selected one trail randomly from each of 16 strata (four districts and four use quartiles). Trail networks were reviewed with geographic information systems to determine if most hiker traffic would be in-and-out traffic, i.e., passing a single entry/exit point. If a given stratum did not have a trail meeting this criterion, an additional trail from an adjacent stratum was chosen. One selected trail in the Darrington (DAR) Ranger District was excluded from the study due to lack of time and resources to access the site during the field season. Trails were monitored from late August 2016 through December 2016 (Table 1).

2.3. Data sources

2.3.1. Cameras

At each trail we installed one Plotwatcher Pro (Day 6 Outdoors, LLC. running Game Finder V1.6) time-lapse video camera and counted the number of hikers captured in images of the trail. The cameras were disguised in a location with a view of the trail entrance or the first

Table 1
Randomly selected trails from a pool stratified by district and use quartile, with the USFS trail name and number.

District	Use quartile	Trail name	Trail number
MTB	very high	Picture Lake	735
MTB	high	Skyline Divide	678
MTB	medium	Tomyhoi/Yellow Aster	686
MTB	low	Goat Mountain	673
DAR	very high	Kelcema Lake	718
DAR	high	Green Mountain (excluded)	782
DAR	medium	Neiderprum	653
DAR	low	Lost Creek Ridge	646
SKY	very high	Lake Serene	1068
SKY	high	Dorothy Lake	1072
SKY	med	Meadow Creek	1057
SKY	low	Tunnel Creek	1061
SNO	very high	Snow Lake	1013
SNO	high	Summit Lake	1177
SNO	med	Snoqualmie Lake	1002
SNO	med	Dingford Creek	1005

straight segment of trail. Cameras were configured to save images at defined intervals based on individual site conditions, such as the depth of field and the speed at which hikers moved through the camera field. Intervals ranged from three to ten seconds. The cameras began recording images each day when available light was sufficient and stopped when the daylight faded, approximately dawn to dusk. Images were stored on a removable SD card which was replaced throughout the season before its storage capacity was reached.

Researchers viewed the resulting time-lapse videos and counted the total number of incoming and outgoing hikers per day from five random weekdays (Mon-Th) and five random weekend days (Fri-Sun) at every site. To assist this counting, and to expedite the processing of very large numbers of images, we developed software to automatically identify frames containing motion by hikers, or anything else within selected regions of the view extent (Sharp and Wood, 2017, Supp File 1). The software, written using Python and the OpenCV library (Bradski, 2000), identified frames in which a certain threshold of contiguous pixels contained different values from those in the previous frames. These "positive" frames were exported and the number of people in the exported images was counted manually by viewing the images. To judge the accuracy of the software, we completed counts with and without the assistance of this software for five randomly-selected sites. Then, we used the partially automated method to complete counts for five random weekdays and five random weekends at all 15 study sites.

2.3.2. Infrared sensors

Alongside the cameras, we installed a passive infrared (IR) pedestrian counter (TRAFx Research Ltd) at each site near the beginning of the trail. Each sensor was installed on a tree and aimed at approximately waist height and in accordance with the TRAFx user's manual. Previous research has indicated that the accuracy of infrared counters depends on site conditions, so effort was taken to install devices at flat and narrow stretches of trail where people walk single-file and their speed is relatively constant (Turner and Lasley, 2013). During installation, the devices were run through a test period to verify the accuracy of the counts and adjust settings for typical speed of travel. The test period involved researchers traveling through the detection zone to observe the accuracy of the counter under various circumstances.

Devices were set to record the date and time whenever motion was detected. Data cleaning involved assigning zeros to days with no recorded traffic while the device was operational. We analyzed daily and monthly counts. Monthly counts were only analyzed for months when the device was deployed for at least 16 days of the month. Even when an IR device was deployed properly, rare instances of malformed data were generated, suggesting the device was not operating normally on a given day. In addition, some sensors became snow-covered for periods in late November and December. In both cases, we removed these days from daily analyses, but it was necessary to fill the missing daily values in order to achieve accurate monthly totals. For months with at least 16 days of complete data, we filled missing weekday (Mon-Fri) values with a linear approximation based on the timeseries of weekday values from the rest of the season at the same site. Missing weekend values were similarly filled with a linear approximation based on weekend values.

2.3.3. Observations of vehicles and hikers

Manual counts of parked vehicles and hikers entering and exiting a trail were made each day that a researcher visited one of the 15 study sites. The total number of vehicles at the trailhead, including those parked at overflow areas, were counted. Vehicles located in areas designated for alternate uses such as camping or picnicking were not included in the vehicle counts. In addition to vehicle counts, the number of hikers entering and exiting the trail was recorded. Date, time, number of hikers, direction of travel, and duration of the count were recorded for periods ranging from 15 minutes up to 3 hours. To compare with daily counts from other measures, we calculated hikers per hour for each day with a count.

2.3.4. Flickr photographs

We estimated visitation rates based on the density of geotagged photographs shared publicly on Flickr (www.flickr.com). These photographs contain metadata including a unique user ID, date the photo was taken, and the latitude/longitude location of the camera when the photo was taken. The geolocation typically comes from a GPS in to the camera (e.g., a mobile phone), but may also be manually assigned by the user by zooming and clicking on a webmap as the user uploads photos to Flickr. We used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software (Sharp et al., 2016) to calculate the number of photo-user-days (PUDs) for each study site for each day from 2005 to 2015, following the method described by Wood et al., (2013). For a specific geographic area defined by a polygon, the InVEST software spatially queries the global database of Flickr metadata and counts unique photographer-date combinations among photographs taken within the polygon. This method does not involve viewing or downloading the actual content of any images. We analyzed average monthly PUDs for each study site. The boundary of study sites were defined using GIS and trail maps for the MBSNF. Polygons were drawn around the trails in the study to include trailhead and parking areas and destinations accessed from the trail such as lakes, camping areas, mountain peaks, or other points of interest (Fig. 1). Areas most likely to be accessed from a different trailhead were excluded from the polygon.

2.3.5. Online trip reports

The Washington Trails Association (WTA) – a non-profit organization dedicated to fostering hiking opportunities for the Washington community – provides an online hiking guide with information on thousands of trails in the state (www.wta.org). The WTA website allows users to contribute publicly accessible "trip reports" for any trail they may have recently visited. People typically post a trip report in order to describe their route of travel, trail and road conditions, and to post photographs of their experience. WTA provided access to the trip report database (93,913 reports posted from 1997 to 2017), which included date of post and trails visited for each report. 20,153 trip reports were posted during 2016. We counted the number of trip reports for each of the 15 trails in our study in 2016, and analyzed the monthly totals for months overlapping our field season.

2.3.6. NVUM annual site-visits

The NVUM Program estimates annual site-visits to NFS units for years in which on-site sampling occurred in each unit. A site-visit is defined as a single person entering a national forest site or area for the purpose of recreation. All recreation sites and calendar days across a unit are stratified by use level during the Inventory Design phase. Site-visit counts to a sample of these stratified sites and days are measured with traffic counters, intercept counts, or other proxy data (fee receipts, mandatory permits, permanent traffic counters, and ticket sales) if it exists. Daily on-site or proxy counts from the stratified sample are expanded across the year and across all sites to produce total annual site-visit estimates for each NFS unit (English et al., 2002).

2.4. Visitation rate comparisons across scales

For the 15 study trails, we assessed pairwise relationships among all data sources using scatterplots and Pearson's correlation coefficients. Vehicle counts, hiker counts, IR sensor counts, and time-lapse camera counts were compared on a daily scale. We assessed the accuracy of user-generated Flickr photographs and WTA trip reports as a measure of recreational use by comparing average monthly PUD from photographs taken from 2005 to 2015, and monthly trip report counts, to monthly IR counts. We did not analyze monthly totals from camera counts because our random sample of days counted may not be representative of entire months. All data sources exhibit a heavily right-skewed distribution, which is typical of count data, so we added one and log-transformed all variables before calculating correlation coefficients.

For 114 units in the NFS, we used a scatterplot and Pearson's correlation coefficients to compare average annual site-visit estimates from NVUM surveys conducted between 2005 and 2015 to average annual PUDs estimated from photographs taken from 2005 to 2015. The NFS units analyzed were limited to those with geographic boundary data available from the Forest Service Geodata Clearinghouse, which was used for extracting geotagged photographs (https://data.fs.usda.gov/geodata/ accessed Aug 2017).

3. Results

3.1. Trail visitation rates

3.1.1. Camera counts, manual vs partially automated

Fully manual counts of hikers tabulated by a researcher watching entire days of time-lapse video were highly correlated with the partially automated counts that used software to detect hiker motion at hourly (Pearson's r = 0.99, n = 814) and daily (Pearson's r = 0.99, n = 32) scales (Supp. Fig. 1). Occasionally, automated counts were higher than manual counts, particularly for high traffic sites and times. Due to the time savings and improved accuracy afforded by the partially automated method, we rely on that method for the following analyses.

3.1.2. Camera vs infrared counts

We collected 1329 days of usable IR counts across 15 study sites between August and December 2016. While the IR counters recorded data cheaply and reliably, we removed five days of malformed data that suggested the device was not recording properly for a portion of that day. In addition, we excluded counts from December and portions of November for 12 of 15 sites, for periods when the device was snow-covered and not operational. A scatterplot of daily total hikers counted by camera and IR sensors showed a 94% correlation (n = 327). Across the sample of sites, IR sensors tended to systematically overcount hikers (Fig. 2). At least one trail (Tunnel Creek) was an exception to this and could be explained by site conditions and device calibration settings. Due to the very strong correlation and the much larger processing time required to achieve daily counts from cameras, we relied on the IR counts to achieve monthly hiker totals for comparisons with other data sources.

3.1.3. Photo-user-days vs infrared counts

Average monthly PUD from Flickr photographs taken from 2005 to 2015 were correlated with total monthly counts from IR sensors in 2016 (r = 0.790, n = 35; Fig. 3). Flickr photographs were relatively scarce

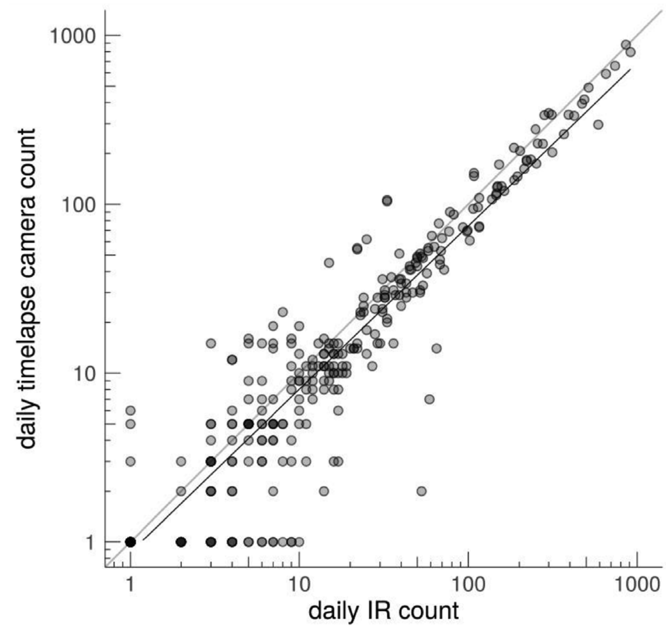

Fig. 2. A comparison of daily hiker counts from passive infrared (IR) counters and timelapse cameras. All values were increased by one in order to plot on a log scale. Darker points indicate more overlapping points. Gray line is 1:1. Black line is the best-fit line using ordinary least-squares.

for some sites at this temporal and spatial resolution. This scarcity was the reason to aggregate the PUDs over 11 years and analyze average monthly PUDs. Even so, only six site-months averaged more than one PUD. Four site-months had zero PUDs. Nevertheless, the variation in even small numbers of PUDs still captured much of the variation in the IR counts. The Dingford Creek trail was a notable outlier with larger PUD values than expected for each month, particularly in December. That trail shares a parking area with other destinations, and parking areas were included in the geographic boundaries of trails for the purposes of selecting photos, perhaps explaining the larger than expected PUD values relative to IR counts.

3.1.4. Online trip reports vs infrared counts

During the 2016 field season, WTA users posted 297 trip reports across the 15 study trails. Only one trail (Neiderprum) received no trip reports during that period. At the monthly scale, there were 21 non-zero trip report values. Correlations with monthly counts from IR devices were strong (r = 0.908, n = 35; Fig. 3). The Dingford Creek trail, which was an outlier in the PUD vs IR scatterplot (Fig. 2), was not an outlier here, perhaps due to a closer correspondence between the geographic area represented by the trip reports and the area captured by the IR sensor.

3.1.5. Observed hiker and vehicle counts vs infrared counts

We found strong correlations between daily hiker counts (measured as hikers per hour) and counts from IR sensors (r = 0.828, n = 88) as well as between instantaneous vehicle counts and counts from IR sensors (r = 0.848, n = 106; Fig. 4).

3.2. National forest visitation rates

Recreation monitoring systems are tasked with measuring use at a variety of spatial scales. To examine the efficacy of social media data to measure recreation use at the forest scale, we compared annual estimates derived from geotagged photographs across entire national forests to those developed from the NVUM Program for each unit within the NFS. Results showed that average annual Flickr photo-user-days from national forests and grasslands were 80% correlated with NVUM

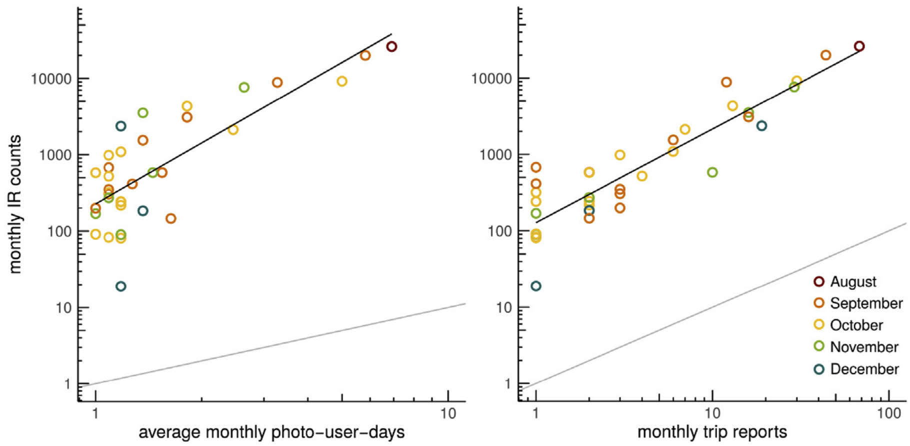

Fig. 3. A comparison of monthly trail use counts from passive infrared (IR) counters to Flickr photo-user-days (left), and WTA trip reports (right). Photo-user-days are average monthly counts from photos taken from 2005 to 2015. Trip reports are monthly totals from reports posted in 2016. All values were increased by one in order to plot on a log scale. Gray lines are 1:1. Black lines are the best-fit line using ordinary least squares.

estimates of average annual site-visits (n = 114; Fig. 5). Specific regional comparisons showed strong correlations as well, ranging from 55% to 95% within regions (Table 2). Some geographic patterns were also apparent. For example, Pacific Northwest and Pacific Southwest region units tended to have more PUDs than expected based on the national relationship; the Southern, Intermountain, and Northern region units tended to have fewer.

4. Discussion

4.1. Effectiveness of social media data and future research needs

Vast public lands without controlled access points are difficult to monitor for recreational use, but the proliferation of mobile devices and public social media platforms has enabled new methods for monitoring such places. Specifically, geotagged photographs from Flickr and trip reports from an online hiking guide provided by the WTA can be less expensive than traditional data sources to collect and represent nearly continuous coverage across space and time. Our results show that these data sources were highly correlated (Flickr: r = 0.790, WTA: r = 0.908) with traditional methods of monitoring site-specific visitor use. At the national level, the direct comparison of social media and NVUM results from national forests across the U.S. shows how user-generated data have the potential to be integrated with the USFS official monitoring program at the national scale. NVUM is designed to estimate annual use of entire NFS units, a geographic scale comparable to scales at which social media have already been widely tested (Sessions et al., 2016; Tenkanen et al., 2017; Wood et al., 2013). Our results agree with these other studies that there is a strong correlation (r = 0.80) between the volume of social media posts and the popularity of the place. These results suggest that user-generated content has great potential to be

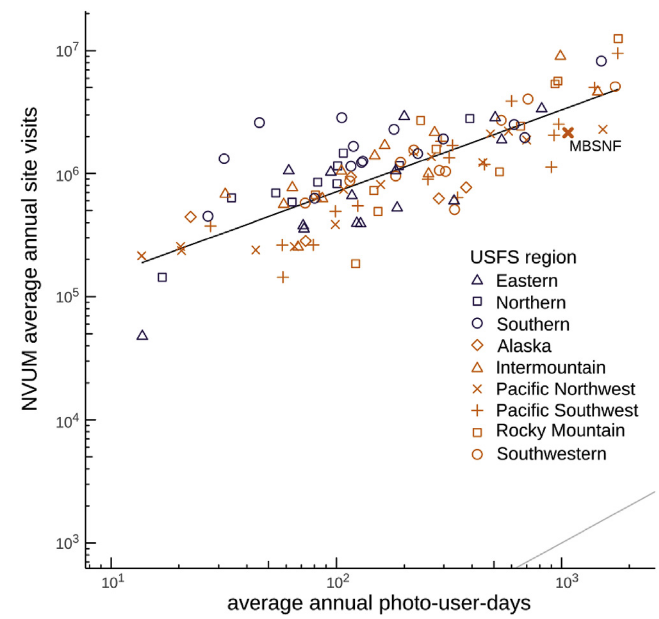

Fig. 5. A comparison of measures of average annual visitation to 114 units in the National Forest System. Region refers to the 9 administrative regions of the USFS. Regions located in the eastern half of the U.S. are colored dark purple; regions in the western half of the U.S. are lighter orange. Gray line is 1:1 line. Black line is the best-fit line using ordinary least squares. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

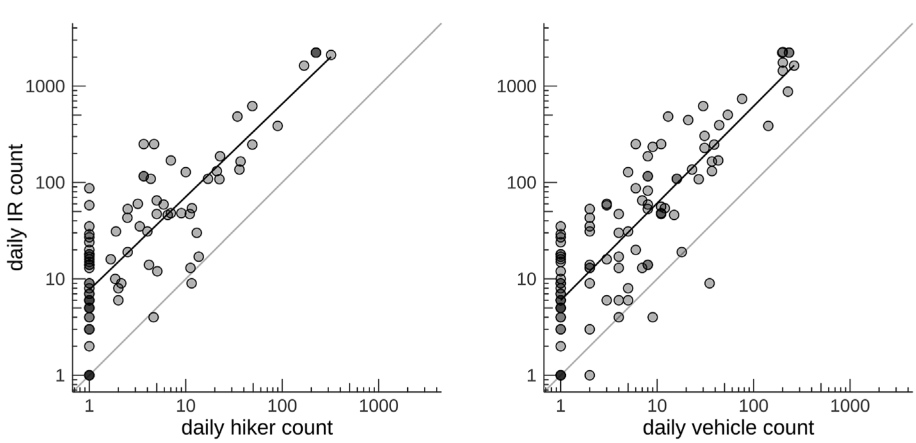

Fig. 4. Observed daily use counts at trails measured by passive infrared (IR) sensors vs intercept counts of hikers entering and exiting trails (measured as hikers per hour), and instantaneous counts of vehicles in trailhead parking lots. All values were increased by one in order to plot on a log scale. Darker points indicate more overlapping points. Gray line is 1:1. Black line is a best-fit line using ordinary least squares.

Table 2
Regional correlations between NVUM average annual site visits and average annual photo-user-days.

Region	Pearson's r	Sample size
Alaska	0.55	5
Eastern	0.83	15
Intermountain	0.88	12
Northern	0.93	10
Pacific Northwest	0.95	17
Pacific Southwest	0.89	18
Rocky Mountain	0.88	11
Southern	0.68	15
Southwestern	0.82	11

used in quantitative models of visitor use for national forest trail systems, and for monitoring use at other sites or landscape scales that are missing in current national and regional-level monitoring data.

The number of trip reports posted to WTA's website is highly correlated with monthly trail use estimated using traditional visitor-counting tools. The state-wide coverage of trip reports probably makes this the best and only source of relative visitation rates to trails across the entire state of Washington. The WTA organization and their website are very well-known among the hiking community in Washington, and their ubiquity, data management practices, and relationships with the local national forests help make the trip reports very useful for visitor monitoring on public lands. In addition, because the scope of WTA is not limited to a single land management agency, the trip report database is a unique example of a visitation-rate dataset that could be integrated across agencies. This data source may be unique to Washington; however, organizations in other states may be following the model of WTA and recreation managers elsewhere may find productive partnerships with local organizations that run similar online platforms. Additionally, because trip reports are narratives, they may also be an excellent source of more qualitative information, such as visitor preferences, management problems, and infrastructure needs.

It is interesting to contrast the visitation measurements from the Flickr and WTA data sources. The different characteristics of the two social media platforms and their user-communities surely influence the relationship between their user-generated content and on-site recreation counts. Trail-level visitation measurements from Flickr images were less correlated with traditional on-site counts than WTA measurements (Fig. 3), but have the potential to be useful in an integrated recreation monitoring scheme. WTA trip reports represent a limited but extremely context-relevant data source; almost by definition a WTA user is a potential trail user. On the other hand, the Flickr database is much larger and not inherently focused on trail recreation. This suggests that Flickr and other widely popular social media platforms are useful for measuring use to dispersed recreation areas, but probably perform best at broader spatial scales than individual trails. This is evident in our results from two extreme scales, where PUDs showed a stronger correlation with visitation rates at the annual scale for entire national forests than at the monthly scale for individual trails. While the global Flickr dataset is large, there are a limited number of posts from remote, low-use areas, which necessitated that we aggregate posts across eleven years of data to achieve average monthly estimates of use, rather than directly comparing posts shared during the field observation period, as we did with WTA trip reports.

Among the many social media platforms with user-generated geographic content, likely not all are well suited for measuring use across a large number of sites in remote areas that lack cellular connectivity. On other platforms such as Twitter, users generally only make posts while they are connected to a network, so a map of geotagged tweets from our study area generally highlights roads and populated places, not visits to trails and remote areas. Instagram users may take a photograph while on a trail and post it later when they return to a cellular network, but Instagram currently does not make the latitude/longitude location of the image publicly available in the post's metadata. Instagram users can publicly tag their images with place-names, however this constrains the geographic resolution that can be analyzed with Instagram metadata. A recent study that compared data from Flickr, Twitter, and Instagram concluded that the platform with the largest volume of data (Instagram in this case) was most strongly correlated with official statistics of national park use, and that measurements that combine multiple social media data sources are more robust than single-source measurements (Tenkanen et al., 2017). Instagram's limited geographic resolution was not a problem for that study, which measured aggregate use to entire park units. User-generated content from platforms specializing in fitness and outdoor recreation may be well suited for measuring visitation rates to dispersed areas, as we show here with the WTA platform. A challenge with using these specialized data from sources such as Strava and MapMyFitness is the lack of, or limitations to, the data that are available through application programming interfaces (APIs). API limitations present barriers to transparent data collection (Norman and Pickering, 2017; Campelo and Nogueira Mendes, 2016).

While our results indicate that social media data show promise as predictors in visitation models, a thorough understanding of the limitations and biases of the data are critical. First, social media users are not a random sample of the population of interest, so they generally are not representative of the population of visitors. The magnitude of this bias likely depends on the type of site, recreational activity, and social media platform (Li et al., 2013; Ruths and Pfeffer, 2014). For the United States, we know that social media users tend to be younger than the population at-large, and that different platforms have different demographic profiles (Duggan and Brenner, 2013). Additionally, the use of social media – even across users of a single platform – might differ depending on whether visitors are from rural and urban areas, or local versus international visitors (Duggan, 2015; Sessions et al., 2016). We do not know for certain if the biases measured at the national scale apply directly to our national forest context, but they serve to remind us of the potential biases in our sample of trail visitors. In our study of trail users in Washington, the WTA data source likely captures more users from Washington than Flickr, given the popularity of the WTA hiking guide in the region. In addition, social media usage may vary due to environmental conditions. For example, if the social media content is created by a camera, then the amount of content from a place and time may depend on weather, available viewpoints, landmarks, or other factors in addition to the number of visitors present (Alivand and Hochmair, 2017). It is possible that some of these biases could be at play in the regional differences we found in the relationship between PUDs and NVUM estimates (Table 2). This geographic variation suggests that future research should replicate the within-unit analysis conducted here for the MBSNF in NFS units from other regions. Finally, relying on social media data to monitor long-term trends brings the challenge of controlling for many endogenous factors related to the popularity of specific platforms and proliferation of mobile devices (Perrin, 2015). Nonetheless, even before accounting for the issues discussed here, the amount of user-generated content that is shared online explains a large portion of the variability in use in national forests. This indicates that social media counts could be calibrated with on-site data, integrated with data on local site conditions, and used to build predictive models that estimate visit numbers for places that have never been monitored, or to forecast use in an upcoming season.

In addition to considering the analytical limitations of using social media data, any use of these data sources should give careful consideration to ethical and privacy concerns. The research potential, efficacy, and ethics of data shared openly on the internet that was produced using GPS-enabled devices has been discussed and has lead to a typology of data sources and guidance on ethical usage (Goodchild, 2007; Elwood et al., 2012; Zook et al., 2017). Because we suggest that social media data should continue to be used for the purpose of monitoring recreation patterns, we also must suggest taking to heart Zook et al.'s primary doctrine, "data are people." In this application, we were careful to analyze and report only statistics from aggregated metadata of public social media posts, but we acknowledge that the contents of individual posts and their metadata could be used to identify individuals and their behaviors. Researchers and practitioners using similar data sources should continue to be mindful of this and take care to use social media data responsibly.

4.2. Recommended data sources for monitoring trail use

Our comparisons of various data sources for measuring use on individual trails within the MBSNF provide several insights into the most useful measures of daily and monthly visitation across sites that range in popularity. We found strong correlations between counts from cameras, passive infrared sensors, and observations of hikers and vehicles at trailheads at daily and monthly scales at 15 locations across the MBSNF. Our first conclusion, based on the lessons learned using each data source, is that timelapse cameras can provide accurate snapshot counts of visitors, and these data are helpful for calibrating other measurements. If situated with a good field of view and a frequent enough capture rate, cameras photographing trail entrances can yield accurate visitor counts during daylight hours (Arnberger et al., 2005; Campbell, 2006; Cessford and Muhar, 2003; Fairfax et al., 2014). There are, however, costs associated with purchasing the camera ($229 US, currently, for the device used here), computer storage resources for accumulating image files, time and expense required to deploy the device and maintain it in the field, and potential privacy concerns. Additionally, visitors are not counted automatically; a researcher must view the still images. We created and used custom, open-source, image processing software (Sharp and Wood, 2017, Supp. File 1) to create a partially automated system to reduce the number of frames to review for counts, which saved time and produced more accurate counts than a fully manual system. The improved accuracy is likely due to reduced visual fatigue, which can happen during prolonged viewing periods and may cause researchers to miss brief, but important, events appearing in the frames. Even with a partially automated system, processing timelapse images into counts of people sometimes required up to two hours to process a single day of images from a particularly busy day at a popular site, and it was not feasible to record daily counts from each camera for the entire study period.

In the MBSNF, passive infrared sensors allowed us to measure trail use over periods of weeks or months, and to collect simultaneous counts across multiple sites, which is key for understanding relative use. We found IR pedestrian counters to be the most accurate source of daily counts of people on trails, based on comparisons to camera counts. Discrepancies between daily IR counts and camera counts typically showed higher IR counts, possibly resulting from sensors detecting dogs or other animals, double-counting hikers that happened to backtrack to a parking area before returning to the trail (a behavior that was observed in camera counts), or double-counting slow-moving individuals or those who happen to stop and linger in front of the sensor. Undercounting with an IR sensor is also possible, but observed less often in our results (Fig. 2). The very strong correlation between IR counts and other observations are consistent with other comparative studies (Cessford and Muhar, 2003; Greene-Roesel et al., 2008; Turner and Lasley, 2013), although systematic under-counting is more commonly reported than over-counting. IR devices were the most efficient method to record trail counts on a continuous basis, yielding relatively few days with missing data thus allowing aggregation to monthly or seasonal totals. Nonetheless, these sampling devices do require time and expense to deploy and maintain – devices cost about $450 - $540 US, currently.

Our results indicate the utility of opportunistic vehicle and hiker counts that are collected as part of regular visits to trailheads by USFS personnel and other project staff. Surprisingly to us, these instantaneous daytime counts are over 80% correlated with daily IR counts, even though our study trails in the MBSNF vary widely in the daily turnover of visitors (Fig. 4). One site (Picture Lake) is along a paved highway and sometimes receives tour groups that arrive in large buses and stay for short time periods (under one hour). We predicted that this high hourly variability in use would make it difficult to estimate daily use with a single on-site count of people or cars. In contrast, we predicted that visitors to more remote trailheads in MBSNF would spend a greater portion of the day parked and hiking on the trail, leading to less variability in the daytime vehicle counts. These sources of variability do cause challenges for using instantaneous counts to predict daily totals, though this could be overcome by modeling the hourly distribution of use at each site and adjusting the instantaneous counts. Even without this additional step, we find that opportunistic vehicle counts provide useful measures of relative visitation rates across sites, especially since they require very little effort if they are collected as part of regular visits to sites that also serve other objectives.

Several potential sources of recreation use data were considered but not analyzed in this study for reasons that are worth discussing. Certain trails and wilderness areas in the MBSNF require visitors to sign a registration book or get a permit at the trailhead. Other public land agencies may have different but comparable information sources. Both systems ask hikers to "sign in" and provide a date or range of dates, the number of people in their party, and possibly other information. Compliance may be mandatory but not necessarily enforced, and compliance rates vary among sites. These data have been used by the USFS for years to meet varying objectives from measuring use levels, to monitoring compliance with wilderness regulations, to piloting more restrictive permitting systems. Due to their abundance and pre-existing protocols for collection, it makes sense to consider these data sources for systematic visitor use monitoring, as NVUM does in its visitation estimates. However, several obstacles make these data challenging to use effectively. First, these data are often not entered into a database as they are collected, and so analyzing them also means devoting resources to digitize them. Second, the continuity of the data varies greatly across sites since it relies on monitoring and re-stocking trailheads with paper permits and registration sheets. This problem generates systematic biases where more popular or more accessible trails are more likely to run out of sign-in materials and miss registrants, more remote trails are likely to be re-stocked less often, and materials may remain depleted over the winter due to more limited seasonal staff, particularly at harder-to-access sites. For these reasons, we chose to devote limited resources to other data collection efforts.

5. Conclusion

New data sources can create new opportunities to monitor recreational use on public lands and guide management decisions. Visitor use can be tracked over time in dispersed areas and at fine spatial scales by integrating traditional trail counting methods and devices with newly available user-generated content from social media. While data from social media is a relatively convenient, cost-efficient source of visitor use data, future monitoring should continue to include traditional counting methods. The user-generated content presented in this paper could allow land managers to monitor relative use for more seasons of the year or at otherwise unmonitored sites, contributing to a more comprehensive understanding of the patterns and values of recreational use. For the US Forest Service, for example, data from social media platforms might help fill gaps between NVUM surveys every five years or reduce costs for collecting landscape or site level visitor use data. The high correlations with on-site visitor counts indicate that there is potential for these data to inform models that can estimate visitation at unmonitored areas.

Future applications of the data presented here could include statistical models for estimating visitation rates and describing spatial and temporal variability in use. Further research could be designed to use these modeled visitation rates to measure preferences of visitors for certain types of sites or experiences. Such approaches may only require relative – not absolute – measures of use, which user-generated content can provide across an unprecedented number of sites. These data and models can assist land managers with questions about the benefits of alternative management options. Development of decision-support tools and data visualizations will make visitation models and social media data more accessible to planners and managers who have limited staff resources and need to quickly detect changing use patterns. We suggest that the development of these models and tools should continue in an applied setting, in partnerships between researchers and recreation managers.

Author contributions

SW, EW, DB, DF, SL, AW designed the research. DF, MT, EL, AW, SW conducted the field research and data analyses. DF, SW, MT, DB, EW, SL, AW wrote the paper. This work was reviewed and deemed exempt by the Institutional Review Board (application #52292) from the University of Washington.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2018.05.045.

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